MIDLAND RADIO
AND TELEVISION
SCHOOLS
INC.

POWER & LIGHT BUILDING, KANSAS CITY, MISSOURI

UNIT NO. 1

YOUR INTRODUCTION TO RADIO AND TELEVISION

LESSON NO. 1

SURROUND YOURSELF

WITH THE SPIRITS OF GREAT MEN

and let them inspire you

and point the way

to YOUR SUCCESS

Your success in life does not depend upon the amount of money you have, or the completeness of your present education. Great men of history and many of our present day capitalists started life without much money or education, struggled for knowledge when knowledge was very hard to get and did not permit a lack of money to discourage them. They set their sights on a definite objective and fought for that objective until they reached it. In other words, they had the will to succeed and stuck to what they started.

Richard Arkwright, a poor barber without an education, who shaved his customers for a penny each, amassed a fortune of two and one-half million dollars, was knighted by a king for his inventions in spinning and won an immortal place in history as Sir Richard Arkwright.

Henry Ford, the son of a hard working Michigan farmer, conceived the idea of the "horseless carriage" and in spite of being ridiculed as the "crazy inventor", overcame many obstacles and became one of the wealthiest men of modern times.

The accomplishments of such men cannot help but inspire you to greater effort and stimulate your desire for YOUR success. That is why this same page in each following lesson will be devoted to true success stories and other stories that will help you avoid the pitfalls which lie between YOU and the kind of a job that will enable you to enjoy life's pleasures. We feel that it is our responsibility to train you right, inspire you, cheer you and guide you over the time worn trail that leads to SUCCESS.

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Unit One

FUNDAMENTALS of ELECTRICITY and RADIO

When undertaking the study of a new subject, most of us have a tendency to hurry. We are prone to skim through the elementary and fundamental parts in our desire to acquire knowledge covering advanced design and operation.

Many young men who have taken up Radio as their life's profession have found their advancement retarded because of their lack of a thorough and complete understanding of the fundamental principles. Because of this situation, I am going to start you out just as though you did not have any knowledge of Radio or Television. First, you will study lessons pertaining to fundamental electrical theories. It is upon these theories that all Radio and Television functions are based.

As soon as you have covered the fundamentals of electricity, you will take up the study of the Vacuum Tube. The Vacuum Tube and its many, many uses will then constitute the major portion of your course of study. First, the Vacuum Tube will be used in simple circuits. I will describe not only the circuits associated with Vacuum Tubes, but also other circuits which apply to Radio and Television fundamentals. Gradually, I will combine these circuits and then the crowning achievement of this unit will be the combination of the various circuits constituting the modern Radio Receiver.

I assure you that it is necessary for you to have a thorough knowledge of all of the various components which go to make up a modern Radio Receiver before it will be possible for you to understand the complicity of a complete set. After you have completed Units I and II, you will be ready to actually build and operate a superheterodyne receiver. Thirty lessons are in this unit.

Lesson One

YOUR INTRODUCTION to RADIO and TELEVISION

"In taking up the study of any new subject, it is always advisable to first secure an insight into the history and development of that subject. Therefore, in this lesson, I am going to give you a short history of the development of Radio and Television.

"Another necessity in being able to grasp a subject fully and comprehensively is to have an outline or a review of the subject you are going to study. In this lesson, you will find a short story on the workings of Radio and Television apparatus. The balance of your study will then consist of learning the details of this interesting story.

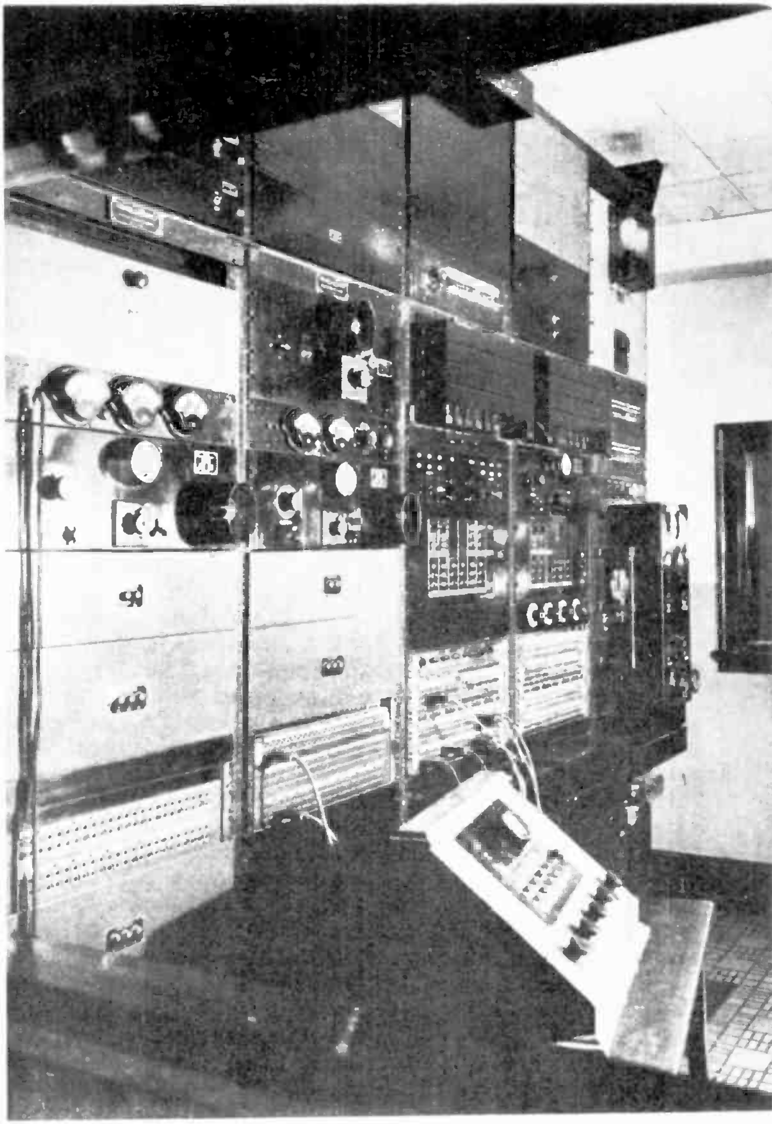
"The latter part of this lesson is devoted to a few hints on how to study and how to secure the most from your studies. Suggestions will also be given for the preparation of your examination papers."

Your desire to train yourself for a job in Radio and Television places you on the threshold of one of the most fascinating and promising industries known to the world today. Looking back to the year 1920, we find that Radio Broadcasting was just being introduced to the public, ushering in a new era of entertainment, advertising and prosperity, while Television was still an undreamed-of possibility.

While Radio's advent was modest, its appeal was tremendous....... voices and music out of the air.......Twentieth Century magic that scored a popularity "bulls-eye". The demand for broadcasting service and receivers sky-rocketed. A new industry had been created ....an industry that swept the phonograph into obsolescence and produced an over-night "mushroom" growth of service shops, Radio stores and factories.

When the call for trained men was sounded over the entire nation, Opportunity knocked upon door after door. But few were able to answer Opportunity's call simply because the majority lacked the necessary training. Those young men that were prepared to enter this great new industry came mostly from the ranks of the experimenters and amateur wireless operators.......fellows that had the foresight to visualize the future of "wireless", or as we know it today, Radio.

Radio has become one of the world's largest industries. It employs thousands upon thousands of men. Yet it is still in its infancy. Millions of dollars are being spent on Radio research work with the result that many heretofore undeveloped phases of the industry are being conquered and developed commercially. Every new development opens fresh markets and brings added opportunity to the man that is trained to take advantage of them. One of the most im-



KMBC
Control Room

portant of the new developments is TELEVISION, a scientific marvel that will do for Radio what sound did for motion pictures.

Regardless of whether you are an experienced Radio man or have had no experience at all, you can secure immense benefits from our carefully prepared, modernized plan of Radio-Television training ....a plan whose sole purpose is to make it possible for you and other ambitious young men to enter one of the most fascinating industries known to the world today. Radio-Television engineering is a highly respected profession, and one who can truly call himself a trained Radio-Television technician is entitled to consider himself a professional in the world's commerce.

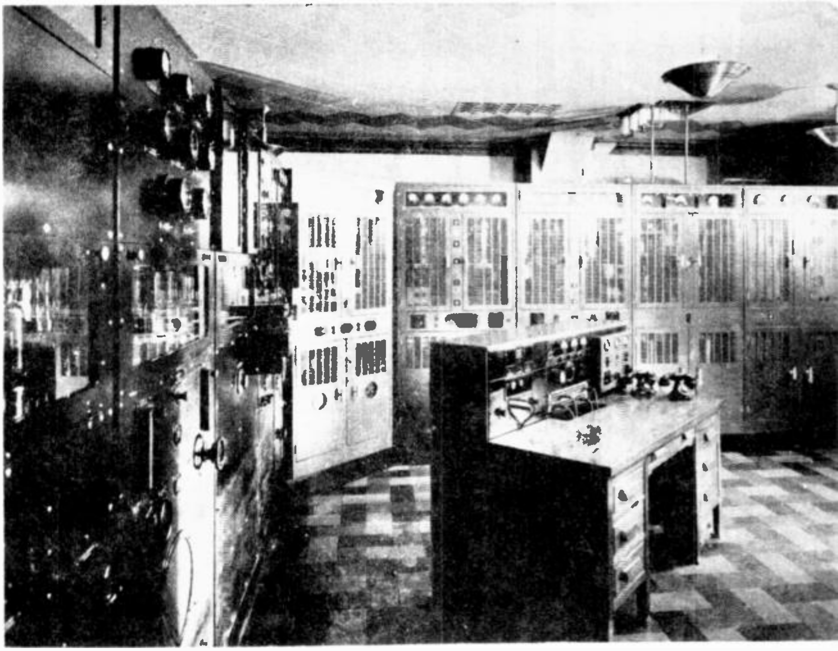
Perhaps you can remember a few years back when we laughed at the absurdity of being able to hear people talk thousands of miles away without the aid of wires. When the first broadcasting stations went on the air, skeptics claimed that it was merely a novelty that would "never amount to a row of pins". Today, practically every American home has a Radio receiver, and the number of Television Receiver equipped homes is rapidly increasing. Citizens of civilized nations throughout the world no longer are satisfied with sound only. They demand the combination of sight and sound. They want to see the performers that they have been hearing for several years. When the public demands something, they get it. Today, the demand for Television Receivers is so great as to assure a gigantic market as Television broadcasting service is extended to all parts of our nation.

Few people have ever really stopped to consider the scope of the industry that you are about to enter. They accept the marvels of their Radio receiver without second thought. In fact, all of us are inclined to take most things for granted. When you turn your Radio receiver on in the evening and tune in a program originating in a studio hundreds or thousands of miles away, do you realize the vastness of the industry that made such entertainment possible?

There are thousands of factories turning out Radio equipment and supplies. Each factory usually has its own research laboratory where engineers and scientists work day and night so that the equipment manufactured may be elevated to a higher standard of perfection. Then there are thousands of Radio service shops and retail stores, as well as hundreds of broadcasting stations. An army of people are required to operate the factories, shops, stores and broadcasting stations. The training that you are just beginning can make it possible for you to enter this great, new industry, to earn a substantial living, enjoy the pleasures of life and at the same time enable you to do the kind of work that you actually enjoy.

When Radio was first introduced to the people of the United States, it was a highly specialized field and practically no plant was equipped to manufacture the apparatus needed. Today, there are hundreds of such plants, but all of these will require changes in manufacturing equipment, as well as the addition of trained men so they can manufacture the new Television Receivers now being placed on the market. Skilled workers, designing engineers, shop foremen, service and maintenance men, broadcasting engineers and many others are going to be needed in greatly increasing numbers as the demands of the American public are met and Television broadcasting facilities are greatly expanded.

Perhaps you are not interested in the manufacturing side of Radio-Television, but would prefer one of the very interesting jobs around a Radio or Television Broadcasting Station. Highly specialized and trained individuals are needed in these jobs because the mistake of one man may ruin the entertainment of millions. The control room of a modern broadcasting station, such as shown on page 2, is the nerve center of all broadcasting activities. The training you are just starting can prepare you to operate such equipment. The work is intensely interesting and the pay is good.



KMBC Transmitter

Perhaps you would be more interested in becoming the transmitter man of a large broadcasting station. We show here the transmitter room of a modern 5,000 watt broadcasting station. On the right is the 5,000 watt transmitter which is in use 18 hours a day. On the left is an auxiliary 2,500 watt transmitter which is switched in whenever a failure occurs in the large transmitter. You cannot deny the desire to be in charge of equipment such as this and to know that the entertainment of thousands of persons depends on you.

The science of Television is going to make Radio work doubly enjoyable. One of the jobs that we know you will want to fill is that of a Television cameraman so that you may participate in the dramatic performances of Television broadcasts. On page 5 is a view of one of the most modern Television studios. It looks similar to the sound stage used by the motion picture industry. Can't you picture the enjoyment of operating such equipment, especially when being paid substantial wages for your efforts?

The usefullness of Radio is not restricted to advertising and entertainment. It plays a very important part in the world's commerce. There are many opportunities for you in this rapidly expanding industry other than broadcasting, servicing or manufacturing. We will list a few of them for you.

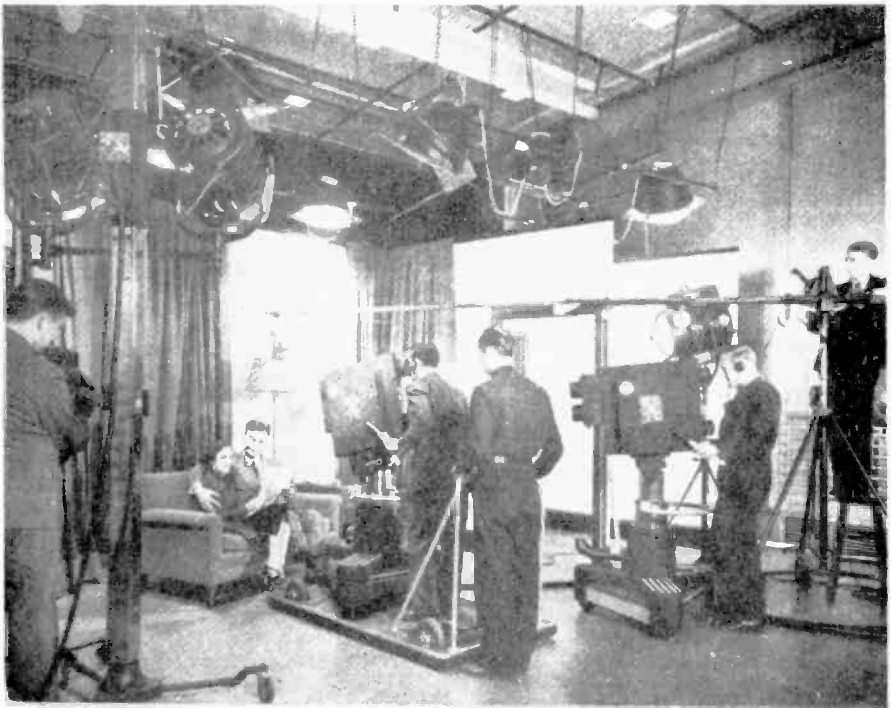
MARINE RADIO. The Radio Operator of a ship enjoys the same privileges as a ship's officer, for his job is recognized as one of great importance. The Marine Radio Operator, or as he is frequently called, "Sparks", not only has the satisfaction of knowing that he is classed as a ship's officer, but the added satisfaction of realizing that hundreds or even thousands of lives are dependent upon his skill and loyalty to his job. Probably all of us have read with great interest, thrilling accounts telling how "Sparks" stuck to his post until the last minute, saved the lives of many persons aboard his ship and how he became the hero of the day. If you have a secret desire to travel and see the world, Marine Radio operating will offer you plenty of opportunity to realize your ambition.

Life on board the modern ocean liner has undergone a radical improvement since Radio's advent. Now it is possible for passengers to talk to relatives at home, they dance to the melodious tunes of American and European orchestras, they receive up-to-the-minute news, which enables them to publish their own daily newspaper. On page 6 is the picture of the Radio room of a modern ocean liner. It is, indeed, an interesting place to work, and of greater importance, the men that work there receive very good pay.

AVIATION RADIO. The substantial growth enjoyed by the airlines of America during the past few years would have been an impossibility without the aid of Radio and the trained Radio man. No longer is the airplane a wandering speck in the sky, speeding onward into unknown weather conditions. No longer is the pilot dependent upon obsolete and questionable aids to navigation to bring him to his destination.

When an airplane departs on a scheduled flight today, its crew is in closer touch with people on the ground than the passengers in an automobile speeding along the highway. The pilot or co-pilot report by Radio to ground bases at frequent intervals. They are at liberty to request weather information whenever it is desired. In fog or rain, they can follow the Radio Beam to their destination,

A Modern Television Studio.



or through the use of the Radio Homing Compass, fly directly to any city in the United States in which there is located a broadcasting station within the range of their special receiver. If, upon arrival at their destination, weather conditions make it impossible to see the ground, they can take advantage of Radio Blind Landing facilities that can guide them to a safe, smooth landing.

Every major airline has its own well-organized Radio department, usually consisting of three separate departments as follows: Engineering, Operating, and Maintenance. Owners of privately owned aircraft are becoming more and more dependent upon Radio aids to

Ship's Radio Room.

Aviation so that at many large airports, aircraft Radio service stations have been added. Airport airplane traffic is controlled by Radio. In fact, there are so many interesting applications of Radio to Aviation that it would be impossible to list them all in this lesson.

Radio is the very nerve center of commercial Aviation as we know it today, and the Radio man has a position of equal responsibility to the pilot, who mans the controls while the ship is in the air. Opportunity in this field is particularly rich.

POLICE RADIO. Practically every city in the United States having police patrol cars now operates Police Radio systems in their war against crime. Radio has so speeded up the activities of the law enforcement bodies of our country that criminals are actually being caught in the process of breaking the law, where before it may have taken days, weeks, or even months in tracking down a criminal.

Practically every large city has two-way Radio communication between control cars and the dispatcher. Most installations of this kind have been broadened to include the fire department, city ambulances and the trouble division of municipal power, light, or water departments. This increased efficiency has made possible an improvement in service of every city department.

State police systems have now installed Radio and new laws are being enacted, making this system more effective. In the past, when a criminal passed over a state line, he was comparatively safe from the officers of the state in which the crime was committed. Besides having this immunity, communication systems were slow and cumbersome. Now there exists intercity communication systems, making it possible to flash news from one large city to another and from one state police department to another. Laws are being devised making it possible to apprehend a criminal, no matter where he may be found. Because of greater distances to be covered, more powerful transmitters are in use. This requires technicians with a higher degree of training to take care of this more powerful apparatus. The higher the type of training demanded, the better the salaries. Besides that, the operator of this equipment has the satisfaction of knowing that he is aiding society in the apprehension of law-breaking criminals.

INTERNATIONAL RADIO. Among the first uses of Radio was the transmission of messages from ship to shore, or shore to ship. The next important use of Radio was the spanning of the Atlantic Ocean, and later, the Pacific. Today, Radio is still one of the most important message carriers where it is not economical to stretch wires or lay cable when great distances are to be covered at a relatively low expense. Radio message systems exist between practically all civilized points, enabling one to send a message to remote places in a very few minutes. Today, it is possible to pick up the telephone in your home and talk directly to any large city in the world. Pictures are being sent by Radio so that the newspapers today may place world events before your eyes shortly after they occur. After completing your training in Radio-Television, it is possible that you may be operating the equipment which will make all of this possible.

THE EVOLUTION OF RADIO. The history of Radio presents a gripping story of unusual interest to all. It proves conclusively that man can accomplish the almost impossible if he has the will to do so. The early-day scientist had very little with which to work. They were grasping for knowledge and information that seemed to be beyond their reach, but they did not become discouraged. The more complicated the problem, the more aggressively they attacked it. Thanks to their persistence, Radio and Television are highly perfected today.

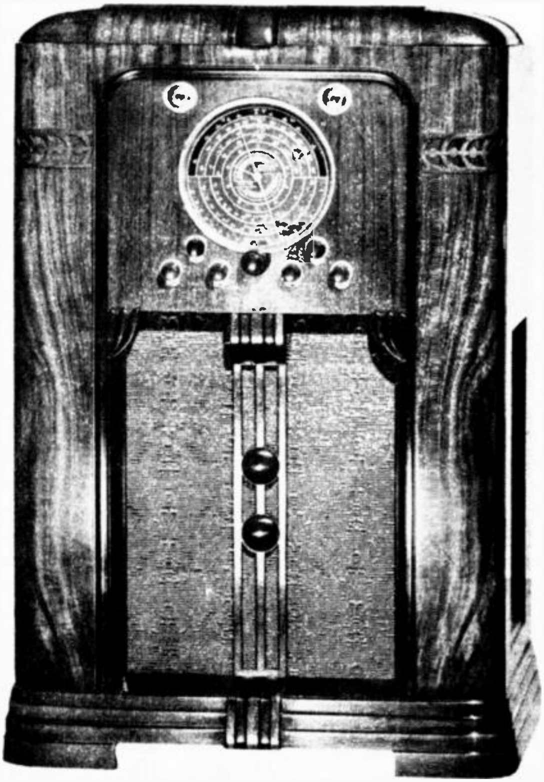
The early history of Radio goes back as far as 1842. In this year, high-frequency oscillations were produced by Joseph Henry, who was born in New York in 1797. Those oscillations are the basis of all modern Radio.

In 1882, Professor Dalbar made a statement, which at that time seemed very fantastic. He predicted that we would have wireless communication between points over one-half mile apart. Professor

Dalbar had just been able to successfully transmit across his laboratory.

A Radio-Telephone conversation over a distance of one-fourth mile was first held by Preece in 1885. Then, in 1887, Heinrich Hertz founded the theory of modern Radio, and in his honor, Radio waves are often called Hertzian waves. Marconi, who is usually conceded to be the "Father of Wireless", was first able to communicate over a distance of four miles in 1897. He later increased this distance until he was able to cover from 15 to 30 miles. Then came that memorable day in December, 1901, when Marconi was able to send the letter "S" from Troy, England, to St. John's, Newfoundland. Soon after that he communicated between Washington, D. C., and Brant Rock, Massachusetts.

Vacuum tubes were unknown during these earliest experiments. A "coherer" was the first Radio detector. This was a glass tube filled with iron filings. It had a tapper similar to that on an electrical bell to tap the glass tube to keep the iron filings from becoming stuck together. This really is a far cry from the modern superheterodyne set shown on this page.



23-Tube High-Fidelity Receiver.

The next development in Radio was the use of the crystal detector. A crystal is a mineral having the property of rectifying Radio waves. In conjunction with the crystal, tuning coils and large loose-couplers were used. These parts were quite bulky and occupied a fairly large table and their cost was extremely high. The headphones manufactured during that period were by no means satisfactory and the best pair cost from $25 to $30.

VACUUM TUBES. Thomas A. Edison conducted the original experiments leading to our modern vacuum tube. However, Dr. Lee DeForest, in 1907, made improvements resulting in the first commercial applications of vacuum tubes for Radio. In approximately 1884, Edison was attempting to develop what we know today as the incandescent light bulb. His early experiments consisted of a lighted filament inside of a glass bulb from which nearly all of the air had been evacuated. Inside of this glass envelope he had a small piece of metal. This piece of metal was not heated, but when connected to the positive terminal of a battery, Edison found that a current would flow from the heated filament to the metal plate. Edison attached no particular significance to this experiment insofar as Radio was concerned and at that time did not dream of the tremendous outgrowth which has since resulted from his efforts.

Following the World War, a rapid development of the vacuum tube began. Successful Radio demonstrations were constantly being conducted by enthusiastic and foresighted Radio experimenters. The Westinghouse Electric & Manufacturing Company of Pittsburgh, Pennsylvania, conceived the idea in 1920 of Radio becoming a home entertainment factor, and in 1921, the Government issued the first broadcasting license to this company. The Radio station is still in operation, the call letters being KDKA.

There still exists a big thrill to the old-timer when he hears KDKA, because back in 1921 and 1922, when there were only a few broadcasting stations on the air, it was the "talk of the town" to receive KDKA. The presidential election of Harding was broadcast by this station and the success of this broadcast resulted in the American public becoming "Radio minded". From that small start, Radio has grown to one of the world's largest industries.

EVOLUTION OF THE RADIO RECEIVER. The crystal detector receiver was the first employed when commercial broadcasting started. Thousands of people built their own receivers using the inefficient crystal detector, a tuning coil and a pair of headphones. It was very simple and easy to construct, but extremely difficult to maintain proper adjustments. Under ordinary conditions, the crystal detector receiver was capable of receiving signals over a distance of 15 to 20 miles, but the thrill of hearing voices from out of the air compensated for any lack of distance.

In the early days of Radio, vacuum tubes and the associated equipment was so expensive that only one-tube sets were used. There were very few factory-made sets on the market, so it was necessary for the Radio enthusiast to construct his own. Many an old-timer today will reminisce with a good laugh at the tricks he played on that one tube. Everything possible was done to secure greater efficiency, making the older sets complicated to operate. Some of the first receiving sets had from eight to twelve controls.

In the early days of Radio, the programs broadcast were of an inferior quality; therefore, the "radio fan" concentrated on "DX" reception instead of listening to and enjoying a chain broadcast as we do today. The letters "DX" in Radio mean "distant reception". Later, as the quality of broadcasting improved, entertainment value became the primary consideration instead of distant reception. However, in recent years, "DX" reception has again become a hobby. The thrill of being able to listen to foreign countries has captured the fascination of many listeners.

After vacuum tubes became a little less expensive, three-tube sets were common and these would operate a loudspeaker. Next came five-tube receivers. However, a five-tube set was the economical limit for quite some time, because all of these tubes had to be operated from batteries.

In 1927, the first practical, all-electric Radio receiving set was introduced to the public. More tubes were used because their price had been reduced and the expense of operation was far less for an eight-tube electric set than for one of the old battery receivers using only three tubes. Radio really became prominent in 1928 when one large manufacturing company sold over a million sets. Today, there are at least three manufacturers selling a million Radio sets yearly.

EVOLUTION OF TELEVISION. While successful Television is quite young, the idea originated many years ago. In 1873, a telegraph operator named May, while working at an Atlantic cable receiving station in the village of Valentia on the southwest coast of Ireland, noticed that his instruments were acting in a peculiar manner. The equipment in this cable office used selenium as a high resistance material, just as carbon is now used. May discovered the fact that as the sun came through the window falling on this selenium, his instruments were affected, indicating that the light from the sun was responsible. At first, it was thought the heat was affecting the resistance of the selenium, but later it was found to be the effect of light. This discovery marked the first development of the photocell or the "electric eye".

A German inventor named Nipkow, in 1884, conceived the idea of Television. Later, he invented the Television scanning disc. This is a disc with small holes in it used to break up the picture into a series of light variations. The vacuum tube had not yet been invented, nor did he have any of the other modern electrical equipment which is now in use. The modern "photo electric cell" was entirely unknown. However, the idea that Nipkow conceived has formed the basic principle of Television down through the years. With the further development of Radio apparatus and electrical equipment, Television has become more and more a reality until today it can be considered as a perfected science.

A few years ago, our movies did not have sound. The addition of sound greatly enhanced the entertainment facilities of motion

A Modern Television Receiver.

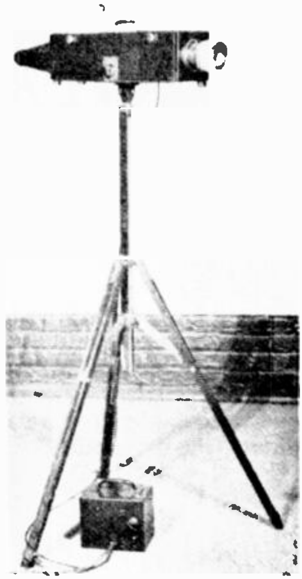
pictures and today we have motion pictures that surpass any possible stage production.

Radio broadcasting, as we have known it, has only sound. We were not accustomed to seeing the persons we had the pleasure of hearing. Television adds the sight to our Radio set. A Television receiver is not an attachment to your present Radio. It is an addition. You may tune in the broadcasting station on your regular Radio receiver to receive the sound portion of the program. When that station is also broadcasting Television, you tune in a special Television receiver so that you may see the artists to whom you are listening.

Radio programs produced by stations in the United States are vastly superior to those of any other country. This is especially true of countries where broadcasting is governmentally owned and operated. In the United States, we are all well acquainted with the fact that broadcasting stations are supported by the revenue they receive from advertising. The advertiser creates a competitive situation, because one advertiser vies with another to create a better program, thereby attracting your attention to his program so that he may call his wares to your attention. Unquestionably you realize the advantages gained by adding "sight" to the already perfected "sound".

Because all of us have gradually become accustomed to Radio receiving apparatus, we do not always give it the attention it justly deserves. In other words, in a large majority of homes, it has become commonplace. However, imagine the Television receiver shown on this page placed in a corner of your living room. On the screen will be motion and action--something at which you will want to look; hence, you will give it a great deal more attention than you would by merely listening to the Radio alone.

It is not possible to read or play cards and at the same time enjoy a Television program as we do a Radio program today. Therefore, since Television demands your attention, an advertiser will have a much better opportunity to display his wares to you. Consequently, he is willing to pay more for the advertising privilege. With Television advertising reaching the entire nation, the incomes of broadcasting stations will be vastly increased. They, unquestionably, will employ many more men, all of whom must be trained men, and these men will be well paid.



The Electron Camera.

Radio has been a tremendous help to aviation, guiding airplanes through fogs and storms. Sometimes the fog becomes so thick that a pilot cannot land his ship safely. Engineers are expending every effort to further perfect blind landing equipment. Along this line of development, a phase of Television is being perfected which will make it possible for this Television apparatus, by means of ultra-violet rays, to actually penetrate the thickest fog. Such equipment has already been demonstrated and a picture of the apparatus is shown on this page. When this equipment is perfected, a pilot will be able to bring his ship down just as easily as if he could see the ground.

If it is ever necessary for the United States to enter another war, think of the part that Television will play. An airplane may be sent across the enemy's lines, equipped with a Television camera and transmitter. He will be able to take pictures of the enemy's movements. These pictures will instantly indicate to the artillery where their shells are landing, without having to wait for the planes to return with a photograph as was done in the last war.

Television developments of today will in no way obsolete present Radio sets. It is designed to be an addition to the Radio set. There is no intention for Television to supplant Radio or moving pictures. This new science will need an ever-increasing number of service men, installation men, and personnel to operate the Television stations. Television can grow in the United States only as rapidly as men are trained to handle this new service.

A CONDENSED DESCRIPTION OF RADIO

When you sit in the quiet comfort of your home and listen to a Radio program originating thousands of miles away, don't you marvel at the possibility of being able to transmit the music of an orchestra or the tones of the pipe organ over all this distance without wire connections?

A thorough study of the transmission and reception of Radio signals constitutes the Radio portion of your course. However, so that you will have a better insight into what occurs between the studio where the program takes place and the sound coming from your loudspeaker, we are going to give you a few non-technical explanations at this time.

THE BROADCASTING STUDIO. Today, the majority of all Radio programs originate in an especially constructed room known as a studio. Even the smallest broadcasting station has at least two such studios and the average-sized station will have more. The three major network broadcasting systems in the United States each have approximately 15 studios in New York with additional studios located in key cities throughout the United States.

These studios will vary considerably in size. A size of studio is used which is best adapted to the type of program to be broadcast. A small studio, generally having the appearance of a living room, is used when speeches are to be broadcast. This type of studio is used so that the speaker will be perfectly at ease during his or her broadcast. A dramatic play, involving only a few actors, is usually broadcast from a slightly larger studio. Such a studio is shown on this page. Orchestras and Radio "shows" generally come from studios such as shown on the next page.

Studio "B" at KMBC.

Studio "A" at KMBC.

Recently, it has become quite a fad for Radio "shows" to have an audience. To accommodate the audience, the Radio studio has taken on the appearance of a small theater, seating from 300 to 2,000 persons. The Columbia Broadcasting System's "Playhouse No. 3" is pictured on page 16 as an example. Here the Radio performers entertain on the stage, the program is broadcast by Radio and also reproduced over a public address system so that the audience in the auditorium may hear as well as see the broadcast.

All broadcasting studios must be especially designed and built if the program is to sound natural. A properly designed, well-constructed broadcasting studio is really a "room within a room". The studio is more or less suspended inside of the frame work of a building so that no outside sound or vibration can enter the studio. The walls, ceiling and even the floor are acoustically treated. This is done to prevent echoes or reverberations within the studio. Voices and music then sound natural so that the reproduction from your loudspeaker is as nearly identical to the original as possible. Were it not for this special acoustical treatment of the studio, the performer would sound as though he were talking in a large, empty room. It would have the so-called "rain barrel" effect.

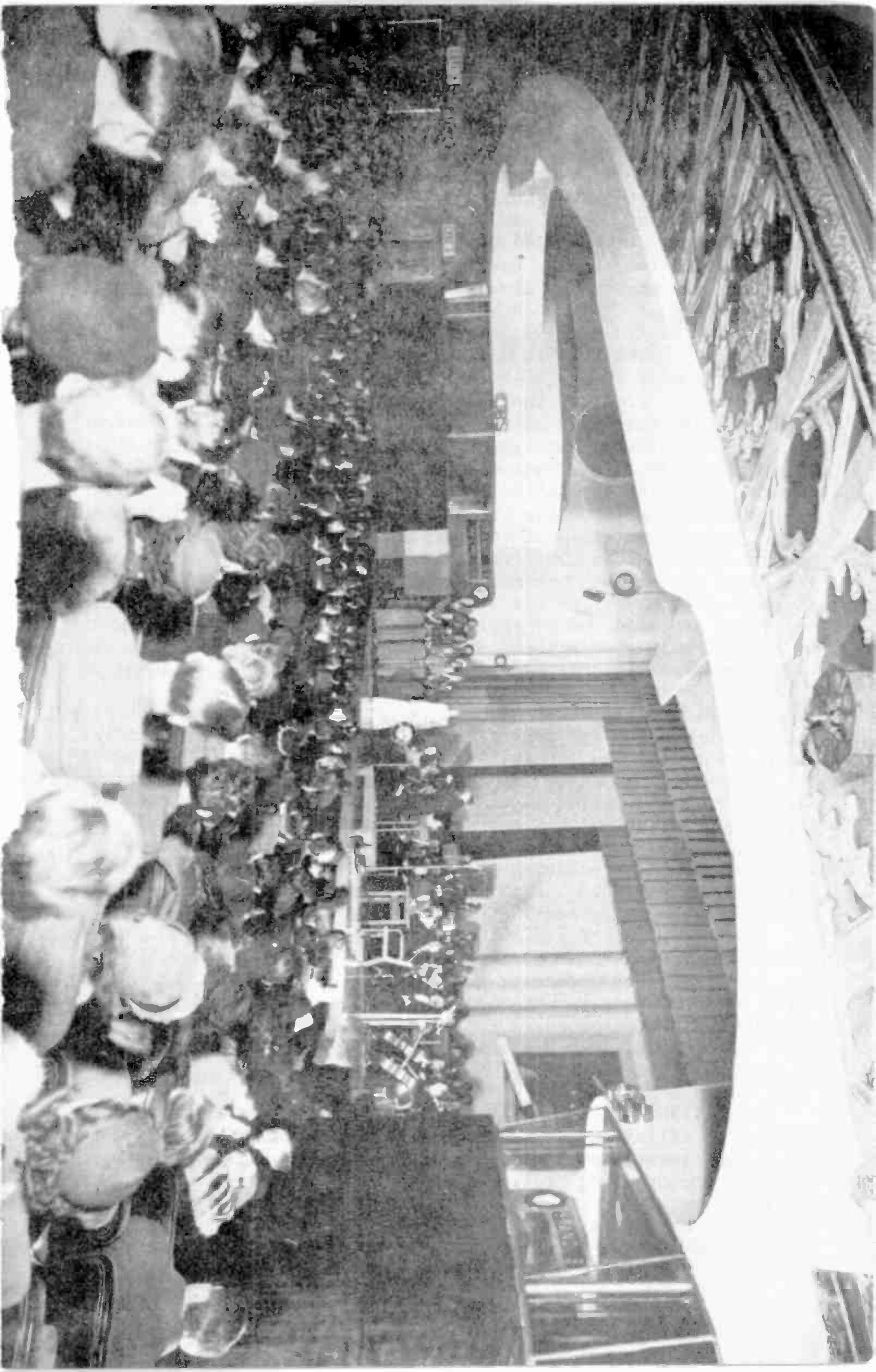
Some Radio programs originate from points of interest away from the studio. Oftimes this results in a hollow-sounding effect, caused by the lack of proper acoustical treatment at the place where the program is originating. Programs are broadcast from night clubs, large auditoriums, athletic arenas and many other spots where events of public interest are held. Programs from these points do not always sound the best, but the type of entertainment well over-shadows the defects in the broadcasting. These programs are called remote control broadcasts.

THE EAR OF RADIO. The instrument which hears the sounds produced during a Radio broadcast is called a *microphone*. It is one of the most important pieces of equipment in a broadcasting station. Sound waves are set up by an artist's voice or the musical instruments of an orchestra. These sound waves reach the microphone wherein they are converted into corresponding electrical impulses or waves. Therefore, the sole purpose of the microphone is to convert the sound waves into electrical waves. The naturalness of the reproduction of a broadcasting program can be no better than the efficiency of the microphone. Three popular types of microphones are shown on this page. We are sure that you are going to find it very interesting when you study the construction and operation of a microphone.

THE BROADCAST STATION NERVE CENTER. The nerve center of a broadcasting station is called the control room. The amplifying system of the broadcasting station is located in this room. The feeble electrical waves or impulses coming from the microphone are delivered to powerful amplifiers where they are amplified, then sent to the Radio transmitter. On some large programs or Radio shows, it may be necessary to use several microphones. The output of each

Three Popular, Modern Microphones.

A Large Theatre-type Broadcasting Studio.



microphone is brought to the control room, where an operator regulates the volume and blends the impulses coming from the various microphones. The control room engineer's job is one of the most interesting and important in the operation of a broadcasting station. It is he who must switch from one studio to another, from a local studio to a chain program, or perhaps to some night club or athletic arena. His pay is good and the surroundings in which he works are of the best. Two of the several reasons for his job being so interesting are that he is always meeting new people and conquering new problems.

RADIO'S POWER PLANT. At the Radio broadcasting station's "power plant", the Radio transmitter is located. If the station has a power of 1,000 watts or more, the power plant is usually located at some point in the country at or near the edge of town. The high-powered broadcasting stations are generally located outside the city limits in order to prevent excessive interference when a listener desires to tune in a distant station. One hundred or two hundred and fifty watt stations are usually located inside the city limits because their lower power will not cause interference over any great distance. Special telephone lines are used to carry the amplified electrical waves from the control room to the Radio transmitter, when it is located away from the studio. These telephone lines must be carefully prepared and properly maintained if the voice and music is to be transferred without distortion. This special preparation and maintenance is generally the job of the telephone company's engineers under the supervision of a Radio engineer.

The Radio transmitter generates what is known as a "carrier wave". The reason for this name is that the carrier wave "carries" the program from the transmitter to the receiver. At the transmitter, the voice and music impulses are impressed on the carrier wave (this process is called modulation), then sent into the broadcasting antenna. The antenna radiates the carrier wave on which the voice and music impulses have been impressed. The radiations are intercepted by a receiving antenna, wherein corresponding feeble impulses are produced. From these impulses, it is possible for the Radio receiver to reconstruct the original program.

Another group of Radio technicians are employed at the Radio power plant. They control the power of the station and keep careful watch over the expensive and complicated equipment. A modern, 1,000 watt broadcasting station costs approximately $50,000, while a 50,000 watt station costs approximately $600,000. It is obvious that the owner of such a station would not place an incompetent man in charge.

RECEIVING A RADIO SIGNAL. It is necessary for best reception to have an efficient antenna. Usually the antenna is erected between two elevated supports. It intercepts the Radio waves coming from the broadcasting station. A "lead-in" connects the antenna to the Radio receiver , and then by means of tuning, we select the Radio wave of the station we desire to hear. The study of tuning circuits and how they perform is undoubtedly one of the most interesting phases of receiver operations.

The Radio waves intercepted by the antenna are extremely feeble and must be amplified. Therefore, in the receiving set, there are multi-stage amplifiers to amplify these feeble waves. How they are constructed and how they operate constitutes a very interesting study.

From the multi-stage amplifier, the Radio wave next goes to the detector. The detector consists of a special circuit wherein the Radio waves are converted. The electrical impulses in the output of the detector circuit correspond to the original sound impulses produced by the microphone in the broadcasting studio. The process of detection constitutes a very interesting study.

Following the detector, it is necessary to have additional amplifiers. The sound impulses in the output of the detector are insufficient to operate a loudspeaker directly; therefore, they must be amplified. The loudspeaker converts the electrical sound waves back into mechanical sound waves and the Radio program is heard. During your experimental activities, you are actually going to build various types of amplifiers such as these.

A CONDENSED DESCRIPTION OF TELEVISION

The latter part of your course of training will thoroughly cover the principles involved in the transmission and reception of pictures through the air.

Broadcasting stations everywhere are installing Television equipment. The three major chain broadcasting systems are considering ways and means of establishing a national Television service.

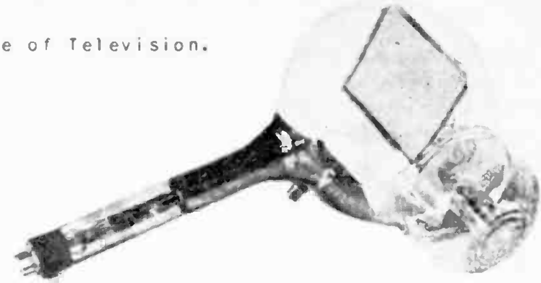
TELEVISION STUDIOS. A modern Television studio of today has all the appearances of a motion picture sound stage. The special sound stage must have the same acoustical treatments that are necessary in sound broadcasting, because sound is being broadcast as well as sight. After the conditions for sound have been fulfilled, it is next necessary to provide the equipment and space for picture transmission.

A picture of one of the most modern Television studios that has ever been built is shown on page 5. Here you see two very modern Television cameras, special floodlights, a microphone boom and all the other necessary equipment for the "shooting" of Television pictures.

In the making of a motion picture, a camera is focused on the artists and a sensitive film records the picture. In a Television studio, a camera is also focused on the artists, but the picture is recorded or "scanned" by an extremely sensitive electric eye called the *"Iconoscope"*. At the same time, a microphone picks up the voice or music and transmits it in the usual manner.

THE EYE OF TELEVISION. In our explanation of Radio broadcasting, the microphone was called the "ear of Radio". The Iconoscope or Television camera is called the "eye of Television". The Iconoscope is a special type of photoelectric cell which sees the picture

The Iconoscope--the Eye of Television.



and converts the elements of light into corresponding electrical waves or impulses. The Television camera is sensitive to light variations and will respond to thousands and thousands of changes per second. This camera actually performs the almost unbelievable job of actually "shooting" the picture. Therefore, it can be truthfully called the "eye of Television". In the output circuit of this marvelous piece of apparatus, electrical impulses are produced which represent the picture on which the camera has been focused. A photograph of the Iconoscope tube is on this page. Can't you just imagine yourself operating an Iconoscope camera?

THE TELEVISION CONTROL ROOM. The output of the Television camera is carried through an especially constructed cable called a "co-axial cable", to the Television amplifiers located in the control room. A modern Television control room is shown on this page.

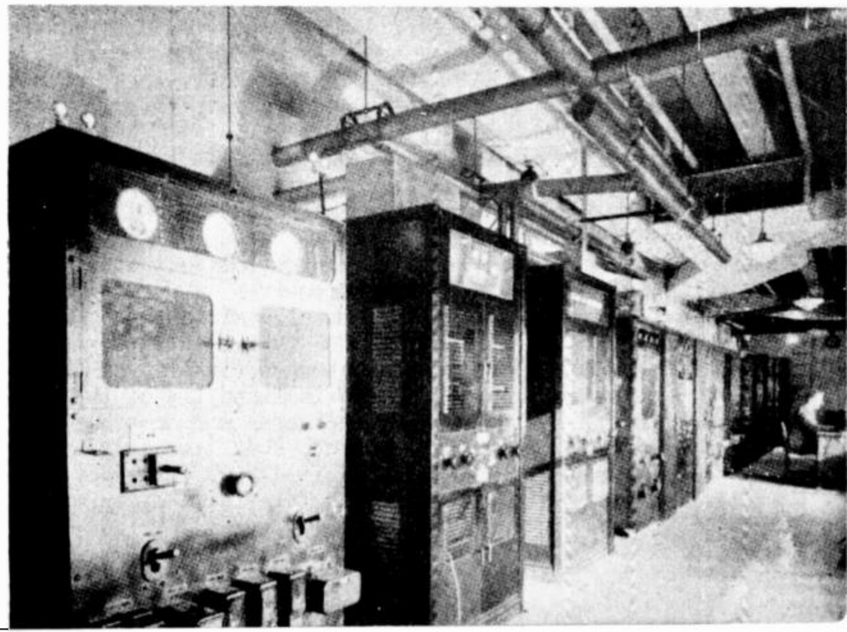
A Modern Television Control Room.

Since the electrical impulses produced by the Television camera are more feeble than the electrical waves produced by a microphone, it is necessary to employ more powerful amplifiers for the Television impulses. A highly trained sight technician is in charge of the Television control room. It is his job to properly maintain the picture intensity and brilliance. At the same time, the voice transmission must be handled by a sound technician. The Television control-relay man must closely watch the performance and his monitor picture so that he may relay instructions to the cameraman and thereby maintain a high-quality picture.

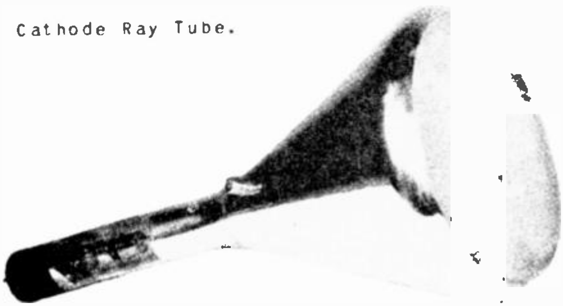
TRANSMITTING TELEVISION IMAGES. Television transmitters are operated on what are known as "ultra-high frequencies". Transmission on these frequencies has the peculiar characteristics that regardless of the power of the transmitter used, the distance of transmission seldom exceeds or extends beyond the horizon. Therefore, the higher the building in which the transmitter is located, the greater will be the coverage of any Television transmitter. For this reason, the National Broadcasting Company have their Television transmitter located at the top of the Empire State Building, the tallest building in the world. A "co-axial cable" connects the Television amplifiers with the Television transmitter. This cable is expensive, both from the standpoint of manufacturing and installation. Therefore, it is customary to locate the transmitter in the same building with the studio.

A Television transmitter is shown immediately below. At first glance, it appears to be very similar to a sound transmitter. However, it has specially designed circuits necessary to handle the picture impulses instead of voice and music impulses. It is neces-

A High-Powered Television Transmitter.



A 9-Inch Cathode Ray Tube.



sary that the engineer in charge be properly trained in the operation and maintenance of this type of equipment.

A monitor is used in the transmitting room so that the engineers in charge there may check the quality of the picture transmission at all times.

The output of the Television transmitter is then connected to a specially designed short-wave antenna. The purpose of the transmitting antenna is to propogate through space the high-frequency waves on which the Television picture impulses have been impressed.

THE TELEVISION RECEIVER. In a Television receiver, it is necessary to have tuning circuits, the same as in a sound receiver. This enables you to select the Television station whose picture you desire to view.

A receiving antenna is used to intercept the radiated picture waves and a lead-in conducts them to the Television receiver. Special types of amplifiers must be used to amplify the high-frequency waves picked up by the antenna.

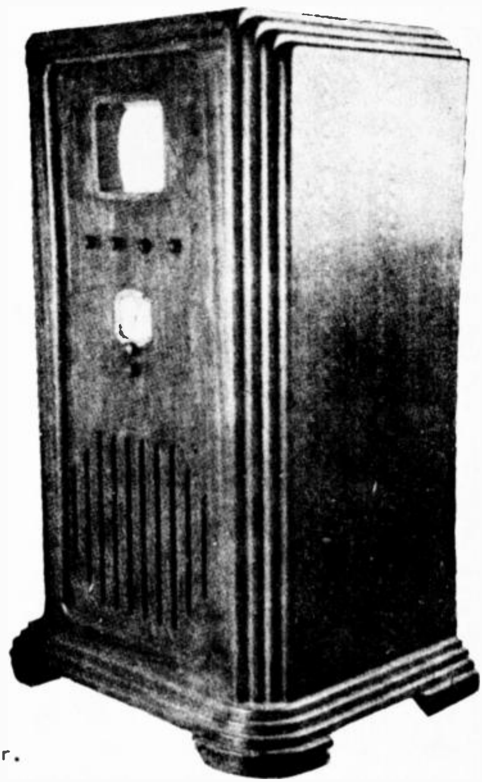
Following the high-frequency amplifiers, a detector is used. Here the high-frequency waves are converted and the picture-frequency impulses are secured in its output. Following the detector, a "video"-frequency (picture frequency) amplifier is employed to strengthen the impulses.

Now instead of applying these amplified impulses to a loudspeaker, they are applied to a special cathode ray tube. Such a tube is shown at the top. The amplified video-frequency impulses reconstruct the picture directly on the end of the tube. Cathode ray tubes are obtainable in varying sizes so that different sizes of pictures may be secured. A receiver such as shown opposite has the tube mounted in a horizontal position and the picture is viewed directly on the end of the tube. The Television receiver shown on page 11 has the tube mounted vertically and the picture is viewed on a mirror mounted on the inclined lid of the cabinet.

Both of these Television receivers are combination sight and sound receivers. As you will notice, they have only one dial. When this single dial is tuned to the ultra-high frequency broadcasting station which is also transmitting Television pictures, the picture signal will be automatically tuned in at the same time. This allows perfect sight and sound reception and the tuning is no more difficult than tuning an average Radio receiver.

While the present-day Television receivers are comparatively simple to operate, their internal construction is quite complicated. Expert engineers are required to design these receivers. After they are manufactured and placed in the hands of the public, expert service men are required for the adjustment and maintenance of them.

The study of this new industry is of great interest, and the personal satisfaction of knowing that you are one of the few who have been properly trained is very self-gratifying. Only a few men understand the secrets of Television transmission and reception at the present time, so your goal should be to place yourself in a position to "demand your own salary" in the future.



A Sight and Sound Receiver.

SUGGESTIONS ON HOW TO STUDY

Few persons have the natural ability or have acquired the knack of being able to study thoroughly and conscientiously. Since your future success in Radio and Television depends upon the thoroughness with which you acquire an understanding of this subject, we deem it advisable at this time to insert a few pointers on how to study.

SET ASIDE A SPECIFIED TIME TO STUDY. While it is not always possible, the first requisite of satisfactory study is to be regular and systematic. Establish a schedule for your time of study, then do everything within your power to live up to it. It would be best to set aside a certain part of each day. If you find this impossible, use the week as the basis of your schedule. Decide upon the number of hours that you are going to study during each week. If you find that you are behind in your schedule over a period of two or three days, put in an hour or two extra until you have caught up again.

You must bear in mind that the amount of time you spend in study will govern the "value received" from this training. Your course of study should not be secondary to other activities, but rather should be the one important project in your life.

There is no best time for studying applicable to all students. However, it has been thought that the early morning hours are the most suitable. Your mind is generally fresher at this time and you do not have a day's worry and work behind you to detract your attention from your studies. Some students may find it impossible to study during the early morning hours, and others reach their maximum effectiveness for absorption during the early afternoon. Still others prefer the evening or late at night. This is partially a matter of habit and also governed by one's nervous disposition.

If the only time available for study is in the evening, it is advisable to rest at least 30 to 45 minutes after eating before starting to study.

HAVE A PLACE TO STUDY. Most students find it extremely difficult to study successfully in the midst of confusion, or even with another person in the room. If noises about your home disturb you, or if interruptions by other members of the household are apt to be frequent, then by all means you should have a place where you can be alone while you are engaged in your studies. Why not consult your family and have a room set aside as your laboratory and private study? Later in your training, you will be building equipment which you do not want disturbed. Undoubtedly you need a place where you can be by yourself to conduct your experiments and engage in study if you are to be successful in your chosen profession. Since you have decided to undertake the study of Radio and Television, thereby improving your position in life, then go about your studies thoroughly and systematically.

If your living quarters are such that you cannot have a private place to study, by all means continue with your studies, regardless of the obstacles placed in your path. Let your study time be suited to its purpose; have it understood in your home that you are engaged in a serious piece of work and must not be interrupted.

PROCEDURE. Through many years of experience, we have found the following procedure best for the average student. These rules may not apply to you, but if you have no rules of study for yourself, then we suggest that you follow this procedure.

First, read through the entire lesson thoroughly and carefully. Now if you are going to study more during this particular day or evening, it is best that you relax by doing something else for at least 30 minutes or an hour. Then start in again at the first of the lesson and go over each paragraph individually and thoroughly. If a reference is made to some previous work about which you are not certain, stop right then and there, go back and review that previous work. Sometimes an explanation may not seem perfectly clear; therefore, it is advisable to compare this explanation with something you have already studied, or something with which you are familiar. Comparison is always an easy manner of fixing things in our minds.

At some previous time, you may have been taught to read your school material rapidly. We know of several instances where grade schools and high schools have advocated this method. In the study of scientific literature, such as the course of instruction you are undertaking, this method of reading is absolutely not satisfactory. The material must be studied, not merely read. After completing a single paragraph, repeat, this time dissecting each sentence thoroughly. Make certain you understand the definition of each word used and the idea conveyed by the entire sentence. Oftimes, a thought is lost because the definition of a single word is not properly understood; therefore, a good, practical dictionary should be at hand.

Next, inspect the examination questions at the end of the lesson. You should not write out the answers to these questions at this time, but it is well to investigate in your own mind if you can answer the questions. After you have gone over the questions, it is best to study the entire lesson again thoroughly and completely, then write the answers to the examination questions.

It appears as though we have suggested studying a single lesson three times, all in the same evening. This is not very advisable. Do something else between each time you study the lesson. An average student should spend not less than 9 hours on the average lesson. Some assignments are a little more difficult and will require more time; other assignments are easier and perhaps 9 hours of study will not be necessary.

An average student should not plan to complete more than a maximum of three lessons a week. Three lessons a week will be sufficient, even though you intend to devote your entire time to this training. Remember that you have experimenting to do besides your regular lesson study. Experience has proven that if you try to learn the material more rapidly than three lessons in one week, later on you will probably find that you have an insufficient foundation. While it may be that you are studying the lessons thoroughly, as a general rule this information will not stay with you if acquired too rapidly.

There is one warning we want to make at this time. Never memorize the answers to examination questions. You should study the subject material until it is thoroughly and completely understood instead of just trying to memorize a particular paragraph or answer. The reason for this warning is that you might memorize the answer to a certain question, then later on, this same question might be asked in a slightly different manner and the memorized answer would not be satisfactory. If you thoroughly understand the subject, you will be able to answer any kind of a question pertaining to that subject.

SEQUENCE OF LESSON MATERIAL. When studying some of the many lesson subjects pertaining to Radio and Television, a new student is inclined to believe that some of the material presented is superfluous and of no consequence. Perhaps you may think that some of the topics are inserted merely to fill up space. This is an incorrect assumption because the engineers who have prepared this course of study have found by experience that all of these subjects are important. Unless you learn the fundamentals thoroughly and completely, it is likely that you will not comprehend the balance of your instruction. "Elementary" is not the word for preliminary material. "Fundamental" is more descriptive. Fundamental material is always necessary in the study of a science because it is the foundation for the more applicable and interesting things to come later.

Throughout your studies, you will encounter several wiring diagrams. Do not just glance at these diagrams, then pass on, because they are extremely important. Draw each diagram several times. Make certain that you understand the reason for the use of every piece of apparatus on the diagram; and be sure you understand the action of the entire circuit. Do not memorize a diagram or a circuit, but rather, be able to construct it in your mind with your knowledge of the relationship which exists between the various components and the manner in which these circuits function.

FORMULAS. Many facts concerning Radio and Television cannot be properly expressed without the use of equations or formulas. Therefore, it will be necessary at various times throughout the course to insert such equations and formulas. It will not be necessary to memorize all of them, but make certain that you are familiar with their use. Most formulas are founded on a basic electrical law. The more commonly used formulas will eventually become so familiar to you that it will not be necessary to refer to the text for them. The formulas which are not used so frequently may be looked up when the necessity arises. After selecting the proper formula, it is only necessary to understand how to use the formula.

Using a formula generally consists of merely substituting numbers for letters, then performing the indicated mathematical function. At the proper intervals, an entire lesson will be devoted to a study of the mathematical functions which you will be using at that time.

All of the formulas used in this training are in reality very simple. At first, some of them may appear difficult, but by thoroughly studying the text, they will be found quite simple. Do not try to make a hard job out of an easy one.

The text of this lesson was compiled and edited by the following members of the staff:

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INC.

POWER & LIGHT BUILDING, KANSAS CITY, MISSOURI

UNIT NO. 1

THE ELECTRON THEORY

LESSON NO. 2

MICHAEL FARADAY

.....A POOR BLACKSMITH'S SON WHO REACHED THE PINNACLE OF SUCCESS!

Born in London, England, in a humble home over a stable in the year 1791, the infant, Michael Faraday, seemed destined to live a life of poverty. At the age of thirteen, he became an errand boy, and a year later was apprenticed to a book maker for seven long years of drudgery. Armed with only a bare rudimentary education, Michael determined to delve into the intriguing mysteries of chemistry and electricity and devoted every spare moment of his time to study.

When his period of apprenticeship was served, he wrote the great Sir Humphry Davy, hoping that he might win his aid. But instead, he received a polite but discouraging note that would have altered his entire life had he permitted it to influence his ambitions. Instead, Michael continued to strive for his objective and entered into crude galvanic experiments, the results of which so enthused him that he longed for time.....more time. He had learned one of the first essentials of success .....that wasted time was forever lost.

While working at his trade as a bookmaker, his longed-for opportunity came in the form of a footman in livery and a note from Sir Humphry Davy. Michael was engaged to care for Sir Humphry's scientific instruments at a salary of six dollars per week.

From this point on, his energy and determination carried him steadily onward until he reached the pinnacle of his success with the discovery that magnets could produce electricity. Following this came other achievements, including the discovery of electric induction. Eminent men came from all parts of the world to see him. Glorious honors were heaped high upon his head.

Michael Faraday, the poor blacksmith's son, had won a permanent and prominent place among the famous men of history!

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Lesson Two

The ELECTRON THEORY

"I am sure that you are going to find the study of the electron very interesting. For years, there were many functions in the study of electricity that could not be proved, but were simply taken for granted. After the discovery and proof of the existence and the actions of the electrons, these uncertainties were removed. A study of the Electron Theory will provide you with the basis for the proof of nearly all modern Radio and electrical theories and make the balance of the lessons very interesting and easily understood."

In order to establish the fundamental knowledge necessary for a complete and comprehensive understanding of Radio and Television, the first requisite is to become thoroughly familiar with fundamental electrical actions. Each piece of electrical apparatus used in the construction of a Radio receiver and transmitter or a Television receiver and transmitter, together with all associated circuits, have an electrical circuit through some conducting material and a magnetic circuit, either through some magnetic material or air.

It is of vital importance that the beginning student of Radio and Television secure for himself a complete theoretical and practical knowledge of each individual piece of electrical apparatus before attempting to unite the individual pieces into a complete circuit. The expenditure of considerable effort on the fundamentals of electricity at the present time will be rewarded by rapid progress and a complete interpretation of the information obtained in future lessons.

Since nearly all electrical laws are based on the electron theory (see Fig. 1), it is quite logical to select a study of this theory as the foundation for our course of study. The electron theory came into existence in the year 1897, being introduced by an English scientist, J. J. Thomson. Prior to 1897, another Englishman, William Crookes, had conducted numerous experiments, all of which terminated in strange data that could not be satisfactorily explained. Thomson became very interested in Crookes experimentation about 1877 and began the compilation of data along the same line. After twenty years of brilliant research work, Thomson announced his startling discoveries to the scientific world (1897). Thomson's announcement of the electron theory was the origin of a new epoch for all chemical and electrical theory.

It is well to begin our story with the construction of matter in order that we may realize the significance and importance of the electron theory.

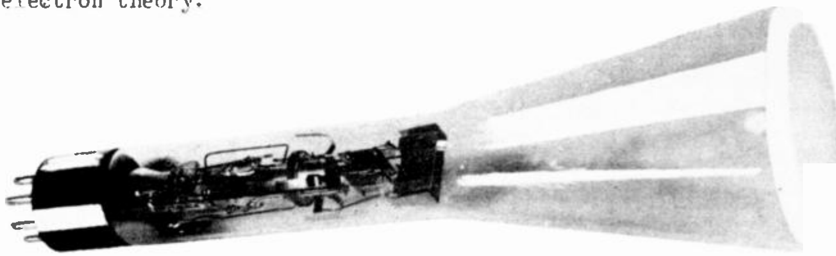

Fig.1 Photograph of a cathode ray tube. The explanation for the operation of this tube is based on the electron theory.

In the next few pages, I shall discuss such subjects as matter, molecules, and atoms. I shall explain and illustrate each of them so that you will have no difficulty in understanding their meanings. You must know about the molecule and the atom before you can understand the electron theory. Read this preliminary material carefully .....don't miss a single sentence!

To make sure that you will recognize the more important statements and definitions, I am going to put them in italics and space them from the body of the text. When you encounter these italicized portions of the lesson, pay particular attention to them! They are the definitions and facts which you should learn and remember.

1. CONSTRUCTION OF MATTER. The information I am going to give you in this lesson concerning the construction of matter and the electron theory is not easy to prove. As you read through this lesson, you must keep in mind that the world's outstanding scholars of science are not definitely certain as to how all matter in the universe is constructed.

By experimentation and mathematical calculations they have been able to compile a quantity of information which is valuable to you as a student in radio. But, there are still many, many problems that puzzle the scientists who have devoted the major part of their lives to an extensive study of the construction of matter. The facts which these learned men have assembled over many years of work is largely responsible for the development of radio and television as we know it today.

As a student beginning the interesting study of radio and television, you should be familiar with the construction of matter in order that your knowledge of the subject will be complete in every detail. However, for you to learn about radio and television, it does not require that you know the exact reason for the construction of matter. The theoretical reasons are immaterial; I want you to learn only the established facts on the subject.

If I were to tell you the basic reasons for the construction of matter, I would have to devote volumes to the subject and would consume much of your valuable time telling you about things for which you will have no use whatsoever in your chosen occupation.

Therefore, while you study the material to follow, keep in mind that I am telling you only about the results that have been achieved by long years of research work. Your interest must lie only in these results and the facts that have been concluded from them. You should not be concerned with the actual process of experimentation nor the mathematical derivations that led to our present knowledge regarding the construction of matter.

2. DEFINITION OF MATTER. I am now going to define the word "matter" for you. I can best do this by asking a question. Do you know of any object which does not have weight or dimensions? After thinking a while, you will certainly conclude that you do not. Every tangible object with which you are familiar can be weighed or measured in some manner. The paper composing this page, the ink used in printing, the chair on which you are sitting, and the air that you breathe, all have weight and dimensions. They are all examples of matter.

Therefore, we can define the word "matter" as being any tangible substance which has weight and dimensions.

Now to make sure that you understand what is meant by "matter," let me give an example of something which does not represent matter. In your daily speech you quite often talk about things which are not examples of matter. You might say, "I think he looks tired." When you use the expression, "I think," you are referring to your power of thought. Thinking is something we all do. However, we cannot place our thoughts on scales and actually weigh them as so many ounces, nor can we measure our thoughts with a ruler. Therefore, a "thought" has no weight or dimensions, so it is not an example of matter.

In the same sentence, we used the expression, "he looks tired." Of course, we all know what the word "tired" means. It is a feeling of fatigue which we experience at times. Again, we cannot weigh or measure that tired feeling into an actual number of ounces or inches. A "tired feeling" is intangible. It has no weight or dimensions and, therefore, is not an example of matter.

All things which are not perceptible by touch or by our senses are intangible and are not examples of matter. However, all tangible objects, such as pencils, books, automobiles, air, etc., can be measured or weighed in some way and are, therefore, examples of matter. Fig. 2 shows a number of these.

3. BUILDING MATTER WITH MOLECULES. Now that we have a thorough understanding of what is meant by "matter," let us proceed to determine its composition. If you were asked to tell the material that was used to build a brick house, your answer would of course be "bricks." Likewise, you would say that a stone house is made of stones; a wooden house consists of pieces of wood, etc.

If we were to regard a brick house as one of the many examples of matter, we would know immediately that the thousands of small bricks used to build the house were the substances of that article of matter.

Now, if we were asked to go still further and tell of what each brick was composed, our answer would be, "Each brick is composed of millions and millions of tiny particles of the same substance." The tiny particles of brick are held tightly together to form a complete brick. Then, all of the complete bricks are assembled in the manner desired and held together with cement to form the building. This is a simple example, but it illustrates an important phase in the construction of matter.

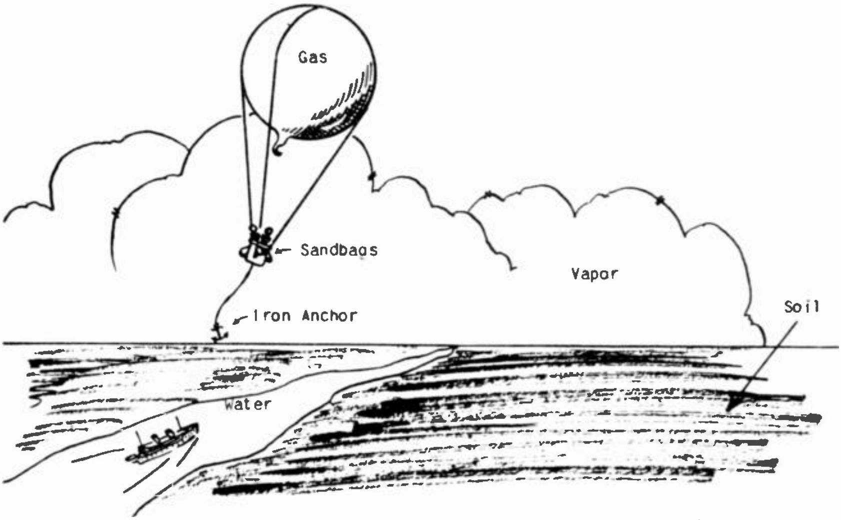

Fig.2 Examples of matter. The gas in the balloon, the sandbags on the basket, the vapor in the clouds, the ground, the ship, the water in the river, and the anchor on the balloon, are all examples of matter.

Let us see how tiny a particle of brick we could obtain. First we would break off a small piece from a single brick and then pulverize the small piece until we had very fine particles. Then, we would take one of these pulverized particles, place it under a high-powered magnifying glass and keep dividing it into smaller and smaller parts.

We would soon reach a limit and would not be able to divide the particles any smaller, because we could not see them. When the size of the brick particle has diminished beyond our power of vision, we must then begin to use our imagination.

Let us suppose that by some "super" mechanical or chemical means, the very tiniest particle of the original brick is divided further and further until we had the smallest possible particle of brick. This most minute piece of brick which we now have (in imagination only) is very important to us; it is the fundamental "building block" from which the entire brick structure is constructed. We know that if we group millions and millions of these tiny particles together, it is possible to form a regular size brick. Then with a sufficient number of complete bricks we can erect an entire building.

Due to its importance, this most minute particle of brick has a special name. It is called a "molecule" of brick.

A molecule of brick is the smallest possible particle of brick that can be obtained.

This statement means that a molecule of brick is the smallest possible piece that can be obtained without destroying the original substance of the complete brick. The tiny molecule has the same properties as the complete brick; the only difference is that the molecule has very minute dimensions.

4. **DIVIDING MATTER INTO MOLECULES.** Let us repeat this experiment. Suppose we were to take a box of table salt, select one grain out of the box, and then keep dividing that single grain until we had the smallest possible particle of salt. What would it be called? A molecule of salt. Similarly, if we were to take a piece of paper, tear off the tiniest piece possible, and then split that tiny piece until it could no longer be subdivided; we would have a molecule of paper. Now, let us define the word "molecule" in order that it may be applicable to any and all cases.

A molecule is defined as the smallest portion of any substance which cannot be subdivided further without its properties being changed.

Thus, it is possible to take any particle of matter and divide that particle (mostly by imagination) into the billions and billions of tiny particles which we know to be constituent[1] parts of it. Since molecules are the very substance of all kinds of matter, we conclude that there are as many different kinds of molecules as there are different kinds of matter.

If you were asked how many different kinds of molecules there are in the universe, you should say that there is an unlimited number, because there is an unlimited number of different kinds of matter.

You should clearly understand that a molecule has the same chemical properties[2] as the substance of which it is a part. If this were not true, it would be impossible for the billions of tiny molecules to combine and form the substance. A molecule of chalk has the same chemical composition as a piece of ordinary blackboard chalk; a molecule of water has the same chemical composition as a glass of pure water, etc.

When we speak of a molecule we do not infer that any chemical change has been made in the original substance. Also, many of the physical properties[3] of a molecule are the same as those of the com-

1 Constituent: The smaller parts which serve to compose the final product.

2 The chemical properties of a substance are the changes in composition which it may undergo when subjected to various conditions.

3 The physical properties of a substance are perceived by the senses or measured by physical means. Physical properties include color, taste, odor, density, solubility in water, conductivity of heat and electricity, etc.

plete substance. Of course, the dimensions are much smaller, but the color, odor, taste, conductivity, etc. remain the same.

5. THE SIZE OF A MOLECULE. Previously, I have said that it is necessary for us to use our imagination to realize the minute size of a molecule. Let me give you an example. We all know what air is. Air is that substance (matter) comprising the atmosphere. It is a definitely proved fact that air has weight. Many, many times scientists have weighed certain volumes of air and found that its actual weight depends upon the percentage of oxygen, nitrogen, helium, argon, and other gases which compose it. Since air has weight and dimensions, it is matter and is composed of millions and millions of tiny molecules of air. Now, for our example to illustrate the size of a molecule.

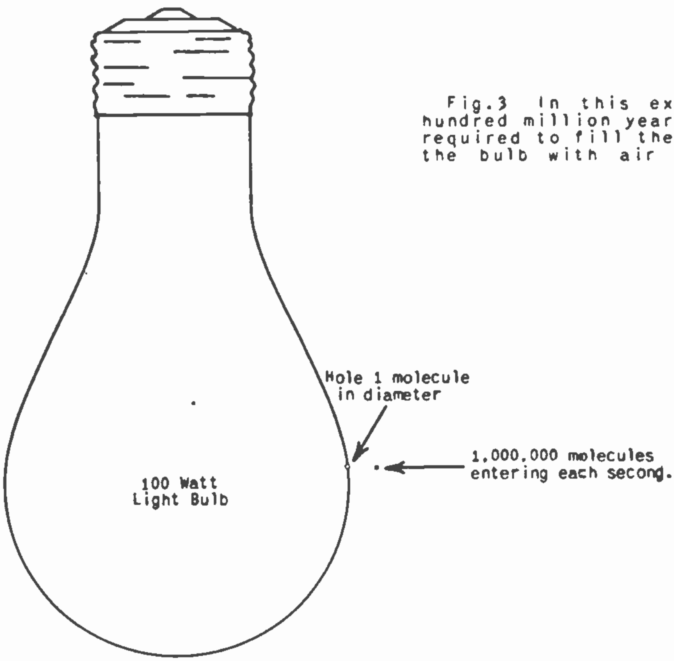

Fig.3 In this example, one hundred million years would be required to fill the inside of the bulb with air molecules.

Suppose we were to take an ordinary 100 watt light globe, completely evacuate the interior, then drill a small hole in it just large enough to allow one molecule of air to enter at a time. If the tiny air molecules rush into the light globe one at a time, at a rate of 1,000,000 molecules per second, it would require 100,000,000 years for the inside of the light globe to become completely filled with air. (Refer to Fig. 3). This example should give you an idea as to the minute size of a molecule.

The greatest scientists have never seen a molecule of any kind, nor will such an accomplishment ever be possible. Our eyes are composed of molecules, and it is impossible for us to see anything which is the same size or smaller than the molecules of our eyes. Even if we did have a single molecule isolated, and if we looked at that molecule through the most powerful microscope available, the ultimate failure to observe the tiny particle would be due to the construction of the human eye itself.

Brilliant men have proved to us that molecules actually exist, but when it comes down to the basic point of looking at one, the eye of the greatest scientist fails him the same as it does you and me.

6. BREAKING DOWN THE MOLECULE. Now that we have studied the construction of matter down to the molecule, let us investigate further to learn of what a molecule consists. Offhand, it seems rather absurd to think that it is possible to obtain a particle smaller than a molecule. However, don't be misled into such an erroneous conception because it is possible to prove that tinier particles actually do exist. This fact has been proved time and time again since the early days of scientific experimentation.

A molecule can be divided further and shown to consist of smaller particles.

All different kinds of molecules have different composition. Molecules of water are composed of different elementary substances than molecules of wood; molecules of air are different from molecules of cloth, etc.

Each different kind of molecule in the universe may be broken down into its elementary constituents. Of course, this "breaking down" cannot be done by ordinary means, but can be accomplished easily by a chemist when he mixes or heats the proper mixture containing the molecule he desires to break apart.

After the chemist has separated a molecule, he cannot see each small particle which composed it. This follows as a logical statement since it has been previously stated that no one can even see a complete molecule. So, again, we delve into the depths of our imagination and try to visualize the size of these particles more minute than a molecule.

7. THE ATOM. First, what shall we name these tiny constituents of molecules? A Quaker schoolteacher by the name of James Dalton expounded the theory that they did exist in 1803. In his formal announcement, he called them, "atoms——the bricks of the universe." Dalton's "atomic" theory gave the reason for many experimental results that had been obtained by himself and by many former scientists. In fact, centuries before Dalton's time, such learned scholars as Kanada, a Hindu, and Democritus, a Greek, had ventured opinions that the tiny particles (atoms) existed. But, they did not have sufficient experimental verification to convince the scientific world.

Dalton's original idea about how molecules are constructed is now proved thousands of times daily. Thousands of manufacturing concerns in all parts of the world use this theory every day to make their products. Research laboratories depend upon it for a large percentage of their development work. In your daily life, you use or see innumerable articles which would not exist if it were not for the fact that Dalton's theory of molecular construction was true. Therefore, I expect you to accept this theory. Remember, I said at the beginning of this lesson that you must not worry about the reasons for these theories. Science has proved them all.

The definition of an atom that I want you to remember is:

An atom is one of the tiny particles obtained when a molecule is broken apart into its constituent units.

Now you will ask the question, "How many atoms are there in a molecule?" I must answer this by saying, "Different molecules contain different numbers of atoms." This is one of the reasons for the existence of different kinds of matter.

You know that a grain of salt is a different kind of matter than a drop of water. One of the reasons is that a salt molecule contains a different number of atoms than a water molecule. Immediately, I must follow this statement by saying "a salt molecule consists of different kinds of atoms than those composing a water molecule."

Now we are confronted with a new problem. I just said that different kinds of atoms exist. This is another fact that has been proved time and time again, so I expect you to accept it as being true. Presently, I shall tell you why atoms are different from each other. As for now, let's learn some more facts about atoms in general.

Throughout the preceding years, scientists have tried and tried to find all of the different kinds of atoms. They think they know exactly how many there are, but they have not been successful in locating and isolating all of them. According to present information, 92 different kinds of atoms exist. Some of these are common to us, but some are extremely rare. You've heard of hydrogen, copper, zinc, mercury, aluminum, oxygen, and sulphur. These are a few of the more common kinds of atoms. But, have you heard of cerium, ytterbium, ruthenium, or protoactinium? These are a few of the rare atoms; they constitute such a small percentage of all matter in the universe that even the most learned scientists do not pay much attention to their existence. Of all 92 atoms, hardly more than 50% of them are found in the different kinds of molecules with which we are most familiar.

8. **BREAKING A MOLECULE INTO ATOMS.** If we were to divide a drop of water into its molecules, then take one molecule and break it down into its atoms, what would we find? We would discover that a molecule of water consists of two atoms of hydrogen and one atom of oxygen. Fig. 4 is an imaginary photograph of a water molecule showing the three atoms.

Breaking down a molecule is a job for a chemist, not a radio man, so don't worry about how a chemist would go about doing this. To us, the important thing is that it can be done.

If a molecule of water can be broken down, it is logical to assume that other kinds of molecules can be treated in the same manner. This has been done by chemists for practically every kind of molecule known to science. When they investigated the construction of the salt molecule, they found that it had contained in it one atom of sodium (a metal), and one atom of chlorine (a gas); sand was found to consist of silicon atoms and oxygen atoms; ammonia contained nitrogen atoms and hydrogen atoms, etc.

Fig.4 Illustrating water molecules (imaginary). Each molecule consists of two atoms of hydrogen and one atom of oxygen.

All creation is composed of the 92 different kinds of atoms, combined and mixed in every conceivable manner.

The kind, number, and arrangement of the atoms determines the kind of molecule formed.

The chemist has most of these atoms isolated and available for research work. When he wants to make a certain kind of matter, he mixes or combines various numbers of the different atoms in an attempt to develop the product he wants. A chemical experiment of this nature is shown in Fig. 5. Perhaps years of experimenting will be required before he finds the right combination. But, when he does,

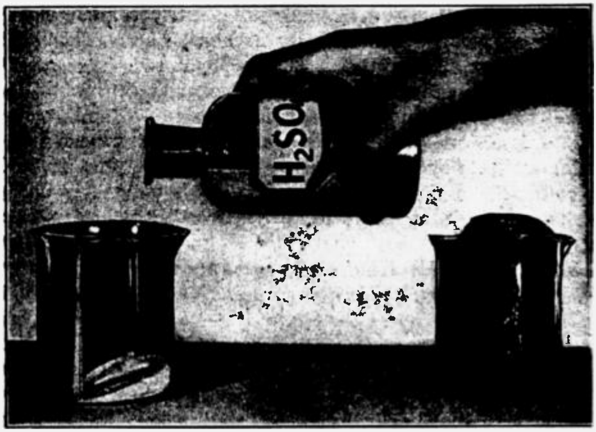

Fig.5 This is a chemical experiment. The H2SO4 is a strong acid (sulphuric). It is being poured onto some sugar. This combination of atoms will result in the sugar being changed to pure carbon as shown on the right.

a new and different product is available to the commercial world and science has advanced a step further.

Thousands of our daily needs are satisfied by these scientifically developed products. Common examples are rayon, synthetic rubber, gasoline, glass, writing paper, medicines, etc. We are living in an age of slavery to science whether we realize it or not. Bear in mind that very few of our present day "necessities" would exist if it were not for the verified fact that all matter consists of molecules; the molecules in turn consisting of different kinds, numbers, and arrangements of atoms.

9. THE SIZE OF AN ATOM. I gave you an example to illustrate the minute size of a molecule of air. Now that we know a molecule of air may be divided into atoms, let's see how small an atom is. Perhaps the analogy[1] will assist you. If five atoms were placed on a postage stamp every second, it would take 300 million years to cover the stamp.

Benjamin Harrow once made a statement which illustrates very clearly the size of an atom. He said, "If the constituent atoms in a tumbler of water could all be labeled for later identification and the water were then mixed with all the water in the world, and if, after thorough mixing, the tumbler were again filled, it would contain two thousand of the original atoms."

10. DIVIDING THE ATOM. I would not be at all surprised if you thought that an atom was the smallest possible unit of matter. Such brilliant men as Dalton, Newton, Priestly, Cavendish, Lavoisier, and many others had the same idea at one time. They even went so far as to ridicule any person who said that an atom could be divided into smaller units. To them, all matter could be divided down to the atom, but the atom was the fundamental "building block for all matter."

This opinion was prevalent throughout the world in the middle of the 18th century. But then, as research work in the structure of matter advanced, certain scientists obtained results from their experiments which could not be explained by the atomic theory. They noticed that with some combinations and mixtures of atoms, they created products different from what they expected. Naturally, they were interested in finding out why their experiments went "wrong," so they set forth into a new field of endeavor to determine the composition of an atom.

While many men worked on this problem, it was J. J. Thomson, an English physicist, who first published his findings. He publically announced,

> *"All atoms consist of inconceivably tiny charges of positive and negative electricity."*

Don't think for a minute that Thomson's theory was immediately accepted by the scientific world. He had to explain and illustrate the basis for his theory time and time again. But, Thomson had the proof; his experiments were so conclusive and his results so convinc-

[1] Analogy: Resemblance in certain respects, or having a similar function.

ing that other scientists were forced to recognize his theory. He could prove many things which had baffled chemists for centuries and he could explain the reason for the existence and nature of electricity. Before that time, electricity was considered a "supernatural wonder of the world," something which could not be understood or explained.

11. IMPORTANCE OF ELECTRON THEORY TO ELECTRICITY. It is true that quite a lot was known about the nature of electricity before Thomson expounded his "electron theory." But there was no definite reason known for the results obtained by the experimenters. They collected facts from which they advanced laws and derived formulas. The laws were proved by the vast quantity of experimental data, but still they could not tell exactly why electricity acted as it did.

Thomson supplied the key which opened the "unknown realm" of electrical wonders. His electron theory proved all of the existing electrical laws, and, most important of all, paved the way for more intelligent experimental activities in the field of electricity.

Using Thomson's theory, all branches of electrical experimentation progressed at a rapid rate. Results of an experiment could be anticipated before it was tried and, invariably, the results expected were obtained. Such modern conveniences as the telephone, telegraph, electric motor, electric lighting, electroplating, etc., were either perfected or invented in this era of electrical history.

Of most importance to us is the fact that during this same time, radio and television were born. Prior to the "electron theory," ideas had been conceived about radio and television but no one had been able to achieve practical results sufficient to justify extensive work along that line.

Since the electron theory was "Aladdin's Lamp" for the electrical experimenters, it is important that you as a student starting the study of radio be familiar with it. The theory is not at all difficult to understand, but I must ask you to start reading the next paragraph with an open mind. As I tell you about the electron theory, try to visualize that you have super-microscopic eyes with which to see these tiny particles of electricity that compose all matter.

12. THE ELECTRON THEORY. So far we have learned that all matter is composed of molecules, and that these molecules may be broken down into various kinds, numbers, and arrangements of atoms. Now let us take a single atom and investigate its construction. In all, there are thought to be 92 different kinds of atoms, each having a different construction. Let us take the simplest atom of all, that of hydrogen.

A hydrogen atom consists of two tiny electrical charges, a positive and a negative charge.

The positive charge is called a "proton" and the negative charge is called an "electron."

It has been definitely proved that each of these electrical charges has a certain weight and certain dimensions; thus, they are particles of matter. In fact, these are the absolute fundamental particles of matter, no smaller particles have ever been proved to exist.

If we are to understand the electron theory clearly, we must learn more about the proton and the electron, as well as how they are arranged in the hydrogen atom.

Since the proton is a positive charge and the electron a negative charge, they offer an attraction for each other. This statement is consistent with the fundamental physical laws:

1. *Like charges repel each other.*
2. *Unlike charges attract each other.*

These laws are illustrated in Fig. 6, using two small balls. Study this drawing carefully and be sure to remember the laws it illustrates.

The magnitude or strength of the positive charge of the proton is equal to the strength of the negative charge possessed by the electron.

Thus a proton has the same repelling force and attracting force as an electron. Of course, a proton would repel another proton and attract an electron; whereas an electron would repel another electron and attract a proton.

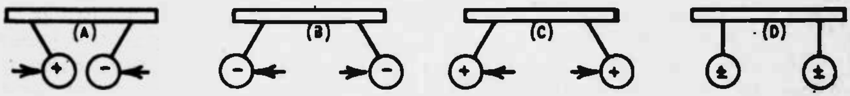

Fig.6 Illustrating that like charges repel, and unlike charges attract.

When an electron and proton are brought close together (as they are in all atoms), the mutual force of attraction holds the two particles together and keeps them from flying apart. Now, it is quite possible that the attraction will not be to the extent that the proton and electron are in direct contact with each other, but, nevertheless, they are each held in such a balanced state that they do not normally tend to separate.

Now, we encounter a most surprising fact about the electron theory.

A proton does not have the same weight as an electron.

It has been found that a proton is about 1,835 times as heavy as an electron.

Remember, though, that the positive electrical charge of a proton is the same strength as the negative electrical charge of an electron. This leads us to believe that the light, negative electron is much more "active" than the heavy, positive proton. Our belief is absolutely right; an electron is many times more active than a proton, and therein lies one of the reasons for a lot of things which we know to be true about electricity.

13. THE ELECTRON. There are three very important properties of an electron which you should remember. These are:

1. *An electron is a negative particle of electricity.*
2. *An electron is inconceivably small.*
3. *An electron exerts a repelling force on another electron.*

It is also necessary for you to understand that wherever an electron is found, it will always be the same size, will have the same weight, and will possess the same quantity of electricity. Likewise, all protons are exactly alike. All matter is composed of electrons and protons and these infinitely tiny particles are of the same composition in all kinds of matter.

As to the exact substance or composition of an electron or proton, do not let such a thing worry you, because even the most outstanding scientists have not been able to definitely solve that problem. Insofar as we are concerned in our study of Radio and Television, the electron consists of a negative charge of electricity, and the proton is a positive charge.

14. SIZE OF AN ELECTRON. Now, I will give you an example to illustrate the size of an electron. Scientists have estimated that the diameter of an electron is less than two million-millionths of a centimeter,[1] which is equivalent to approximately one-six billion-billionths of an inch.

Perhaps this minute particle can be visualized easier in the following example. Suppose that a single drop of water were magnified to be 1,000 times the diameter of the earth. The atoms in this enlarged drop would be about one mile in diameter, and the electrons in the atom would be approximately one inch in diameter. By comparing an object having a diameter of one inch to one having a diameter of 1,000 times that of the earth, we can obtain an idea as to the size of the electron, compared to a drop of water.

Compared to an average atom, the electron is about the same relative size as a pin head in the center of a cathedral. Thus, the electron is an extremely minute particle, far beyond our power of visualization.

No one has ever seen a single electron and no one ever will. However, that does not prevent us from learning many things pertaining to its actions, because it is easily possible to study millions of them grouped together and arrive at definite conclusions.

It has been proved that a proton is about 1,835 times as heavy as an electron. Thus, a proton is relatively heavy, but if considered alone, it is still an extremely light and small particle of positive electricity. Fig. 7 illustrates the relative weight of a proton and an electron.

15. THE CHARGE OF AN ELECTRON. We have been saying that an electron consists of a negative charge of electricity, but so far have not mentioned the extent of this charge. It has been exper-

[1] A centimeter is .3937 inch.

imentally determined that approximately 6,280,000,000,000,000,000 electrons are required to constitute one coulomb of electrical charge. The unit "coulomb" is used in electrical work to designate a quantity of electricity. This unit will be completely defined in Lesson 3. Since 6,280,000,000,000,000,000 electrons are required to constitute one coulomb, the negative charge possessed by a single electron is extremely minute.

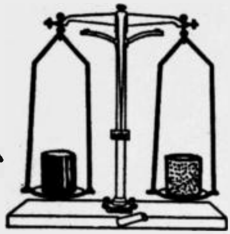

Fig.7 Illustrating the relative weight of a proton and an electron. A proton weighs 1,835 times as much as an electron; hence 1,835 electrons will be necessary on one pan to balance one proton on the other.

The figures just given as to the size, weight and charge of an electron have been determined by extensive experimentation and precise calculations. It is beyond the scope of this study to include a description of the method of calculation or the procedure followed during experimentation to arrive at these figures. However, as stated previously, it is not important that you know why these figures are true, but rather you should know what they are in order to understand your future study in Radio and Television.

16. THE PROTON. We have been discussing the electron in detail; now, let us turn our attention to the proton. We have already established certain facts concerning the proton.

1. *A proton is a positive charge of electricity.*
2. *A proton is about 1,835 times as heavy as an electron.*
3. *A proton is inactive compared to an electron because of its greater weight.*

Whereas both the proton and the electron possess the same quantity of electrical charge, the electron is by far the more active due to its lack of weight and inertia.[1] Therefore, when we are explaining chemical and electrical actions by use of the electron theory, we are mainly concerned with the activity of the electron and are not so interested in the proton

17. THE SOLAR SYSTEM. Now that we have learned what electrons and protons are, let us see how these tiny particles of electricity are arranged in the structure of an atom. This can best be understood by comparing the structure of an atom to something with which we are more familiar. An excellent analogy of the construction of an atom is found in the arrangement of our solar system.

It isn't necessary that you have a complete knowledge of as-

[1] Inertia: That property of matter whereby it opposes a change. If at rest, it opposes being set in motion; if in motion, it opposes being stopped.

tronomy in order to understand this analogy. Since ancient Greek times, astronomers have studied the moon, earth, stars, etc., and have accumulated a sufficient quantity of evidence to prove the motion of the various planets about the sun. We are all familiar with the fact that the various planets are in a continuous state of rotation around the sun and that the distances between the sun and the planets (and between the planets themselves) is tremendous in comparison to the size of the planets.

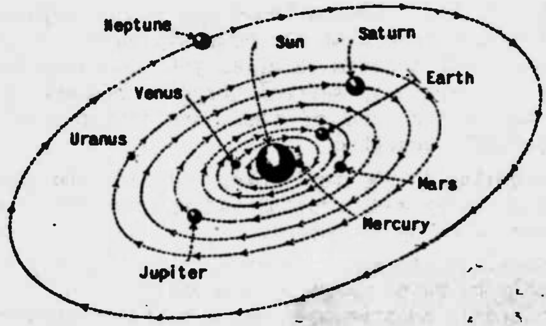

Fig. 8 Comparison of atomic structure to the solar system. The sun represents the nucleus and the planets represent the revolving electrons.

In Fig. 8, the sun is situated at the center of the solar system. The various planets revolve in their orbits about the sun in a regular and continuous manner. The planets all move around the sun, and all of them are continuously rotating about their own axes. We know that the earth is in constant rotation because the sun rises and sets each day. When the sun is on our side of the earth, there are a certain number of hours of daylight, and when the earth has revolved so that our side is not toward the sun, there are a certain number of hours of darkness. Thus it is proved that the earth is in constant rotation about its own axis through the north and south poles, as well as revolving about the sun in its normal orbit. Astronomers have also proved that the other planets revolve about the sun, and that each of them is in a constant state of rotation about its poles in the same manner as the earth.

Of course, no one can explain why our solar system is constructed as we know it to be. No one can explain why the planets in the solar system are kept apart, nor can anyone explain the exact composition of the sun and all the planets. Thus, you see this is a deep, scientific problem, one which as yet has never been completely solved. Even though no one understands the exact composition of the solar system, it still provides us with an excellent analogy for the structure of an atom.

18. HOW ATOMS ARE CONSTRUCTED. In an atom, there is always a nucleus at the center, the same as the sun is the center of our solar system. Revolving around the atom's nucleus, there are several planetary or free electrons, the same as the planets revolve

about the sun in our solar system. The electrons which revolve in the planetary orbits surrounding the nucleus of an atom do not bump into one another, just as the planets in our solar system never collide. It is also true that the planetary electrons surrounding the nucleus of an atom are separated by great distances, compared to the relative sizes of the electrons themselves. This again is very similar to the distances between the planets when we compare those distances with the sizes of the planets.

19. THE NUCLEUS. No one knows the exact composition of the sun; it is likewise true that the composition of the nucleus in an atom is a scientific problem which as yet has never been satisfactorily solved. There are several theories concerning the nucleus of an atom, but so far none of them have been proved sufficiently to become generally accepted.

> *According to the most common belief, the nucleus of an atom contains many protons and several electrons (except in an atom of hydrogen).*

All of these electrons and protons are held tightly together[1] and cannot normally be moved apart or separated.

The nucleus of an atom has been a baffling problem for years, and those scientists who have experimented considerably in an attempt to determine its construction differ somewhat in their opinions. We are really not interested in delving deeply into the discoveries that have been made, so we shall accept the general opinion, which is as follows:

> *All atoms have a nucleus at their center which consists of one or more protons. In all except hydrogen, the nucleus also contains several electrons, but never as many electrons as it has protons. Since the nucleus of an atom contains more protons than it does electrons, the resulting charge on the nucleus of an atom is positive. It is this positive charge which holds the planetary electrons surrounding the nucleus confined within their normal orbits, and keeps them from breaking away to destroy the normal structure of the atom. Since the planetary electrons are all negatively charged, they are attracted by the positive nucleus. They also repel each other, thus preventing collisions between them as they revolve.*

There are three important points to remember about the nucleus of an atom. These may be listed as follows:

1. *The nucleus of an atom is always positive because it contains more protons than electrons.*
2. *The nucleus of an atom offers an attraction for the electrons in the planetary orbits, thus holding the atom together in an electrically balanced condition.*

[1] Protons normally repel each other. In the nucleus they are held together by what the scientists call "binding energy." No one knows what this "binding energy" actually is.

3. *The nucleus of an atom is very heavy (due to the large number of protons which it contains); therefore, it is inactive, both chemically and electrically.*

20. ELECTRICAL BALANCE OF AN ATOM. In a normal atom, the total number of electrons is equal to the total number of protons. Whereas the nucleus contains all of the protons and a few of the electrons, the remaining electrons necessary to equal the total charge of all of the protons are contained in the planetary orbits surrounding the positive nucleus. This is an important fact and you should remember it.

An atom is balanced electrically, which means that it does not possess an excessive negative nor an excessive positive charge.

All atoms are electrically neutral when in a normal condition; hence, a normal atom does not show evidence of being charged with electricity.

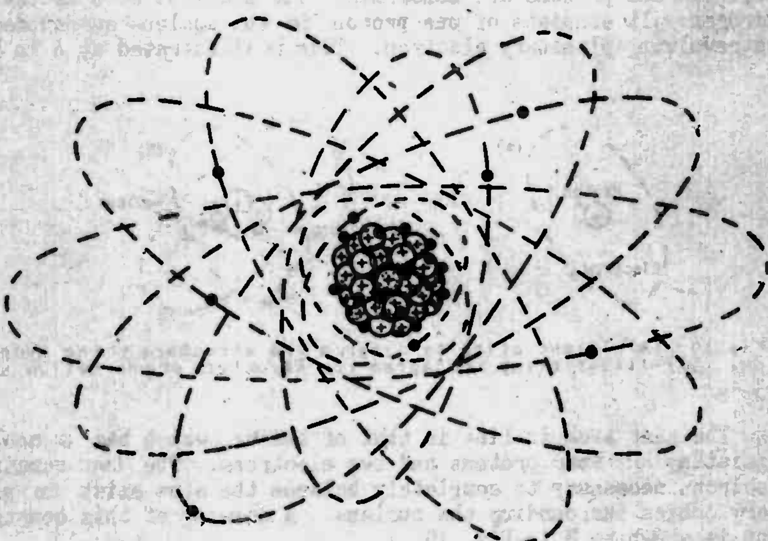

Fig.9 Drawing to illustrate the structure of a complete atom. Notice the nucleus and the free planetary electrons.

Perhaps the thought has come into your mind as to what exists between the planetary electrons and the nucleus, as well as between the planetary electrons themselves. This space is called the "ether." The ether is another of those intangible things that you will have to visualize in your mind. Really, it is a purely imaginative substance, because it does not consist of any tangible particles known to science. Ether may be called that space between the planetary electrons and the nucleus of an atom. It has often been stated that radio waves travel through the ether. This will be discussed in a later lesson and I am sure you will understand much more about it at that time.

21. THE COMPLETE ATOM. Fig. 9 shows an imaginary view of an atom with its nucleus at the center, the electrons revolving in the planetary orbits, and the ether which constitutes the intangible substance between the planetary electrons and the nucleus.

From this description of the construction of an atom, I am sure you have a picture of it fixed in your mind. Again I want to stress the point that even though we cannot satisfactorily explain the composition of an electron or a proton, we know that they do exist and that they are the particles of electricity which compose all atoms in the universe. No one can satisfactorily explain the reason for the existence of the electrons and protons, but it has been proved time and time again that they are the basic particles from which all matter is composed.

All atoms are constructed differently insofar as the number of electrons and protons are concerned. The simplest atom is that of hydrogen. It consists of one proton in the nucleus surrounded by one revolving planetary electron. This is illustrated at A in Fig. 10.

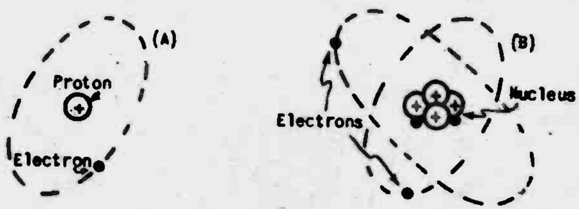

Fig.10 (A) Illustrating by diagram the structure of the hydrogen atom. (B) Illustrating by diagram the structure of the helium atom.

The next atom in line is that of helium, which has a nucleus consisting of four protons and two electrons. The two remaining electrons necessary to completely balance the atom exist in planetary orbits surrounding the nucleus. A drawing of this construction is shown at B in Fig. 10.

All other atoms have a more complicated atomic structure. The exact structure of all atoms is not clearly understood and we shall not attempt to give any information regarding the construction of the more complicated ones. Our work in Radio and Television does not require that we know the exact structure of all kinds of atoms, but we must remember that all atoms consist of a positive nucleus surrounded by free negative electrons.

22. ATOMS DIFFER FROM EACH OTHER. The reasons that atoms differ from each other in physical, chemical, and mechanical characteristics is because of the difference in the number of electrons

and protons contained in them, and the differences in the arrangement of the electrons and protons.

For many, many years, chemists tried to change the atoms from their original construction. For example, they made many attempts to change iron and copper into gold. All of these attempts were unsuccessful, simply because they were unable to destroy the original construction of the nucleus in the iron and copper atoms. It is not possible to change an element into another element unless the nucleus of the atom is changed.

Our modern scientists still try to change the atoms, but, so far, they too have been unsuccessful except for a very few of the invaluable elements, such as magnesium, neon, and carbon.

23. THE PLANETARY ELECTRONS. Getting back to the relationship between the electron theory and the study of Radio and Television, we shall now consider the importance of the electron theory in fundamental electrical actions. We have previously stated that an atom is electrically balanced, meaning that it has the same number of protons that it has electrons, when in a normal condition. If an atom contains 12 protons, it also has 12 electrons.

An electrically balanced atom does not exhibit any electrical influence on a neighboring atom. In the foregoing example, it was stated that 12 electrons and 12 protons were contained in the atom. It is immaterial as to whether the 12 electrons exist entirely in the nucleus, entirely in the planetary orbits, or part of them in the nucleus and part of them in the planetary orbits. In reality, the structure of an atom of this type is such that some of the electrons are held with the positive protons in the nucleus, and the remaining electrons exist in the planetary orbits surrounding the nucleus.

23. POSITIVE AND NEGATIVE IONS. Those electrons which are held tightly within the nucleus of the atom are called the "fixed" electrons, and it is impossible[1] to remove them from the nucleus. On the other hand, the planetary, or "free" electrons are in a state of constant revolution about the nucleus and it is very possible for one or more of these electrons to be temporarily removed from the atom by some external force. Of course, when this is done, the atom is in an unbalanced condition and will possess more protons than it has electrons. Since the total of the positive charges then exceeds the total of the negative charges, the atom will exhibit a positive electrical influence on neighboring atoms.

An atom in an unbalanced condition is known as an "ion." If an ion has more protons than it has electrons, it is known as a "positive ion," whereas if it has more electrons than protons, it is known as a "negative ion."

Even as it is possible to remove the free electrons from an atom, it is likewise possible to add electrons to the planetary orbits. If this is done, the total of the negative charges exceeds the total of the positive charges, and the normal atom has become

[1] Except for the few atoms previously mentioned.

a "negative ion." Hence, an atom may be unbalanced either in a positive or negative direction, depending upon whether it has a deficiency or an excess of electrons in its planetary orbits.

Removing or adding electrons to the planetary orbits of an atom does not mean that the atom itself is changed from one element to another. You will recall that in a previous paragraph, we stated that in order to change from one element to another, it was necessary to change the composition of the nucleus.

24. THE FREE ELECTRONS IN MOTION. Of all the electrons and protons composing an atom, we are primarily interested in the free (planetary) electrons which are revolving about the nucleus. These electrons are free to move whenever an external force of such a nature is applied that it can set them into motion. Herein, we have the underlying explanation for many electrical actions.

> *The free electrons can be moved from atom to atom in a definite direction through a conductor. This is called the "flow" of an electric current.*

Also, it is possible to accumulate many, many electrons at one particular point and, at the same time, cause another point to be very deficient in electrons.[1] The point that has been caused to accumulate an excessive number of electrons is highly negative, and the point which has been robbed of its electrons is left with an excessive number of protons and is highly positive.

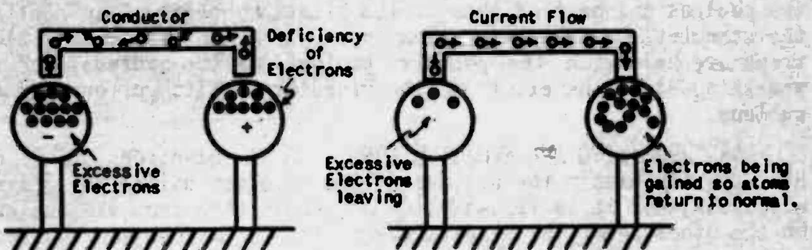

Fig.11 Illustrating how an electron-moving force produces a current flow through a conductor.

This is exactly what happens in a battery; that is, the positive pole of the battery has been robbed of electrons from its atoms, whereas the negative pole of the battery has had an excessive number of electrons added to its normally balanced atoms. The chemicals in the battery cause this electron transfer.

Fig. 11 at A shows two round balls which have been "charged" electrically; that is, electrons have been taken from the one on the right (leaving it positive) and added to the one on the left (making it negative). A conductor is shown above these balls, but notice that the conductor is not in contact with either of them, so

[1] Electrons cannot be created nor destroyed; a gain at one place means a loss at another.

the free electrons in the conductor are moving at random in all directions.

Now when the conductor makes contact with both balls as shown at B, the excess electrons on the left ball pass through the conductor to the right ball. Thus, we have a current flow through the conductor from left to right. This flow continues until the previously accumulated charge is lost entirely. If these balls represented the poles of a battery, they would be kept charged for a long time by the chemical action taking place inside the battery.

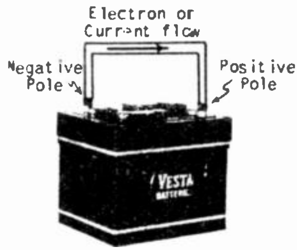

Fig.12 Electrons move from the negative to the positive terminal of a battery.

In Fig. 12 the two poles of a battery (the positive and negative poles) are connected across an electrical conductor. An electrical current will pass from the negative pole of the battery to the positive pole. This electrical current flow, as we call it, actually consists of an electron movement from the negative pole, which has an excessive number of electrons accumulated on it, through the conductor to the positive pole which has a deficiency of electrons. The fundamental laws of attraction and repulsion cause this movement. Much more information on this action will be given in a following lesson.

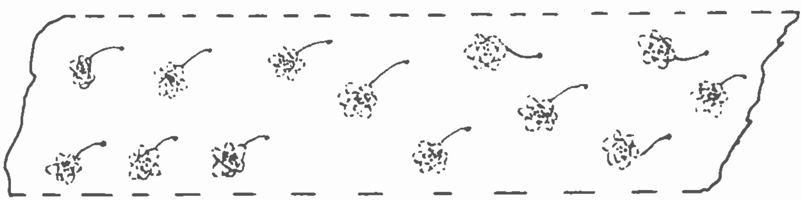

Fig.13 Enlarged view of conductor, showing several atoms--electrons drifting from left to right.

Knowing the electron theory, it is possible for you to understand exactly the nature of an electric current flow, and later it will be possible for you to explain and predict the many actions in electrical circuits. The importance of the electron theory should be quite evident for this reason.

Since the electron theory clearly explains what happens when an electrical current flows through a conductor, let us investigate this phenomenon a little further to see how the electron transfer takes place.

In Fig. 13 we have shown a greatly enlarged section of a copper conductor. Let us assume that a pressure (electron-moving force) is applied across this conductor in such a direction as to cause the electrons in the atoms to move from left to right. Only a few of the atoms in the copper conductor are shown; it is impossible to show all of them.

The electron-moving force will be in such a direction as to cause a continuous movement of the electrons from atom to atom, from the left to the right. The free electrons in the outer orbits of the respective atoms are the ones that are going to move from atom to atom. The fixed electrons in the nucleus will not be moved.

This electron movement from atom to atom constitutes what we normally call the flow of an electric current through the conductor, and it is this flow of current which does the work in an electrical circuit. The movement of electrons produces heat in the conductor and establishes a magnetic field around it. These are the two important effects of current flow which you will study thoroughly in a later lesson.

25. THE ELECTRON-MOVING FORCE. Now you might ask the question, "How is it possible to develop an electron-moving force across a conductor in order to produce an electron movement from atom to atom?" This can be done by the use of a battery, a generator, by friction, or by several other methods which will be subsequently explained.

The electron-moving force applied across a conductor to cause an electron movement is known as the "voltage."

26. CONCLUSION. It would be possible to go much further into the details concerning the structure of an atom and give you more information regarding the electron theory. However, such a detailed discussion is not essential for the study of Radio-Television. In this lesson, I have presented sufficient facts so that you will be able to understand clearly the information to follow in the future lessons.

I have not given definite proof for several of the statements that I have made; however, you must understand that even the greatest scientists are not absolutely certain as to the manner by which many of these facts could be proved. I expect you to accept such statements as being true.

We know that electrons and protons actually exist and we know that all atoms are composed of these tiny particles of positive and negative electricity. Then, again, we know that the atoms combine to make molecules and that the molecules are the substance of all matter. *The number of molecules in the universe is unlimited; there are 92 different kinds of atoms; and all electrons and protons are alike.* These are the important facts for you to remember. If you will do so, you will have no difficulty in understanding the information given in the lessons to follow.

In the next lesson, I am sure you will be interested in the connection between the electron theory and such fundamental electrical terms as: voltage, current, resistance, power, etc. All fundamental electrical operations have long been dependent upon the electron theory, but it has only been in the past few years that scientists have been able to explain the electrical actions using this theory.

Since you are just starting the study of Radio and Television, you must know the fundamental laws of electricity; all of these laws will be very easy and simple now that you understand the basic principles of the electron theory.

The text of this lesson was compiled and edited by the following members of the staff:

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POWER & LIGHT BUILDING, KANSAS CITY, MISSOURI

UNIT NO. 1

FUNDAMENTAL DEFINITIONS

LESSON NO. 3

JACK AND BILL . . .

Jack and Bill were pals. Being about the same age, they went to school, made the team and enjoyed their youth together. Both boys came from respectable families who had great hopes for their futures. Jack and Bill had great hopes, too. They were confident that success in life would be theirs.

Then, almost without warning, their school days were over. Bill went away to college, but Jack had to stay home because his folks had to meet unexpected expenses. They parted with the remark, "We'll meet each other at the top of the ladder." But for some reason, the passing years saw Jack making steady, upward progress, while Bill seemed to be slipping. Why?

The answer to this question is quite simple. Bill failed to set a definite goal for himself and drifted into a rut. On the other hand, when Jack found he could not go to college, he got a modest job and set out to educate himself at home through the medium of an Extension Course. He mixed work, pleasure and study wisely and one day found himself in possession of one of the main essentials to success.......specialized training that fitted him for a job in an industry that was expanding.

Armed with his specialized training, Jack went after a job with determination. He didn't merely hope and wish for success as Bill did. He backed his hopes up with energy and action and got what he wanted. "Gee, but Jack was lucky," said Bill. "Wish I would get a break once in a while." But it wasn't luck and it wasn't a break that put Jack over the top. It was his grim determination to stick to what he started and to qualify himself for the kind of a job that would enable him to enjoy life's many pleasures. Make up your mind NOW that you are going to follow Jack up the ladder to success. Stick to your studies with determination.

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Lesson Three

FUNDAMENTAL DEFINITIONS

"I know that you are anxious to jump right into the study of Radio; however, everyone agrees that a good foundation must be built to support a strong and sturdy building.

"These fundamentals of Electricity are not to be memorized; however, you must be so familiar with them that they will nearly become a second nature to you. The material in this lesson will be used constantly throughout the balance of your course."

1. THE DEFINITION OF ELECTRICITY. Electricity may be defined as a material agency which, when in motion, exhibits magnetic, chemical and thermal[1] effects, and when at rest is accompanied by an interplay of forces between associated localities in which it is present. Electricity in motion is often called dynamic electricity, while electricity at rest is often called static electricity.

It is necessary to have some fundamental understanding of electrical actions in order to interpret the definition of electricity just given. For that reason, if you find the definition is not entirely clear, disregard it for the present, and after learning the fundamental electrical laws as explained in the next few lessons, refer to this definition again to obtain a more complete understanding.

Several authorities prefer to define electricity as being a conveyor of energy. This means that by the use of electricity, it is possible to transport or transmit energy from one point to another point. A mechanical analogy for this particular definition is found in the manner by which a belt transmits energy from a steam engine to a pump (See Fig. 1). The belt itself only serves as a means of transporting the energy generated by the steam engine to the pump. Likewise, we consider that electricity is used to transport or carry the energy from an electrical generator to an electrical device of some kind.

For explanatory purposes, we have found that it is preferable

[1] Thermal: Pertaining to heat.

in several cases to consider electricity as being analogous[1] to a fluid rather than attempting to base all explanations entirely upon the electron theory. The fluid analogy does not conflict in any way with the electron theory and is used only in those cases where the particular electrical action can be made more clear. We would

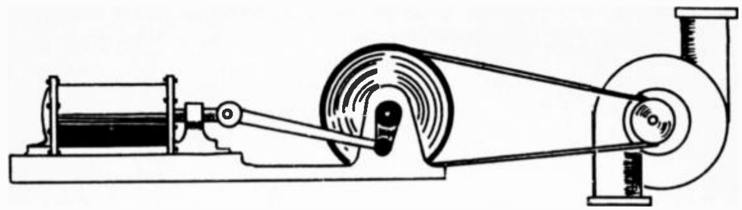


Fig.1 A mechanical analogy for the transmission of energy. The energy produced by the steam engine is transferred to the centrifugal pump by the belt.

like for it to be understood that throughout our explanations of electrical actions, we shall utilize the type of explanation which is most easily understandable, is correct according to all electrical laws, and conveys an interpretation which can be applied in all cases. For certain actions, we deem it advisable to employ the electron theory, while for others we shall use water or air analogies.

2. THE NATURE OF ELECTRICITY. Far more important than the actual definition of electricity is a description of how it acts and how it can be directed and controlled so as to do useful work. Everyone is familiar with the fact that electricity can be made to

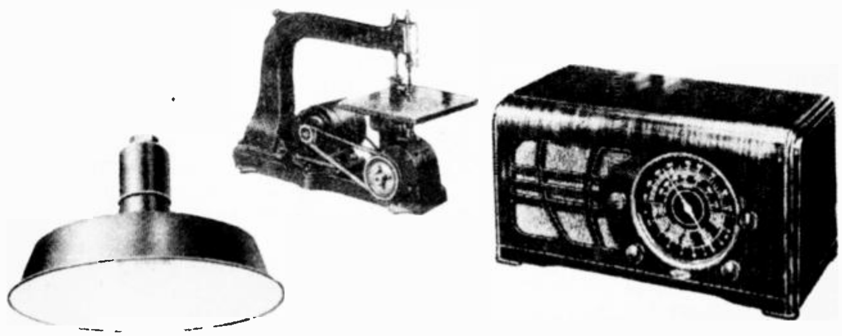


Fig.2 Electricity has the ability to do work. The incandescent lamp will produce light, the electric saw will run, and the Radio set will play when electricity is supplied to them.

furnish illumination, cause bells to ring, motors to run and do useful work by producing heat. (See Fig. 2) These are the important facts and represent the practical application about which it is necessary for us to possess a useful and working knowledge.

[1] Analogous: Resembling in certain respects, or having a similar function.

When studying the electron theory, we found that all matter is ultimately composed of minute particles of negative and positive electricity. Using this as a basis, we can safely make the statement that electricity acts as though it were a weightless, invisible, non-compressible fluid, permeating all space and saturating everything. It must be borne in mind that electricity is not really a fluid, but if the student will visualize that electricity acts as an imaginary, special kind of fluid, then many of the actions will be clearer and more understandable. Many years ago, Benjamin Franklin advanced the theory that electricity was a fluid, because so many of the electrical performances substantiated this theory. It has since been proved, however, that this is not true. The proof lies in the electron theory.

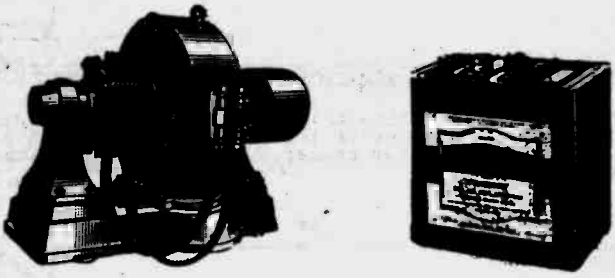


Fig. 3 Electricity cannot be created. The generator and the battery shown are merely devices whereby electricity already in existence can be set into motion.

Being certain that all matter consists of tiny electrical charges, we are next confronted with the fact that it is impossible to "generate" electricity. This statement may seem rather absurd because we are accustomed to calling certain electrical machines "generators" and also the assumption that a battery generates electricity is quite popular. These devices in reality are merely arrangements whereby electricity already in existence may be forced to move, but they, themselves, do not actually create or generate the electricity. (See Fig. 3) Every object in the entire universe may be regarded as an enormous reservoir of electricity (the electron theory) and the electricity in the object can be made to move under suitable conditions. When these suitable conditions are satisfied and electricity is moved through an object (dynamic electricity), work is done; but as long as the electricity remains stationary or at rest (static electricity), no useful work is accomplished.

In order to clarify these statements into a more definite understanding, let us use a water analogy as our first example. In Fig. 4, we have a hydraulic circuit consisting of a water pump, a water wheel, a valve, a reservoir and the connecting pipes. We shall illustrate how this hydraulic circuit is similar to the electrical circuit as shown in Fig. 5. The electrical circuit consists of a battery, an electric bell, a switch, and the connecting wires.

Considering the hydraulic circuit, we know that the pump is capable of producing a pressure which will cause the water to flow around through the pipes if the valve is open. If the valve is closed, there will be no movement of water through the pipes, regardless of the pressure produced by the pump, because it is impossible for the water to pass through the closed valve. As soon as the valve is opened, the water will pass through the nozzle of the

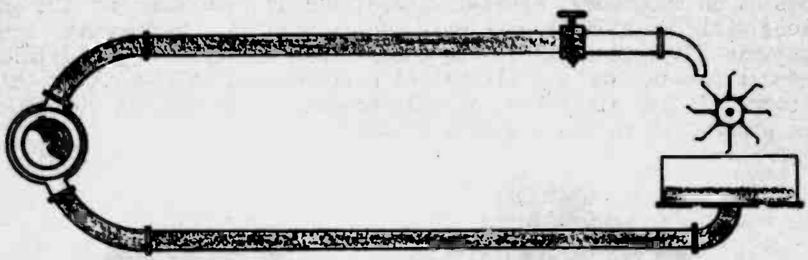


Fig.4 This hydraulic circuit is capable of doing work (turning the water wheel) when the valve is opened and the water motor is in operation. The water motor causes the movement of water through the circuit.

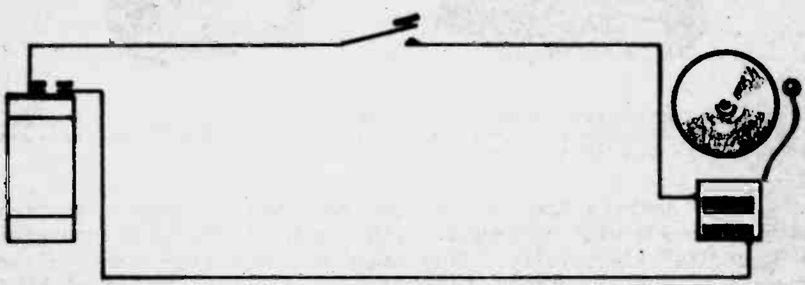


Fig.5 This electrical circuit is also capable of doing work (ringing the bell) when the switch is closed. The battery causes the movement of electricity through the circuit.

upper pipe and strike the blades of the water motor. The water, upon striking these blades, will cause the wheel to turn. The water then falls into the reservoir beneath and passes back to the pump through the bottom pipe. In this case, the moving water has done work, the work consisting of moving the wheel on the water motor. It is particularly important to bear in mind that every portion of this entire hydraulic circuit consists of matter. The pump, the pipes, the valves, the blades of the water wheel, and the water itself all have an actual physical existence, and are therefore composed the same as all other matter; that is, composed of molecules, atoms, electrons, and protons. Now consider the electrical circuit as shown in Fig. 5. Here the battery corresponds to the water pump, the switch corresponds to the valve, the bell corresponds to the water motor, and the wires are analogous to the connecting pipes.

The electricity (static) which fills the electrical circuit corresponds to the water which fills the hydraulic circuit.

As long as the valve remains closed in the water circuit, there will be no water flow and the wheel of the water motor will not be revolved. The same is true of the electrical circuit; that is, as long as the switch remains open, there will be no flow of electricity around through the circuit and the bell will not ring. As soon as the valve is opened in the hydraulic circuit, the pump will force water through the pipes and over the blades of the water wheel, thus setting it into motion. Likewise, in the electrical circuit, the instant the switch is closed, electricity will flow around through the electrical circuit, causing the bell to ring. The energy[1] expended by the water pump is responsible for the water flow and the motion of the wheel. In a similar manner, the energy expended by the battery is responsible for the flow of electricity through the wires and the ringing of the bell.

The battery in this circuit does not "generate" electricity any more than the water pump in the hydraulic circuit "generates" water. The battery serves merely as a force to cause the electricity to move, the same as the water pump causes the water to move through the hydraulic circuit.

3. VOLTAGE OR ELECTRICAL PRESSURE. In the above example, it would have been impossible to cause any water to flow through the hydraulic circuit were it not for the pressure produced by the water pump. The water pump served as a means of supplying the pressure to move the water.

The same is true in the electrical circuit shown in Fig. 5; that is, in order to ring the bell, it is necessary for electricity to flow through the wires, and the only means whereby the electricity can be set into motion is by the electrical pressure produced by the battery. If the battery were removed from the circuit, regardless of whether the switch was opened or closed, there would be no movement of electricity through the wires and the bell would not ring. It is quite obvious, then, that in order to cause a movement of electricity through a circuit, an electrical pressure is required. To secure this electrical pressure, it is necessary to expend some other form of energy.[2]

There are five ways by which this electrical force or pressure may be produced; however, only two of them have much commercial value. These five ways are: 1. Friction (expending mechanical energy); 2. Induction[3] (expending mechanical energy); 3. By the expenditure of chemical energy; 4. By the expenditure of heat energy. (See Fig. 6); 5. The expenditure of light energy. The first, fourth and fifth of these methods are very seldom employed, while the second and third methods of generating an electrical force or pressure

[1] Energy is defined as the capacity for doing work.

[2] The law of the conservation of energy states that man is unable to create or destroy energy. He can only transform it from one kind into another.

[3] "Induction" is a process relating to the association between electricity and magnetism. It will be completely explained in Lesson 10.

are quite common in our everyday life.

Every time you start an electric motor, turn on an electric light, or ride on an electric trolley car, you may be assured that the pressure or force which is causing the electricity to move and thus accomplish the work being done has been secured by induction. The large steam turbine which drives the high-powered generator in a power plant, the gasoline engine which drives the farm generator, or the large water wheel which turns the electrical generator are all illustrations of the expenditure of mechanical energy in order to obtain the electrical pressure from the generator by induction. These devices merely serve to transform energy from mechanical into electrical and do not actually cause the creation or origination of electrical energy.

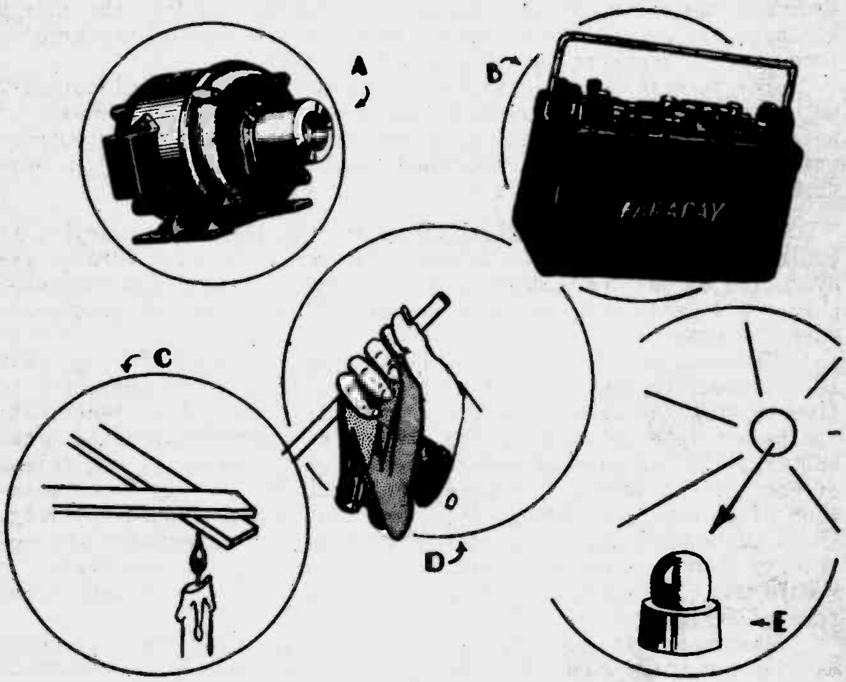


Fig.6 These illustrations show the five methods of producing an electrical voltage. (A) Induction. (B) Chemical. (C) Heat. (D) Friction. (E) Light.

All batteries are representative of the third method given for the production of an electrical pressure. The reason batteries are capable of causing a movement of electricity through a circuit is due to the chemical action which occurs between the elements and compounds composing the battery. As soon as no more chemical energy is available from the battery, it is necessary to discard the battery and replace it with a new one or to recharge it.

When a battery wears out or runs down, it signifies that the chemical energy formerly possessed by the battery is depleted and there is no more energy available to cause the production of an electric pressure or force.

From this discussion, it should be very apparent that it is absolutely necessary to have an electric force or pressure in order to establish a movement of electricity through the circuit. Next, we will consider exactly what constitutes the movement of electricity through the wires composing the electrical circuit.

4. CURRENT OR ELECTRON FLOW. Let us assume that the wires used for connecting the parts of an electrical circuit are made of copper. By referring to the electron theory, we know that the copper wire consists of copper atoms, each of which in turn is composed of a nucleus with planetary electrons revolving around it. When an electric pressure is applied across a wire or circuit consisting of such atoms, the electric pressure will cause a movement of electrons from one atom to another. In other words, the pressure is really an Electron Moving Force because it is of such a nature that it is capable of establishing this electron movement from one atom to another. *The exact meaning, then, of electricity moving through a wire is that electrons are being transferred from one atom to another through the wire.* The direction of the force which is applied across an electrical circuit will determine the direction of the electron movement through the wires. The electron-moving force may be applied in one direction, thus causing the electrons to move in that direction; then if the electron-moving force is reversed, the direction of the electron movement through the circuit will also reverse. It is quite important to bear in mind that the movement of electrons from one atom to another through a circuit is caused by the presence of the electron-moving force, and without this force, there could be no movement whatsoever.

We are now prepared to apply definite names to the electron-moving force and the electron movement of which we have been speaking. The electron-moving force is very often called an electromotive force, (abbreviated e.m.f.), but the word *voltage* is more popular. Regardless of whether the expression electromotive force or the word voltage is used, we always mean exactly the same thing; that is, *the electrical force which causes an electron movement from atom to atom through a conducting medium.*

The flow of electricity through a wire is actually the movement of electrons from one atom to another and the phrase applied to this phenomenon is current flow. *The definition for current flow is that it consists of the movement of electrons through a conducting medium.* A conducting medium is defined as any object which will serve as a medium for the transmission of electricity. A current movement or flow through a conducting wire may be considered the same as the flow of water through a pipe. It is impossible for water to move through a pipe without a pressure of some kind behind it; likewise, it is impossible for electrons to flow through a conductor without an electrical force.

It can be seen in Fig. 4 that a water pressure exists behind the closed valve, but that no water will flow. Likewise, in the electrical circuit shown in Fig. 5, electrical pressure or voltage exists behind the open switch, but no current will flow until the switch is closed, thus completing the circuit. From this we can conclude that *it is possible to have voltage without a flow of current, but a current flow cannot be established through a circuit unless a voltage is applied.*

5. UNIT FOR MEASURING VOLTAGE. In everyday life, we are accustomed to using certain units and their subdivisions to express distances, time, numbers, values, etc. The inch, foot, yard, mile, etc., are all units for measuring distances, and the penny, nickel, dime, quarter, half-dollar, dollar, etc., are all used to express certain amounts of money. In electrical work, also, certain units must be employed in order to express the values of current and voltage. These practical units have been very carefully selected and at the present time are adopted as standard by nearly all countries of the world in order that they may be the same internationally. The units used in Radio and Television work must also be the same

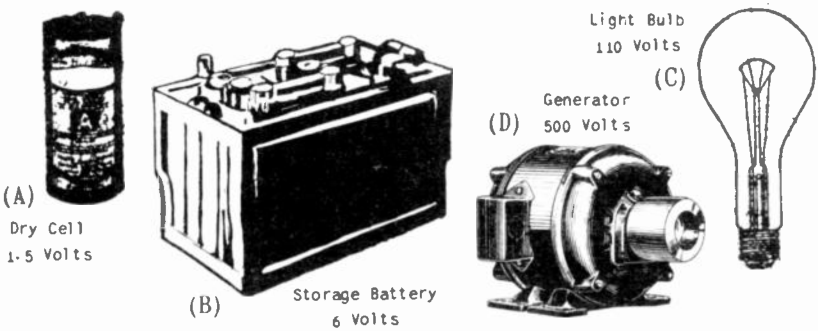


Fig.7 Illustrating the word "voltage." The dry-cell produces 1.5 volts; the battery 6 volts; the light bulb requires 110 volts to illuminate it, and the generator delivers 500 volts.

as those used in all other types of electrical work. It is easy to understand the confusion which would result if different trades adopted different units or if the units did not have the same value in all countries. The units given for measuring voltage and current in the following paragraphs are the standard International practical units.

The volt[1] is the standard unit used to measure electromotive force (electrical pressure). As examples of various values of voltage, the single cell shown at A, Fig. 7, will produce a voltage of approximately 1.5 volts, the storage battery shown at B produces a voltage of approximately 6 volts, the incandescent lamp shown at C

[1] The great Italian physicist Count Alessandro Volta (1745-1827) was the inventor of the electroscope, the condenser, and the voltaic pile. He was ennobled by Napoleon for his scientific services. The volt, the practical unit of electrical pressure, is named in his honor.

usually requires 110 volts to illuminate it to full brilliancy and the electrical generator shown at D is capable of producing an output voltage of 500 volts. These are given merely to illustrate the meaning of the word volt; that is, the volt is always employed to designate the extent or amount of electrical pressure.

6. UNIT FOR QUANTITY OF ELECTRICITY. Before defining the unit employed for the rate of current flow, it will be necessary to learn of the unit which is used to designate a quantity of electricity. This unit was given in the preceding lesson; however, we deem it advisable to give a more thorough definition of it at this time. The unit of measurement for a quantity of electricity is the coulomb; and by definition: *One coulomb consists of 6,280,000,000,000,000,000 electrons.* An electron, you will recall, represents a negative charge of electricity. Now by grouping 6,280,000,000,000,000,000 (6.28×10^{18}) electrons, we will have one coulomb of electricity. So, the unit coulomb is merely used to specify a larger quantity of electrical charge than that possessed by a single electron.

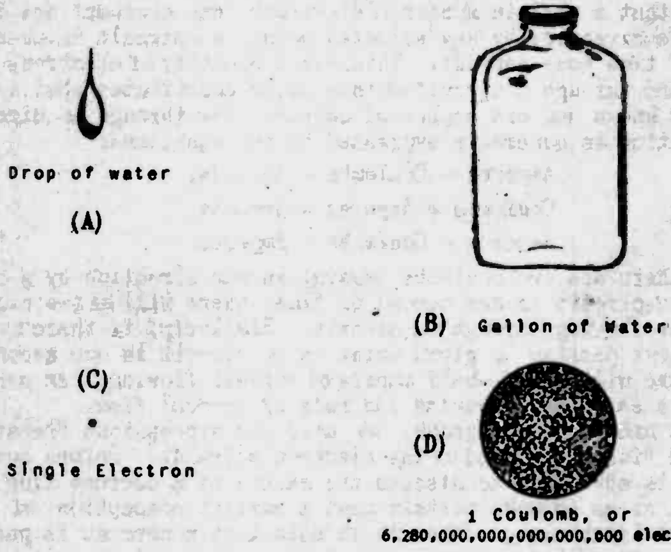


Fig.8 Illustrating the coulomb. One electron is a small part of a coulomb, the same as one drop of water is a small part of a gallon.

This can be compared to water, thereby securing a more clear conception of the relationship. One drop of water as shown at A, Fig. 8, is a quantity of water; however, it is a very small quantity.

If we group or amass a sufficient number of drops into a single container, we will then have a gallon of water. A gallon of water as shown at B, Fig. 8, is also a quantity of water, but it is a much larger quantity than a single drop. Likewise, a single electron represents a certain quantity of electricity as shown at C,

Fig. 8, and when 6,280,000,000,000,000,000 of these electrons are grouped together (D), we then have one coulomb of electrical charge. The unit coulomb, then, designates a definite quantity of electrical charge. In several of the future lessons, it will be necessary to use the unit coulomb considerably; however, at the present time we are interested in the coulomb only as it will be used to define an ampere.

7. UNIT FOR MEASURING CURRENT. Previously we found that current flow means an electron movement through a conductor. Now we are vitally interested in two important facts about this electron movement. First, we are interested in the number of electrons that are moving; and second, we are interested in the relative speed at which they are moving. The forward speed of the electrons is just as important a factor as the quantity. The unit ampere has been chosen to represent both the quantity and the relative speed of the electron movement. *By definition, one ampere is equal to one coulomb passing a given point in a circuit in one second of time.* Analyzing this definition and stating it in a little different manner, it means that a certain number of electrons (one coulomb) are passing in one direction by any selected point in a circuit in a certain length of time (one second). This exact quantity of electrons moving forward through a circuit at this speed constitutes what is universally known as one ampere of current flow through a circuit. This relation is generally expressed by the equations:

$$\text{Amperes} = \text{Coulombs} \div \text{Seconds},$$

$$\text{Coulombs} = \text{Amperes} \times \text{Seconds},$$

$$\text{Seconds} = \text{Coulombs} \div \text{Amperes}.$$

If there are two coulombs passing in one direction by a given point in a circuit in one second of time, there will be two amperes of current flowing through the circuit. Similarly, if there is one-half coulomb passing a given point in a circuit in one second of time, there will be one-half ampere of current flowing. *An ampere, then, is a unit for measuring the rate of current flow.*

In a preceding paragraph, we used the expressions "relative" speed and "forward" speed of the electron movement. Before continuing, it is advisable to discuss the nature of a current flow more in detail so as to make certain that a correct conception of this phenomenon is obtained. When it is said that a current is passing through a wire, it is very true that there is an electron movement in a definite direction through the wire from negative to positive. However, these electrons do not move at a high rate of speed through the conductor; that is to say, the progressive or forward motion of the electrons in one direction through the conductor is very slow. Several seconds will possibly be required for one single electron to move a distance of one inch through the wire. This slowness of the actual forward movement of the electrons is due to the fact that they are constantly colliding with the atoms in the metal wire, consequently retarding their progressive motion. On the other hand, it must not be thought that the actual velocity of the electron when passing from one atom to the next is slow. If it were not for the constant collisions with the atoms of the metal in the wire, the electrons would attain velocities many millions of times as great as their average forward movement. However, since the size of the atoms or molecules in the wire is many thousands of times as great as the size of the electrons, the numerous collisions prevent a rapid progressive motion. The electrons, therefore, bound and rebound at tremendous velocities in the wire, but always move toward the positive terminal of the voltage source, thereby producing an electron drift toward the positive pole through the entire conductor.

An electron would acquire a tremendous velocity if it did not collide with the larger masses of the atoms or molecules. An example proving this statement is seen in hot metals. Heating a body increases the vibrating movements of the atoms and molecules tremendously. Under this condition, the electrons may be accelerated to such a high degree that they are actually forced out through the surface of the metal. As the electron departs from the metal, its velocity may be in the order of thousands of miles per second.

Even though the progressive motion of an individual electron is slow, the electrical impulse or disturbance created when an electron moves is exceedingly fast and actually attains a velocity as fast as the speed of light (186,000 miles per second). The rapid movement of this impulse can best be understood with an analogy: Suppose we have a pipe 10 feet long which is filled from one end to the other with marbles. If the outside marble on one end of the pipe is pushed, a marble will fall from the other end of the pipe almost immediately. Now the actual forward movement of the marble which was pushed was only a very short distance; however, the impulse created by the progressive motion of that marble was transmitted from marble to marble through the entire 10 feet of the pipe at a very rapid rate, resulting in the marble at the other end falling out almost at the same instant the first one was pushed. Likewise, the impulse created by an electron when it moves forward travels at a tremendous rate of speed through the entire length of conducting wire even though the electron itself moves only a short distance.

From this discussion, it is evident that a long period of time would be required for one certain electron to start from the negative terminal of a voltage source and reach the positive terminal. It has been estimated that about 3 hours are required for a single electron to progress a distance of 1 yard through a wire when the measured rate of current flow is 1 ampere. If it were not for the many collisions and rebounds encountered by the electron, it would progress this distance in a small fraction of a second. *The progressive or forward speed of the electron is that speed which must be taken into consideration when calculating the amperes of current flowing through a conductor.* As has been stated, this forward speed is extremely slow; hence, an exceedingly large number of electrons must be set in motion in order to have 1 coulomb passing by a given point in one second of time. One coulomb per second constitutes one ampere.

Summarizing this discussion, the actual progressive movement or forward speed of an electron through a conductor is very slow because of the collisions encountered and the distance lost when it rebounds; however, the impulse or disturbance which an electron creates when it moves forward is transmitted from atom to atom throughout the entire circuit at an extremely high velocity. The significance of this is that when a switch is closed in an electrical circuit, electrons are moved, current flows, and electrical work is done throughout the entire circuit almost instantaneously, but the actual forward speed of one individual electron in the circuit is extremely slow.

Fig.9 Using the word "ampere". A current of .25 ampere passes through the incandescent lamp, 5 amperes pass through the element of the toaster. and 10 amperes run the electric motor.

To become familiar with the use of the unit ampere, we shall refer to the illustrations shown in Fig. 9. One-quarter of an ampere flowing through the 25 watt lamp at A will illuminate it; 5 amperes are necessary through the electric toaster wire as shown at B, in order to heat it to the proper temperature; 10 amperes will be necessary through the electric motor shown at C, in order to drive a load connected to it. These values are only for the purpose of demonstrating the use of the word ampere.

Now that we have learned the definitions of "volt" and "ampere", let us study an analogy to make certain that we understand these two units thoroughly. Fig. 10 shows an elevated reservoir of water with pipes connecting to five small tanks. A valve (faucet) is connected in each pipe directly above each tank.

Let us first consider tank A. The valve in the pipe connecting to this tank is completely closed; therefore no water is flowing into the tank. Compared to an electrical circuit, the water pressure exerted on the top of the valve is the voltage, the valve is the switch, and the rate of water flow is the current. With the valve closed, no water flows; in an electrical circuit this is the same as opening a switch....no current flows. Here we have an example of voltage (electrical pressure), but no amperes (current flow).

In tank B, the valve is opened enough to allow the water to flow at the rate of 1 gallon per second into the tank. Compared to an electrical circuit, let us say that the 1 gallon per second is the same as 1 ampere of current flow. Notice that we are comparing amperes to gallons per second. In other words, the number of amperes means the coulombs flowing per second in an electrical circuit, the same as the rate of water flow means the gallons per second.

A gallon is a quantity of water, the same as a coulomb is a quantity of electricity. Gallons per second means the speed at which water flows and likewise, amperes means the speed at which coulombs move.

Now if we were to open the water valve more, as shown at C in Fig. 10, we would have a water flow of two gallons per second into the tank. Remember that this water is flowing because of the pressure obtained from the reservoir the same as an electrical current flows through a wire because of the electrical pressure obtained from a voltage source. Two gallons per second of water flow corresponds to two amperes of current flow through an electrical circuit. Amperes can be compared to gallons per second because it means the speed at which a quantity of electricity moves through a wire.

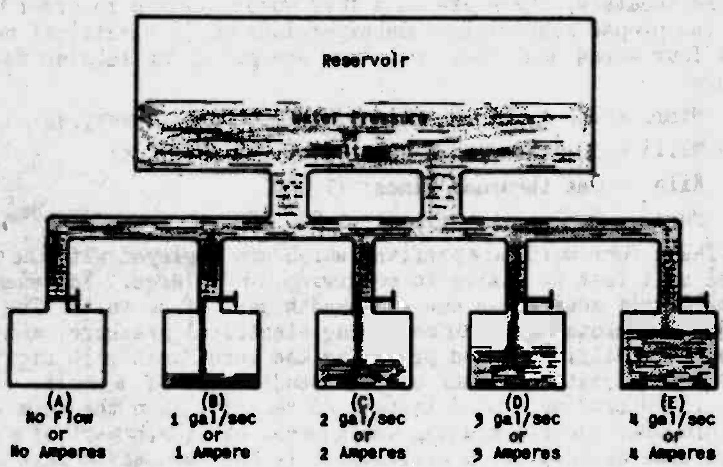


Fig.10 Water analogy to illustrate "current and "voltage".

At D, the valve is opened to permit three gallons per second to flow, and at E, four gallons per second flow. These two conditions may be compared to three amperes of current flow through a wire, and four amperes of current flow through a wire, respectively.

From this analogy, you should be able to see that when we use the word "ampere" we mean the rate or speed at which a quantity of electricity (coulomb) moves through an electrical circuit. And, if we say "voltage" we mean the electrical pressure which causes the coulombs to move at a certain speed.

In an electrical circuit we can measure the pressure (voltage) with an instrument called a "voltmeter" and we can measure the rate of current flow (amperes) with an "ammeter". You will learn how to use and connect these measuring devices in a lesson to follow very soon.

8. SUBDIVISIONS OF THE VOLT AND AMPERE. Subdivisions of the aforementioned units used for measuring the voltage and current will be very useful in all future work. These subdivisions will be convenient for the same reason that we have measurements of time and length subdivided into smaller units as well as increased into larger units. For example, if the only available unit for time measurement was the year, it would be rather difficult to express the exact amount of time elapsing during the tick of a clock. Likewise, if the only unit available to measure time was the hour, it would be rather difficult to express the length of a person's lifetime. As a result, we find that time may be expressed in seconds, minutes, hours, days, weeks, months, etc. In Radio and electrical work, it will be necessary to speak of extremely small voltages and currents in some cases, and quite often we shall desire to designate a larger value than the volt or the ampere.

Fortunately, there are only four words to learn in order to secure the proper subdivisions and expansions of all electrical units, These four words and their meanings are given in tabular form as follows:

Micro = One-millionth part of; (.000001); ($\frac{1}{1,000,000}$)

Milli = One-thousandth part of; (.001); ($\frac{1}{1,000}$)

Kilo = One thousand times; (1,000).

Mega = One million times: (1,000,000).

These four words are prefixes which are employed with the electrical unit that we desire to subdivide or enlarge. For example, one millivolt would mean one-thousandth part of a volt. The volt is the fundamental unit for measuring electrical pressure, and when the prefix "milli" is used preceding the word "volt", it signifies that the new unit now means one-thousandth part of a volt. Likewise, if "micro" were used instead of "milli", then the term would be microvolt, and its meaning would be one-millionth part of a volt. By the same definition, a milliampere is one-thousandth part of an ampere, and microampere means one-millionth part of an ampere. "Milli" and "micro" are the two prefixes used when we desire to express units smaller than the fundamental "volt" or "ampere". The two prefixes "kilo" and "mega" are used to enlarge the fundamental unit. For example, one kilovolt means 1,000 volts, while one megavolt means 1,000,000 volts. Also, one kiloampere is 1,000 amperes.

It is advisable to learn very carefully the meaning of these four prefixes. They are employed with the electrical units, volt and ampere, as well as with all of the other electrical units of measurement which we shall encounter in future lessons.

On the following page you will find a conversion table. If you will learn to use this table, you should have no difficulty in changing from one unit of measurement into another. The multiplying factors given are obtained directly from the definitions of the prefixes milli, micro, kilo, and mega.

For the present it is permissible for you to use this table in all your problems. As you become more familiar with the units, try to work problems without referring to the multiplying factors.

You will soon find that the conversions become very clear, and you will no longer need the table.

CONVERSION TABLE

	Multiply	By	To obtain
1.	Amperes	1,000,000	Microamperes
2.	Amperes	1,000	Milliamperes
3.	Volts	1,000,000	Microvolts
4.	Volts	1,000	Millivolts
5.	Volts	.001	Kilovolts
6.	Ohms	1,000,000	Microhms
7.	Ohms	1,000	Milliohms
8.	Ohms	.000001	Megohms
9.	Watts	1,000,000	Microwatts
10.	Watts	1,000	Milliwatts
11.	Watts	.001	Kilowatts
12.	Watts	.000001	Megawatts
13.	Milliamperes	1,000	Microamperes
14.	Milliamperes	.001	Amperes
15.	Microamperes	.001	Milliamperes
16.	Microamperes	.000001	Amperes
17.	Millivolts	1,000	Microvolts
18.	Millivolts	.001	Volts
19.	Millivolts	.000001	Kilovolts
20.	Microvolts	.000001	Volts
21.	Kilovolts	1,000	Volts
22.	Megohms	1,000,000	Ohms
23.	Milliohms	.001	Ohms
24.	Milliwatts	.001	Watts
25.	Milliwatts	.000001	Kilowatts
26.	Microwatts	.000001	Watts
27.	Kilowatts	1,000	Watts
28.	Megawatts	1,000,000	Watts

Let us work several problems to illustrate the use of the table:

Example 1: Change 15 ma. into amperes.
From number 14 in the table we obtain the multiplying factor .001. Multiplying the milliamperes (15) by .001, we obtain .015. Thus, 15 ma. = .015 amperes.

Example 2: Change 1.5 megohms into ohms.
From number 22 in the table we obtain the multiplying factor 1,000,000. Multiplying the megohms (1.5) by 1,000,000 we obtain 1,500,000. Thus, 1.5 megohms = 1,500,000 ohms.

Example 3: How many volts in 2.6 kilovolts?
The multiplying factor is given as 1,000 in number 21 of the table. Multiply 2.6 kilovolts by 1,000 to obtain 2,600 volts. Hence, there are 2,600 volts in 2.6 kilovolts.

Example 4: How many watts are equal to 600 microwatts?
Number 26 in the table is for converting microwatts to watts; the factor is .000001. Multiplying 600 by .000001, we obtain .0006. Thus 600 microwatts = .0006 watt.

Example 5: How many microamperes are equal to .05 amperes?
To convert from amperes to microamperes, use the factor given under number 1 in the table. Thus, multiply .05 by the factor 1,000,000. This gives 50,000, so .05 amperes = 50,000 microamperes.

9. INSULATORS AND CONDUCTORS. It is commonly known that some materials will allow an electrical current to pass through them with comparative ease, while others offer considerable opposition to the

passage of an electric current. *A material which readily permits the passage of an electric current is known as a conductor, while those materials offering a high opposition to an electric current are called insulators.* The majority of metals, such as copper, gold, silver, etc., are excellent conductors of electricity (See Fig. 11), while other materials, such as porcelain, wood, bakelite, hard rubber, etc., are very poor conductors, and hence are called insulators (See Fig. 12).

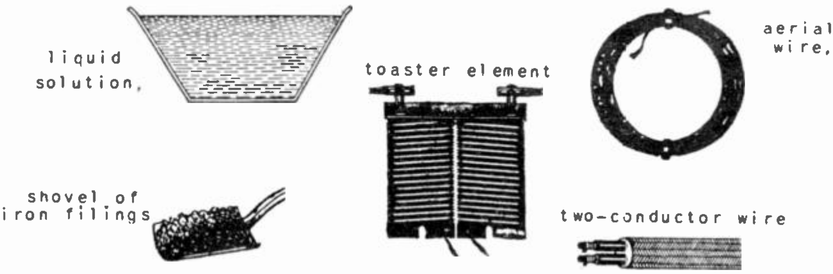


Fig.11 Examples of conductors.

The electron theory may be used to an advantage in understanding why some materials are better conductors than others. We know that the current flow through a material consists of an electron movement between the atoms. If the structure of the atoms of the material through which the current is passing is such that the free electrons are very loosely held to their respective atoms, then these electrons may be moved quite easily. If the electrons may

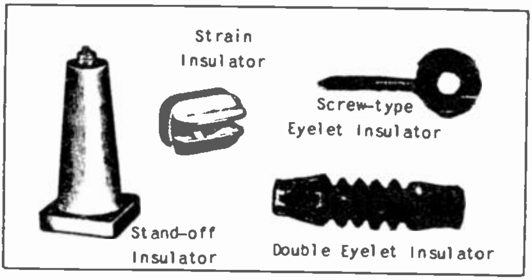


Fig.12 Examples of insulators. The objects shown are all made of porcelain, glass or isolantite. Other good insulators are mica, air, paper, amberoid, victron, pyrex, etc.

be easily moved into or out of an atom, then with a given voltage applied to the conductor, a relatively high current will flow. On the other hand, if the structure of the atoms in the material is such that it is very difficult for a free electron to be moved into or out of the atom, then with a given voltage applied to this material, an exceedingly small electron movement from atom to atom will result. A material with an atomic structure of this kind is a very poor conductor and is commonly known as an insulator.

Consequently, whether a given material is known as a good conductor, a fair conductor, or a poor conductor, or whether it is known as a good, fair, or poor insulator depends entirely upon the structure of the atoms of which it is composed. If the nucleus of the atom has a very strong attraction for the free electrons, it will make a good insulator; on the other hand, if the nucleus of the atom has an exceedingly weak attraction for the free electrons, it is said that the atom is constructed loosely and the material will be a good conductor of electricity.

It has been found that a number of liquids and chemical solutions are also good conductors of electricity. These liquids and chemical solutions are commonly known as electrolytes.

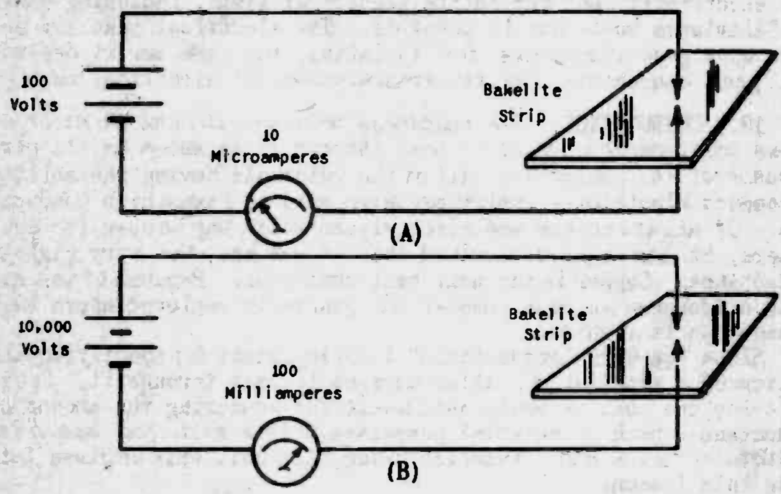


Fig.13 Showing how a material may be a good insulator at low voltage, but a poor insulator at high voltage.

It is impossible to establish a definite dividing line between insulators and conductors, because whether the material is an insulator or conductor depends largely upon the voltage applied to it and the temperature of the material. For example, consider the common insulating material, bakelite. At low voltages, bakelite is an exceedingly good insulator. By actual measurement, it has been found that with 100 volts across a small thickness of bakelite, less than .00001 ampere (10 microamperes) of current will pass through it. (See Fig. 13) This exceedingly slight current flow is so small as to be negligible; hence, at this voltage, bakelite may be considered a very poor conductor, or a good insulator. If the voltage across the same thickness of bakelite is increased to, say 10,000 volts, then by measurement we would find that approximately 100 milliamperes (.1 ampere) of current would flow through it. This current flow is so high that for Radio and Television work, it would not be possible to disregard it. Consequently, at this latter voltage, bakelite is not considered either a good conductor or a good insulator. For insulation at extremely high voltages, it is necessary to use some material other than bakelite.

Fortunately, there are materials of such atomic construction that current flows through them easily, and also there are other materials which offer a very high opposition to the passage of current. Were it not for the fact that good insulators are available, it would be impossible for us to use wires, etc., to conduct or carry electrical energy from one point to another because all of the energy would be lost or distributed through the air or any other medium which surrounds the supposed conductor. Were it not for the existence of good insulators, we would not be able to isolate one electrical circuit from another; hence, no work could be accomplished with electricity, and the entire electrical field, including Radio and Television would not be possible. The electrical industry depends upon good insulators for isolation, the same as it depends upon good conductors for the transmission of electrical energy.

10. CONDUCTANCE. *The readiness or ease with which a material allows an electric current to pass through it is known as the conductance of that material.* All of the materials having the ability to conduct electricity easily are also said to have a high conductance. Of all the metals and electrolytes which may be used for conductors, it has been determined that silver has the very highest conductance. Copper is the next best conductor. Because of the extreme difference in cost, copper is generally employed where high conductance is required.

Since the word "conductance" is so important for specifying the ability of a material to allow current to pass through it, it is quite logical that we would need a unit for measuring the amount of conductance which a material possesses. *This unit for measuring conductance is the mho.* Examples using this unit will be given later in this lesson.

11. RESISTANCE. As previously stated, materials such as air, bakelite, glass, etc., are considered good insulators of electricity. This means that these materials offer a very high opposition to the passage of electric current through them. *The opposition which is offered by a material to the passage of current through it is known as the resistance of that material.* We are all familiar with the fact that the word "resist" means to oppose or hold back. This exact meaning is also used in conjunction with electrical circuits.

Since insulators offer a high opposition to the passage of a current, all of them are considered to have a high resistance, and since the conductors offer a very low opposition to the passage of an electric current, they are said to have a very low resistance. It is quite evident from this statement that the meaning of the word "conductance" and the meaning of the word "resistance" are just opposite each other, since the former means the ability to conduct, while the latter means the ability to oppose an electric current. Having found it necessary to employ a unit for the measurement of the conductance of a material, it is also essential to employ a unit for the measurement of the resistance of a material. *The practical unit which has been internationally adopted for denoting the resistance of a material is the ohm.* This word was selected in honor of the scientist George Simon Ohm, who first established the relationship between voltage, current, and resistance, known as Ohm's Law. A complete discussion of Ohm's Law will be given in Lesson 5.

Since it was stated in a previous paragraph that the conductance of silver and copper was extremely high, then it follows that the resistance of these materials is very low. Silver, then, will possess the lowest resistance of any material, followed by copper. The resistance offered by copper to the flow of an electric current is just slightly greater than that offered by silver, which accounts for the fact that copper is used to such a large extent commercially for transmission purposes.

It will be noticed that when speaking of conductance and resistance, the statement was not made that the conductance of any material was infinitely high nor that the resistance of any material was zero. Regardless of the type of material used and regardless of the size or amount of the material, it will always offer some opposition to the passage of an electrical current. In other words, *it is impossible to secure a material which will be a perfect conductor.* By a perfect conductor, we mean one which offers no resistance. Likewise, it is true that *it is impossible for any material to be a perfect insulator.* In other words, there is no material that has a resistance which is infinitely high or a conductance equal to zero. This point was brought out in the discussion of insulators. Even the very best insulator available will possess a slight conductance if a sufficiently high voltage is applied across it.

12. FACTORS DETERMINING RESISTANCE. Throughout our entire course of study, we will constantly encounter the word "resistance". The student must remember that resistance is the opposition offered to the flow of an electric current, and the unit for measuring the resistance of a conductor is the ohm.

The four factors which determine the resistance of a conductor are:

1. *Length of the conductor.*
2. *Diameter of the conductor.*
3. *Kind of material from which the conductor is made.*
4. *Temperature of the conductor.*

Discussing each of these factors individually, we will first consider the length of the conductor. *The resistance of a conductor will increase directly with its length.* This statement means that when a given conductor is made longer, the resistance of that conductor will increase in direct proportion. For example, we have a conductor 1 foot long having a resistance of 1 ohm. If the length of this conductor is increased to 2 feet, the resistance of the conductor will increase to 2 ohms. If the same conductor were made 10 feet long, then the resistance would increase to 10 ohms. This may be clearly understood from a water analogy. We are all familiar with the fact that the longer the pipe through which water is forced to flow, the more opposition is offered to the water. The opposition offered to water when passing through a pipe is due to the friction between the water molecules and the inside of the pipe itself. The longer the pipe through which the water must flow, the greater will be the frictional opposition offered to it. (See Fig. 14).

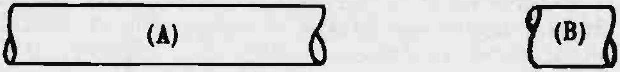


Fig.14 Illustrating how length affects resistance. The long conductor (A) will offer more resistance than the short conductor (B).

Next, considering the diameter of a conductor, *the resistance of a conductor varies inversely*[1] *with the diameter of it.* This statement means that as the diameter of the conductor is decreased, the resistance will increase, and as the diameter of the conductor is increased, the resistance will decrease. With other factors remaining constant, a given conductor with a diameter of $\frac{1}{4}$ inch will have less resistance than a conductor having a diameter of $\frac{1}{8}$ inch. This may be illustrated by a water analogy, because it is a well-known fact that a water pipe with a large diameter will offer less opposition to the flow of water through it than a pipe with a small diameter. (See Fig. 15)

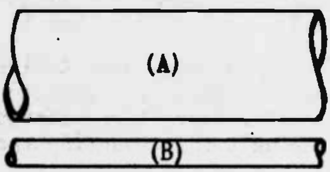


Fig.15 Illustrating how diameter affects resistance. The smaller diameter conductor (B) will offer more resistance than the larger diameter conductor (A).

The next factor taken into consideration is the kind of material used for the conductor. This was discussed considerably in a preceding paragraph of this lesson wherein it was stated that *different materials will have different conducting abilities*. The explanation for this lies in the electron theory, and the necessary information has been given before.

The common expression which is used to compare the various materials as to their conducting ability is the "specific resistance per circular mil foot". This means the resistance of a conductor having a length of 1 foot and a cross-sectional area of 1 circular mil. Inasmuch as most wire is round, it is inconvenient at times to measure the cross-sectional area of wire in square inches. The cross-section is circular, not square, so a circular measure and not a square measure should be used. In circular measure, use is made of a circular unit of area instead of a square unit of area. This

[1] Inversely: Opposite in effect.

circular unit of area is a circular mil. It is the area of a circle whose diameter is 1 mil. This is shown in Fig. 16. The term mil always means .001. Thus, in our coinage system, one mil equals .001 dollar; in distance, one mil equals .001 inch; etc. One circular mil, then, is the area of a circle, the diameter of which is 1 mil, or .001 inch. To find the area in circular mils of a circle with a given diameter, we have merely to square the number of mils in the diameter. This may be demonstrated as follows: If the diameter of a conductor is 10 mils, then the circular area is 10 × 10 or 100 circular mils. If the diameter of a wire is 5 mils, the circular area is 5 × 5 or 25 circular mils.

Fig.16 Illustrating the meaning of the "circular mil". If the diameter of the conductor is 1 mil (.001 inch), then the cross-sectional area is 1 circular mil.

Assuming that the temperature of all conductors is the same, by comparing the "specific resistance per circular mil foot" for various conductors, we thereby obtain a comparison as to their conducting ability. In the following table we have shown the "specific resistance per circular mil foot" in ohms for some of the more common materials. The temperature considered for the figures given in this table is 75 degrees Fahrenheit.

Silver	9.6 ohms
Annealed Copper	10.5 "
Hard Drawn Copper	10.7 "
Aluminum	17.7 "
Zinc	37.9 "
Brass	45.4 "
Phosphorous Bronze	51.8 "
Iron Wire	65.1 "
Nickel	85.1 "
Steel	90.1 "
German Silver	128.7 "
Very Soft Iron	697.0 "

The kind of material used for the conductor, therefore, will determine to a large extent the total resistance which the conductor offers.

The fourth factor to be taken into consideration when determining the resistance of a conductor is the temperature of the conductor. As the temperature of a metal is increased, the activity of the electrons in their atomic orbits becomes increased and it is more difficult to remove an electron from its orbit because of the increased attraction which the nucleus has for the outer electrons. Since it is this attracting or holding power which determines the resistance of a material, it follows that as the temperature of a metal is increased, the resistance will also increase. The atoms composing a carbon conductor and the atoms composing all liquid conductors act exactly in an opposite manner. In other words, as their temperature is increased, the power of attraction which the nucleus has for the free electrons becomes decreased; therefore, the electrons may be more easily removed from their respective atoms and the resistance will be decreased. *In all metals, then, as the temperature of the conductor is increased, the resistance will also increase, while in carbon and all electrolytes (liquids), as the temperature is increased, the resistance will decrease.* (See Fig. 17).

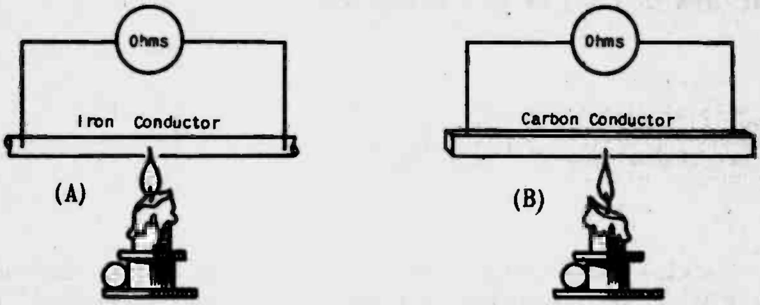


Fig.17 When heat is applied to the iron conductor at A, the resistance will increase and the ohmmeter (meter for measuring the number of ohms resistance) reading will increase. When heat is applied to the carbon conductor at B, the resistance will decrease and the ohmmeter reading will decrease.

Because of this fact, all metals are said to have a "positive temperature coefficient of resistance", while carbon and the electrolytes are said to have a "negative temperature coefficient of resistance". For example, suppose that the resistance of a copper conductor is 9.6 ohms at 32 degrees Fahrenheit, and at 75 degrees Fahrenheit the resistance increases to 10.5 ohms. The exact amount of increase in the resistance is determined by the use of a number which is known as the temperature coefficient[1] of copper. Since it is generally not necessary for the student to use such calculations in practical work, we shall not concern ourselves with the temperature coefficients of various metals at this time.

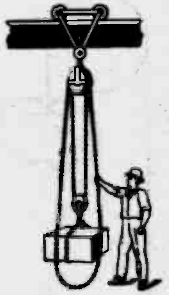
When the temperature of a conductor does not vary over an exceedingly wide range, the effect of temperature on the resistance is generally disregarded. It is only in extreme cases where the temperature is changed over a range of possibly 100 or 200 degrees that it is necessary to consider the temperature effect in practical work.

From this discussion, it is evident that we must consider *the length, the diameter, the kind, and the temperature* of a conductor when it is desired to determine its resistance.

[1] A coefficient is defined as a multiplier. Example: If 27.6 has a coefficient of .002, it means that these two numbers are to be multiplied together. By multiplying we find the product to be .0552. In this example, .002 is the coefficient; that is, the multiplier.

13. ELECTRICAL POWER. Before defining electrical power, it is advisable to review a few physical definitions. *First, work of any kind means the overcoming of opposition through a certain distance.* Work is measured by taking the product of the opposition and the space through which it is overcome. *Work is generally measured in foot-pounds.* A foot-pound of work is the amount of work done in raising a weight of one pound a distance of one foot. This same statement may be made in a slightly different manner; such as, a foot-pound is the amount of work done in overcoming a force of one pound through a distance of one foot. An example of work is shown in Fig. 18. Here, a weight of 10 pounds is being raised a distance of 10 feet. The work done in accomplishing this will be 10 pounds times 10 feet, or 100 foot-pounds.

Fig.18 Example of work. The man is raising the 10 lb. weight 10 feet. The work is 10 times 10, or 100 foot-pounds.



The word "power" takes into consideration the amount of work done and the time factor involved. By definition, *power is the rate of doing work.* More power is required to do a certain amount of work in a short length of time than is required to perform the same amount of work in a longer period of time. For example, it would require more power to raise a 10 pound weight 10 feet in one second than it would require to raise the same weight an equal distance in five seconds. It should be clearly understood that the expression "power" takes into consideration both the amount of work done and the time required to perform that work. The unit commonly used in mechanical calculations for determining the rate at which work is done is *"horsepower"*. By definition, *one horsepower is required to raise 33,000 pounds one foot in one minute.*

In electrical circuits, the rate at which work is done (power) is measured in *watts* instead of horsepower. There is a definite relationship between horsepower and watts. It has been determined that *746 watts equals one horsepower.* Using this relationship, it is possible to express electrical power in either horsepower or watts, but as stated before, watts is the more commonly used term for electrical circuits.

Since the word "energy" will be used considerably throughout this and following lessons, it is quite important to know the meaning of this word. *Energy is defined as the capacity for doing work.* This means that any body or medium which is capable of doing work is said to possess energy. This definition can best be understood by use of a few examples. The spring in a watch which has been wound possesses energy because the coiled spring has a capacity for doing work. The work in this case would consist of driving the watch's mechanism. Any moving object possesses so-called "kinetic" energy, because it can overcome the resistance or opposition which is offered by the air, water, or whatever medium through which it is traveling and thus do work. When the statement is made that a device possesses electrical energy, it means that it is capable of doing electrical work. The word "energy" is used only when we desire to state that there is a capability or capacity to do work and does not necessarily mean that the work is actually being done. When the stored energy is expended or used, then work is actually done.

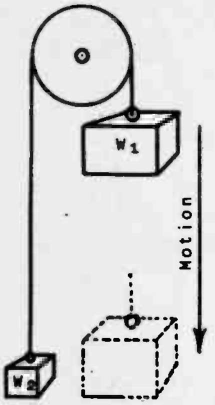


Fig.19 The elevated weight W1 is heavier than the lower weight W2. If released, the elevated weight will fall, causing W2 to be raised. The elevated weight (when stationary) possesses "potential" energy. As the weight falls, it possesses "kinetic" energy because it is overcoming the opposition offered by the pull of W2 and the resistance of the air. As W1 falls, work is done, the work consisting of raising W2.

The student should familiarize himself with the exact definitions of the words *"work"*, *"energy"*, and *"power"*.

Electrical power is the rate at which work is done (energy being used) in an electrical circuit and is measured in watts. The number of watts of power in an electrical circuit is found by taking the *product of the voltage applied to the circuit and the current flowing through the circuit. One watt is that amount of electrical power expended in a circuit when a current of one ampere is flowing through the circuit under a pressure of one volt.* For example, if we have five amperes of current flowing through the element of an electric iron under a pressure of 110 volts, then the electrical power being consumed by the iron is equal to 110 × 5, or 550 watts. As another example, suppose we have 100 milliamperes of current flowing through a resistor under a pressure of 100 volts. The rate at which electrical work is accomplished in the circuit (power in watts) will be equal to 100 volts times .1 ampere (100 milliamperes equals .1 ampere). The product is found to be 10 watts of electrical power.

14. LETTERS USED AS ABBREVIATIONS. In electrical work, we quite often find it necessary to use formulas. As is customary in formulas, letters are used as abbreviations instead of writing out

the words. The letters given in the following tabular form should be memorized because they will be used frequently in succeeding lessons.

E is the letter used to abbreviate voltage.
I is the letter used to abbreviate current.
Q is the letter used to abbreviate coulomb.
R is the letter used to abbreviate resistance.
G is the letter used to abbreviate conductance.
W is the letter used to abbreviate power.

The student should learn all of these abbreviations very thoroughly.[1]

15. FORMULAS. In keeping with the information given thus far in our study, there are a few formulas which should be learned. In a previous discussion, we made the statement that conductance and resistance are exactly opposite in effect or the reciprocal to each other. This can be stated in a formula as follows:

$$\text{Conductance} = \frac{1}{\text{Resistance}}$$

or

$$\text{Resistance} = \frac{1}{\text{Conductance}}$$

Using the letters just given for abbreviation, these formulas become:

$$G = \frac{1}{R} \quad \text{or} \quad R = \frac{1}{G}$$

Where: G is the conductance in mhos, and R is the resistance in ohms.

The reciprocal of a number is 1 divided by that number. As shown by the two formulas, resistance and conductance are reciprocal to each other; hence, are considered to be exactly opposite in effect.

In the discussion of electrical power, we made the statement that one watt of electrical power is the rate at which work is done in an electrical circuit when one ampere of current is flowing through the circuit under a pressure of one volt. This fundamental law may be expressed as a formula, thus making it possible to calculate the power in an electrical circuit:

$$\text{Power} = \text{Volts} \times \text{Amperes}$$

Using the letters for abbreviation, we have:

$$W = E \times I$$

Where: W is the electrical power in watts, E is the pressure in volts, and I is the current in amperes.

We shall work out a few examples using this formula.

Example 1: The current flowing through an electric light bulb

[1] Some authors use letters other than those listed to abbreviate some words. As an example: P is used for power, and V for voltage. You will become acquainted with these differences as you acquire experience in Radio and Television work.

is found to be .25 ampere, and the voltage applied across the bulb from the power supply line is 110 volts. Find the electrical power in the circuit.

Given: $E = 110$ volts
$I = .25$ ampere

By formula: $W = 110 \times .25$
or
$W = 27.5$ watts

Example 2: The voltage applied to a heating element is 75 volts and the current flowing through the element is 50 milliamperes. What is the electrical power in this circuit?

Given: $E = 75$ volts
$I = .05$ ampere (50 milliamperes equal .05 ampere)

By formula: $W = 75 \times .05$ or $W = 3.75$ watts

Example 3: A large power drill is being driven by an electric motor. The power drill represents the mechanical load on the motor and by measurement we find that the motor is drawing 10 amperes from a 220-volt supply line. What is the electrical power necessary to drive the load?

Given: $E = 220$ volts
$I = 10$ amperes

By formula: $W = 220 \times 10$
or
$W = 2{,}200$ watts.

The electrical power consumed by this motor can easily be converted into horsepower by dividing the 2,200 watts by 746 (746 watts equal 1 horsepower). Dividing, we find that the motor requires approximately 2.9 horsepower of electrical power in order to drive its load. The rate at which work is done in an electrical circuit may be expressed in either horsepower or watts; however, for nearly all practical applications, the unit "watt" is used.

16. SUBDIVISIONS OF THE OHM, MHO, AND WATT. Four prefixes and their definitions were given earlier in this lesson. It is very advisable to review this information and then refer to the following:

1 megohm	1,000,000 ohms
1 micromho	.000001 mho
1 kilowatt	1,000 watts
1 microwatt	.000001 watt
1 milliwatt	.001 watt

All of these expressions are used quite frequently and the student should be familiar with them.

Notes

(These extra pages are provided for your use in taking special notes)

The text of this lesson was compiled and edited by the following members of the staff:

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UNIT NO. 1	THE ELEMENTS OF RADIO BROADCASTING	LESSON NO. 4

CARL LINNE

"....HIS WILL TO SUCCEED WAS MARVELOUS TO BEHOLD."

One of the most inspiring examples of man's ability to succeed in spite of adversity is contained in the biography of Carl Linne, the son of a poor clergyman residing in a small village in Sweden.

Early in his youth, Carl evinced a keen interest in plant life and when he had reached the age of four, he knew the names of many flowers, weeds and vegetables, as well as their usefulness. As Carl became older, his father grew more and more concerned over his son's future. He could not visualize any future for his boy as a gardener and determined to apprentice him to a shoemaker.

Poor Carl. He hated the smell of leather and the everlasting "pegging away". Finally, he induced his father to let him attend school. Shortly afterwards, Carl won the interest of Doctor Rothmann and moved himself and his meagre effects into the Doctor's home.

When he was 20 years of age, he attended the University of Stockholm on a meagre allowance of about forty dollars a year and money earned doing part-time work. Now, adversity and discouragement attacked Carl in all their fury. He lacked money for his meals. He feared to face his landlady because he had no money with which to pay her. Fate seemed to decree that all his hopes and ambitions be cast aside and that he seek ways and means of making a living which would lead only to poverty and obscurity.

Just when the clouds were the darkest and all seemed lost, opportunity presented itself abruptly in the guise of one Dr. Celsius, a notable physician and botanist, who employed Carl as an assistant.

Eventful years passed and dark uncertainty was left far behind. Carl now wrote his name in Latin, "Carolus Linnaeus". He had become a recognized authority and an accomplished writer, whose books were eagerly sought. Achievement followed achievement. Hardships, suffering and want of years gone by were forgotten in the brilliant glory of his accomplishments.

Botany is a subject far removed from Radio and Television, but the object lesson created by the dramatic and inspiring success story of Carolus Linnaeus should convince you that success CAN be yours IF you really want success.

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Lesson Four

The ELEMENTS of RADIO BROADCASTING

"Now that you have a good start in your radio studies, I thought it advisable to give you a lesson covering the fundamental principles of radio transmission and reception.

"It is not the purpose of this lesson to explain in detail the principles of broadcasting, but rather to give you a picture of the subjects to be covered as your training advances".

INTRODUCTION. Undoubtedly there are a few of our students who now possess some knowledge of radio theory and practice; knowledge which has been secured by studying elementary textbooks or through practical experience in radio service work or amateur station operation. To those who have been fortunate in this respect, we wish to make it clear that we regard your knowledge with the highest esteem and offer our complete cooperation toward assisting you through the fundamental lessons as rapidly as possible. But, let me offer this bit of advice; *a complete and accurate knowledge of radio requires a substantial foundation.*

Even though you may have a fairly complete knowledge of the basic principles, we strongly advocate that you read through each lesson carefully and thereby review certain facts which might have slipped your mind. A little knowledge is dangerous when starting a complete study of radio, so avoid the possibility of future collapse by reading each lesson carefully. If you are certain that you understand each subject discussed, we have no objection to your rapid progress into the interesting advanced lessons following those on fundamental principles.

To those students who have no knowledge of radio or electricity, except that gained from the three previous lessons, we want to impress the fact that all of the following lessons in this course of training have been prepared for men of your status. Years of practical experience and a scientific study of successful training methods have been moulded into a systematic sequence of presenting the lesson material you are to study.

We are starting you from the bottom and will build for you a foundation so solid and complete that you may later branch off into that phase of radio or television which holds the greatest appeal for you. Nearly an unlimited number of fields will be found open for specialization; broadcast station operation, police radio operating, aviation radio, radio service work, public address work, television control room, sound recording, etc., are but a few of the many interesting phases of radio. The entire field is broad enough that you may enter that branch which most completely satisfies your personal desires.

As you study the following fundamental lessons, keep in mind at all times that we are preparing you with a basic knowledge sufficient to permit your entrance into any of these fields. Each lesson is important and you must study it carefully if you are to secure the complete training for which you are enrolled.

Fig. 1 Artists performing before a microphone.

Don't be discouraged if your progress seems a little slow at first. Radio and television is one of the most interesting and encompassing phases of electrical engineering. Having such a wide scope requires careful attention to many details; you must learn these details in a systematic manner so as to establish a concrete foundation. You will probably progress through the fundamentals much more rapidly than you realize; then, before you expect it, you will be right in the midst of the interesting lessons devoted entirely to your chosen occupation---RADIO.

2. COMMUNICATION BY RADIO. Since I know you are extremely anxious to learn how radio broadcasting and reception is carried

on, I am going to review this briefly for you. Projecting speech and music over great distances is undoubtedly the miracle of our age. To the layman, this "magic" feat is veiled with deep mystery, but to you as a student in radio and television, the whole story will soon unfold into a clear picture.

I am going to give you a "bird's-eye" view of how radio broadcasting is carried on and how a radio receiver operates. Of course, I cannot go into detail about these subjects at the present time. The details involved in broadcasting and receiving radio signals constitute most of the material you will study in future lessons. However, if you will study the following information very carefully, you will be able to explain many mysterious facts about radio to your friends. Also, you will have an insight to the interesting study which lies ahead of you, and you will be able to see how each of your future lessons fits into the complete picture of radio.

Most radio programs originate in the studio of a broadcast station; however, some of them as you know are picked up from speaker's platforms, on the street, in theatres, dance halls, etc. Fig. 1 shows artists performing before a microphone in a broadcasting studio. Regardless of where a program originates, if speech or music are to be transmitted, a microphone must be used to transform the sound waves into electrical current variations. If the music from a phonograph record is to be broadcast, a device known as a "pick-up" must be used to generate current variations corresponding to the music on the record. Let's investigate the construction and operation of both a microphone and a phonograph pickup.

> *In the following discussion, I shall find it necessary to use words and terms which are entirely new to you. As you encounter these, do not be greatly concerned if you do not fully understand them. Each of the expressions will be fully defined and explained in future lessons.*

3. THE MICROPHONE. In Fig. 2A, a simplified drawing of a popular type of microphone is shown. This is known as a "dynamic" microphone. A photograph is shown at B. The microphone contains a strong permanent magnet built in a cup-shape with a circular pole protruding from the center of the cup. The top pole piece is a round, flat plate with a large hole in the center. When the plate is bolted to the top of the cup, the magnetic lines of force produced by the strong magnet are concentrated between the inner edge of the hole in the top plate and the pole coming up the center. This is shown at C in Fig. 2. Now, in the intense magnetic field across this gap, a very small coil of wire (voice coil) is lightly suspended, and a diaphragm is attached firmly to the coil. When the diaphragm vibrates, the coil of wire moves back and forth through the steady magnetic field, creating a voltage in the coil. Let us see how the diaphragm is set in motion.

A rapidly vibrating body can set up waves in the air called "sound waves". Our vocal chords and all musical instruments produce sound waves. Waves of sound travel from their source to our ears (or to a microphone) by causing pressure variations of the molecules in the air. Fig. 3 illustrates the appearance of normal air molecules at A; the same molecules are shown at B when a sound wave is passing through it. Notice how the sound wave causes *pressure variations* of the air molecules.

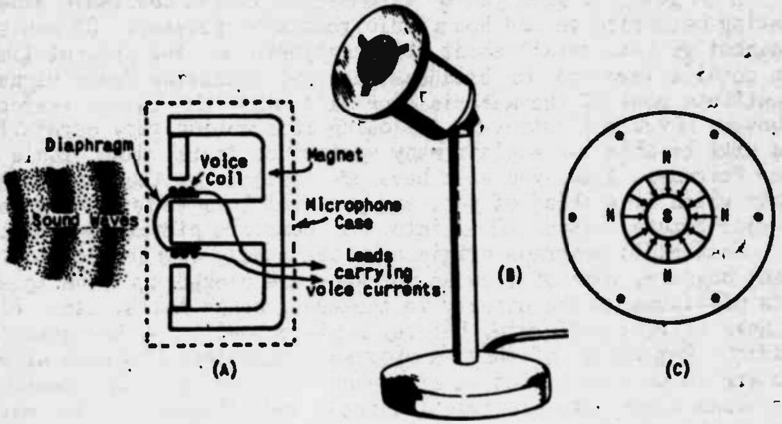


Fig.2 (A) Outline drawing of dynamic microphone. (B) Photograph of a dynamic microphone. (C) Top cover plate of a dynamic microphone. The voice coil fits in the radial gap between N and S.

Upon striking a microphone, sound waves (pressure variations) cause the diaphragm and voice coil to vibrate in exact accordance. Remember that the diaphragm and voice coil are very light and are freely suspended. Thus, the voice coil is made to move in perfect coordination with the sound waves produced by a human voice or a musical instrument.

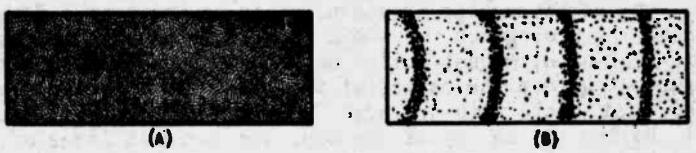


Fig.3 (A) Normal air molecules. (B) Air molecules compressed and rarefied by sound waves.

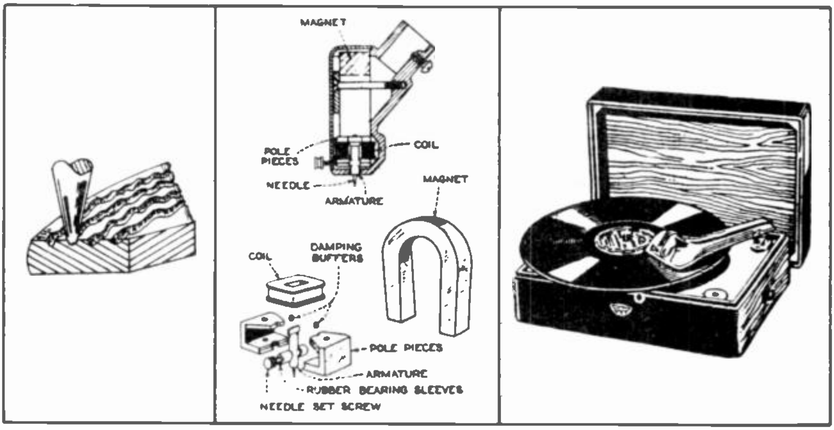
When the voice coil is rapidly vibrated through the strong magnetic field, electrical currents are set up in the coil which represent the exact form of the sound waves. These currents are called "audio" currents;[1] I shall speak of audio currents, also audio voltages, quite frequently from now on.

Even though I have only briefly described the microphone and its operation, you should understand that it converts sound waves

[1] The word audio is of Latin derivation, meaning "to hear".

into electrical audio currents. Next in the process of broadcasting, these audio currents must be magnified or increased in intensity until they represent a high-powered audio wave. Vacuum tube amplifiers are employed for this purpose. Before going into vacuum tube amplifiers, let us see how a phonograph pickup works; then we will be familiar with both methods of producing an audio current.

4. THE PHONOGRAPH PICKUP. A in Fig. 4 shows an enlarged view of a portion of a phonograph record. Notice how the grooves in the record vibrate back and forth. These vibrations represent the pressure variations of the original sound wave and they must be converted into corresponding audio currents by the needle and pickup head.



(A) (B) (C)

Fig.4 (A) Section of phonograph record. (B) Cutaway view of phonograph pickup. (C) Photograph of pickup on record.

A cutaway view of a phonograph pickup is shown at B in Fig. 4. The needle is held in the chuck by a screw; the chuck in turn is a part of an armature assembly. The armature assembly is light and is suspended freely so it can readily vibrate back and forth with the variations of the grooves on the record. The armature assembly is mounted in the center of a coil of wire. The inside diameter of the coil is large enough to prevent restriction of the armature's vibration. The coil is situated so as to be in the magnetic path of a strong horseshoe magnet.

All of these parts are essential for operation of the unit, described as follows: When the needle and armature are moved rapidly in a lateral direction by the varying track in the record groove, the strength of the magnetic field passing through the coil is changed in accordance; this causes an audio current to be produced in the coil. The generated audio current varies exactly the same as the original sound waves which were impressed on the record.

By the above operation, a weak audio current is obtained from a phonograph pickup when the needle is placed in the groove of a revolving record.

In the output of either a microphone or a phonograph unit, the audio current is very weak; hence it must be built up with high-powered vacuum tube amplifiers. Let me now tell you a few interesting facts about a vacuum tube and how it works.

5. THE VACUUM TUBE. Fig. 5 at A shows a cutaway view of a three-element vacuum tube. Before explaining how this tube operates and amplifies the audio signal coming from the microphone, I am going to tell you how it is constructed. By carefully inspecting the drawing, you will see a thin wire in the middle of the tube. This wire is about the size of a hair, but it is a type of wire which will stand a very high temperature without melting. On the outside of this wire, the manufacturer has sprayed a thin film of thorium. Thorium is used because of an important property which it possesses; I will tell you what this property is in just a moment.

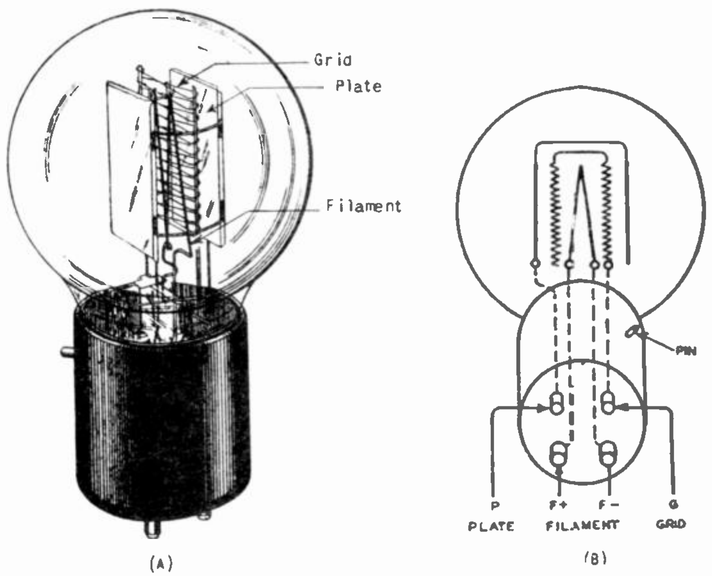


Fig.5 (A) Side view of three-element vacuum tube. (B) Drawing of vacuum tube to show base connections.

The thin, coated wire in the tube is called the *filament* or sometimes, *the cathode*. Its purpose is to supply a quantity of free electrons in the space immediately surrounding the wire. To supply these free electrons, the wire must be heated, and this is done by passing a current through it. Heating a wire with an electric current is not new to you; every time you use your electric toaster, percolator, or iron, you know that heat is produced. In the vacuum tube this same thing is done; the glow you have often seen inside a tube is produced by the heated filament wire.

When the filament wire is hot, the thorium atoms on the outer film throw off electrons into the space around the wire. Only a few kinds of atoms can expel electrons efficiently when heated. Thorium is one of the best; this is the important property of thorium.

The heating current is led to and from the filament wire by two of the prongs on the base of the tube. B in Fig. 5 shows the base arrangement. Let us account for the other two prongs. One of them is connected to a large rectangular piece of metal, called the *plate*, or sometimes called the *anode*. To make the tube operate properly, the positive side of a voltage source (battery or generator) is connected to the plate. The negative side of the voltage source is connected to one side of the filament wire. With this arrangement, you can see that the electrical pressure of the voltage source is making the plate positive and the filament negative.

The positive voltage on the plate attracts the negative electrons that have been expelled or emitted by the filament, hence a steady current of a few milliamperes flows inside the tube from the filament to the plate. Now let us see how this current flow can be changed.

The fourth prong on the base of the tube connects to the zigzag wire which you see in Fig. 5 to be located between the filament and the plate. This wire is called the *grid*, because in the very first tubes, it was made in a mesh-like form. The grid, situated between the filament and the plate, occupies a commanding position, somewhat the same as a water valve in a water pipe. It is directly in the stream of electrons passing to the plate just as a control valve is directly in the stream of water through a pipe. If a water valve is opened or closed, the water flow through the pipe can easily be regulated; likewise, the grid can be made to regulate or control the electrons (current flow) to the plate.

The grid controls the number of electrons passing through it to the plate by offering an electrical repulsion to them. If the grid is to repel the negative electrons, it must be made negative itself. By using a separate voltage source, the negative side is connected to the grid and the positive side is connected to one side of the filament. Thus the grid is made negative and can repel the electrons which try to pass through it to the plate.

Should the negative voltage on the grid be changed, the extent of the repulsion will be changed and the electron flow to the plate will be varied in accordance. For example, if the grid is made more negative, the additional repulsion prevents as many electrons from passing through and the electron flow is decreased. This means that the current flow through the tube is decreased. Now, if the grid is made less negative, more electrons can get through to the plate, so the plate current flow through the tube is increased.

The ability of the grid to control the current through a vacuum tube is a very important operation. I do not expect you to understand this action thoroughly at the present time; later in your study I am going to devote special lessons to the operation of vacuum tubes. In these special lessons, you will learn all of the minute details concerning the grid, plate, and filament. I know you are anxious to get to these lessons and I assure you that your anxiety will be rewarded with a very clear and interesting discussion of vacuum tube operation.

6. SYMBOL FOR VACUUM TUBE. When an engineer makes a drawing to represent a radio circuit, he uses symbols for the parts that are contained in the circuit. The symbol for a three-element vacuum tube is drawn as shown at A in Fig. 6. This figure also shows the cloud of negative electrons surrounding the heated filament wire, the grid repelling some of the electrons to keep them from passing to the plate, and a few electrons passing on through the grid to the plate.

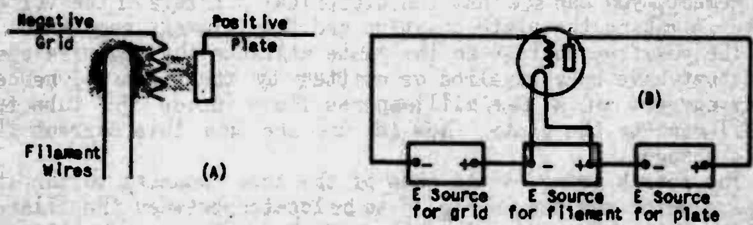


Fig.6 (A) Symbol for three-element vacuum tube. (B) Drawing to show how voltages are applied to the tube's electrodes.

The drawing at B in Fig. 6 illustrates how the three voltage sources are connected to operate the filament, grid, and plate. Later I shall tell you all the details concerning vacuum tube operation; since we are only interested in obtaining a "bird's-eye" view at the present, let us proceed to see how the microphone is connected to the vacuum tube.

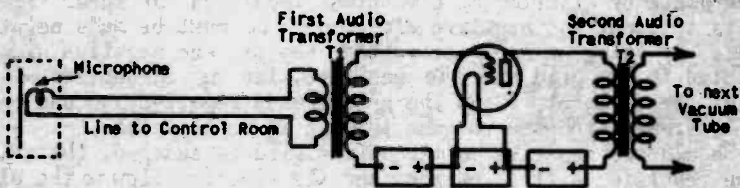


Fig.7 Showing how the microphone is connected to the vacuum tube amplifier.

7. MICROPHONE CIRCUIT. The microphone is located in the studio at the broadcast station and the amplifiers (vacuum tubes) are in the control room. A special cable is used to conduct the audio currents from the microphone out of the studio and into the control room. An engineer would draw this part of the radio circuit as shown in Fig. 7. The microphone is represented by two "twists" (a small coil of wire) and a straight line (the diaphragm). The

line to the control room terminates in the primary of an audio transformer. This piece of equipment is very essential, so we might briefly discuss its construction and purpose.

8. AUDIO TRANSFORMER. An audio transformer is built by stacking several thin sheets of special iron plates to form a "core", then winding two coils of wire onto the core. The core plates are shaped as shown in Fig. 8. The coils are composed of thousands of turns of wire and are wound over the center leg of the core. The coil wound onto the core first is called the *primary* and the second or outside coil is called the *secondary*. A layer of chemically treated insulating paper is placed between the two coils to prevent a short-circuit from occurring between them. The symbol for an audio transformer is shown in Fig. 7, and at B in Fig. 8.

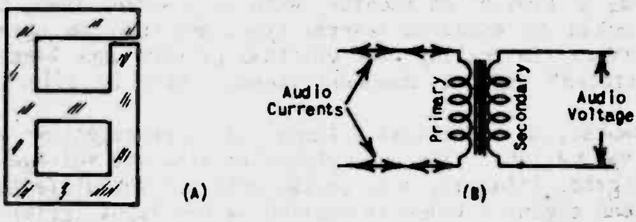


Fig.8 (A) Shape of audio transformer core plates. (B) Symbol for audio transformer.

In Fig. 8, the double-headed arrows indicate that an audio current is circulating back and forth through the primary coil. These currents you will remember are those generated by the microphone. As the audio currents change through the primary, they set up magnetic field variations around the primary turns which cut through the turns on the secondary side and produce audio voltages in the secondary winding of the transformer.

This is a very important function of a transformer, and you will learn much more about it in a later lesson. As for now, let us be content with knowing that audio currents through the primary are "transformed" into audio voltages on the secondary side. You must remember that these audio voltages have exactly the same form as the audio currents. The audio currents in turn are representative of the sound waves which struck the microphone. We now have the original sound wave changed into electrical voltage variations and we can apply these voltages to a vacuum tube and amplify them.

9. VOLTAGE AMPLIFICATION. Referring again to Fig. 7, the wiring (schematic) diagram shows that the audio currents produced in the microphone leads are conducted through the primary of the first audio transformer (T1). These currents are then transformed into audio voltages on the secondary side. The audio voltages are applied directly to the grid or input circuit of the first amplifying tube. The varying audio voltage on the grid causes the current through the plate circuit of the amplifying tube to change in exact accordance. These varying audio currents (amplified) then pass

through the primary winding of the second audio transformer (T2) and produce audio voltages of identical waveform in the secondary winding.

Through the amplifying action of the tube, the original audio currents (or voltages) have been increased in strength. The amplified output of one tube may be fed to the input of a following tube, amplified more, and so on until the desired audio power is obtained. This may require as many as ten or fifteen tubes in the audio amplifying system at the broadcasting station.

Amplifying an electrical voltage with a vacuum tube can be illustrated by an example with which I am sure you are familiar. It is the same principle as though you were to take a small piece of film such as used in a motion picture theatre and project it on a large screen. If you were to examine the film you would find that the figures were too small to be distinguished easily. But, upon using a projection machine, with a powerful lamp, the small figures could be enlarged several times and made to appear on a large screen. In reality the original picture has been enlarged or "amplified" several thousand times. This is illustrated in Fig. 9.

Likewise, an electrical voltage can be enlarged or amplified with a vacuum tube. The tube, together with its voltage supplies for the grid, filament, ant plate, acts as the projector. Then when a weak signal voltage is applied to the input (grid) circuit, an enlarged voltage of the same waveform appears in the output (plate) circuit.

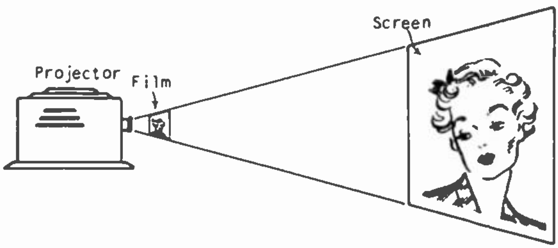


Fig.9 Photographic analogy of voltage amplification.

10. THE CARRIER WAVE. Building up the audio power with large amplifying tubes is only one of the three important things which must be done at a radio broadcast station. The other two are (1) generating and amplifying a "carrier" wave, and (2) impressing the audio power onto the carrier wave. Let us see why a "carrier" wave is necessary.

I know you will understand when I say it is necessary for a "radiation" of energy to take place from the antenna of a radio station. Radiation means the expulsion of radio energy in all directions from the antenna. Quite often the antenna is called the "radiator", because it is that part of the complete radio transmitting system which radiates the radio signals.

Radiating a radio signal in the form of electric waves from an antenna can be compared to a simple, understandable process. You know that water waves can be set up on a calm pool by creating a disturbance in the water. Suppose you were to move a paddle back and forth in the water as shown in Fig. 10. A regular motion of the paddle would cause a series of successive waves to be sent out over the surface of the water. Now, if a second paddle is dipped into the water and suspended on a free-moving pivot, it will swing back and forth as the water waves strike it. By attaching a string and hammer to the second paddle, it can be made to ring a gong at the crest of each water wave. Thus energy has been transmitted or "radiated" over the water waves.

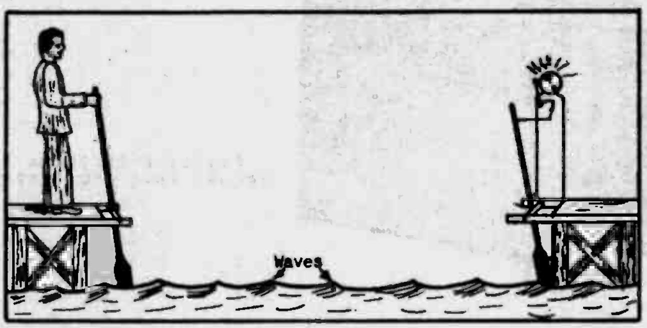


Fig.10 Illustrating the transmission of energy with water waves. A radio "carrier" wave is also a means of transmitting energy.

In a like manner, radio (electrical) waves are sent out from a broadcasting antenna and made to carry energy to far-distant radio receivers. As is the case with the gong in the above example, a radio receiver will respond according to the variations of the wave which it intercepts. The radio waves are analogous to the water waves in that they serve as the "carrier" of the energy from the transmitter to the receiver.

If we were to feed only the amplified audio power into the antenna, we would find that no radiation of energy occurs. Audio power cannot establish the electric fields around the antenna that are necessary to expel the radio energy into space. Technically, we would say that the "frequency" of the audio power is too low for efficient radiation. To radiate efficiently, the "frequency" of the electrical energy fed into the antenna must be high. For this reason, a high-frequency electrical wave must be generated and amplified by the transmitter so as to carry the audio power from the transmitting station to the receiver. This high-powered, high-frequency wave is called the *carrier wave*.

The carrier wave is generated in the very first stage of a radio transmitter by a vacuum tube circuit known as an "oscillator". Fig. 11 shows a photograph of a vacuum tube oscillator as used in some of the transmitters made by the RCA Manufacturing Co. Advanced lessons in your course of training will discuss the design and theory of operation of these important radio circuits.

The high-frequency voltage output of the oscillator is very weak and must be amplified by more vacuum tubes. To distinguish amplifiers of this type from those which amplify an audio frequency voltage, they are called *radio-frequency* amplifiers. Understand that vacuum tubes of practically the same construction are used, but they are somewhat larger. Also, in designing the circuit, it is necessary to use different kinds of transformers from the types that were used in audio amplifiers.

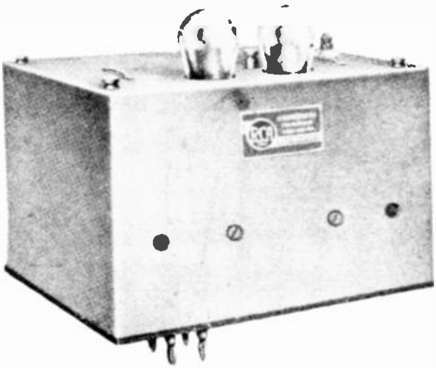


Fig.11 Photograph of RCA vacuum tube oscillator.

The radio frequency amplifiers build up the strength of the weak carrier wave generated by the oscillator until it is the maximum power that the government will allow the station to use. The Federal Communications Commission assigns each radio station a "maximum carrier power" which it must use to carry on its radio broadcasting. Also, each station is assigned a certain frequency on which to broadcast. These frequency assignments are made in "kilocycles", abbreviated kc. For broadcast stations, the frequencies are between 550 kc. and 1600 kc. The dials of most modern radio sets are calibrated in kilocycles, so when you want to receive a certain station, you must look in a log book or the newspaper to find its frequency in kilocycles, then tune to that number on your dial. The frequency has nothing to do with the distance from the radio station that the program can be heard;[1] this is determined entirely by the power of the carrier wave.

You should also understand that a certain radio station will come in at the same kilocycle marking on a receiver dial regardless of whether the receiver is used close to the radio station or thousands of miles from it. This is proved by the fact that you can ride along in an automobile for miles and miles and listen to a certain radio station without changing the tuning dial. However, you may find it necessary to keep turning the volume control up as

[1] This is true of frequencies in the broadcast band. In the high and ultra-high frequency spectrums, the frequency of the carrier wave does affect the distance of transmission.

you get farther from the station. This is because the radiated carrier wave becomes weaker and weaker as it travels away from the broadcast station, finally becoming so weak that the station cannot be heard satisfactorily without getting a lot of noise and static at the same time.

Fig. 12 shows in block diagram form the essential components at a radio transmitting station which we have discussed. At A, the sound waves are converted into audio currents by the microphone; B and C are audio amplifiers which build up the audio waves to a high power. D illustrates the oscillator, where the carrier wave is generated; E and F are radio frequency amplifiers which increase the oscillator power until it is the proper number of watts for feeding into the antenna. Notice in Fig. 12 that a line is drawn from C to F, indicating that the output of the last audio amplifier is fed into the last radio frequency amplifier. If this is done, the audio and the carrier wave will be "mixed" in such a manner that the carrier will have the audio impressed on it. Thus, the carrier wave will be radiated from the antenna, carrying the audio wave with it to the receiver.

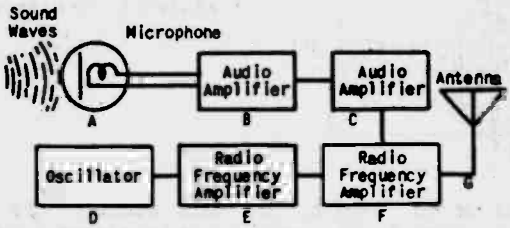


Fig. 12 Block diagram to show the essential components for radio transmission.

11. MODULATION. The mixing of the audio and carrier waves is called "modulation"; let us investigate this phenomenon a little more closely.

When an engineer wants to draw a diagram representing a high-frequency carrier wave, he does so as shown at A in Fig. 13. The several lines extending above and below the straight line through the center represent "cycles". You will learn all about these cycles in a lesson to come very soon. When the cycles are drawn close together (as at A in Fig. 13), the engineer intends to represent a high frequency wave, and when he draws them far apart (expanded), he means to represent a low frequency wave. An audio wave is a low frequency wave, so the single cycle shown at B in Fig. 13 can be used to represent the amplified audio wave which we want to impress on the high frequency carrier wave.

The manner of connecting a vacuum tube and its associated circuit so that "modulation" will take place is far too complicated for presentation here. Let it suffice to say that in such a circuit, the carrier wave and the audio wave are both delivered to a high-powered vacuum tube. Then in the output of this tube, we will obtain a mixture of the two input waves. The mixed or modulated wave can be illustrated diagrammatically as shown at C in Fig. 13. Notice that the wave at C is simply the combination of the waves at A and B. When the audio wave rises, it adds to the carrier wave and makes the modulated wave increase above its normal height. Then, when the audio wave falls below the center line, it bucks against the carrier wave and causes the modulated wave to

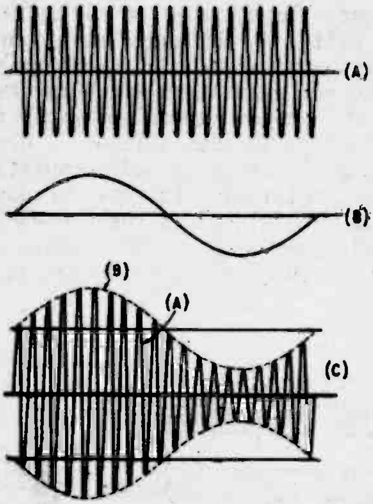


FIG.13 (A) High frequency carrier wave. (B) Low frequency audio wave. (C) High and low frequency waves together. This is called a "modulated carrier wave".

fall below its normal height. In this manner, the audio signal which we want to send to the receiver is impressed onto the carrier wave; the resultant modulated wave is then fed into the antenna at the broadcasting station and radiated out into space.

12. RADIATION. Another of the important electrical operations which takes place at a radio station is the radiation of the modulated wave from the antenna. The story of how this radiation occurs is one of great interest, but at the same time, it is a long story and one requiring an accurate knowledge of all fundamentals before it can be understood. I am not going to confuse your mind by attempting to present such advanced information in this lesson. Fig. 14 is a photograph of a modern broadcast antenna.

The tower type of antenna is rapidly supplanting the older flat-top antenna for broadcast station use because of its better radiation ability. The tower is made of steel angles and bars, with the joints riveted, welded, or bolted. Most antennas are insulated from the ground by setting the base on strong insulators. Beneath the tower, a large quantity of copper screen or long lengths of copper wire are buried about one foot in the ground. The buried copper is the ground connection for the radio station, and the insulated steel tower is the radiating antenna. These are similar to the aerial and ground wires which you install on your radio receiver.

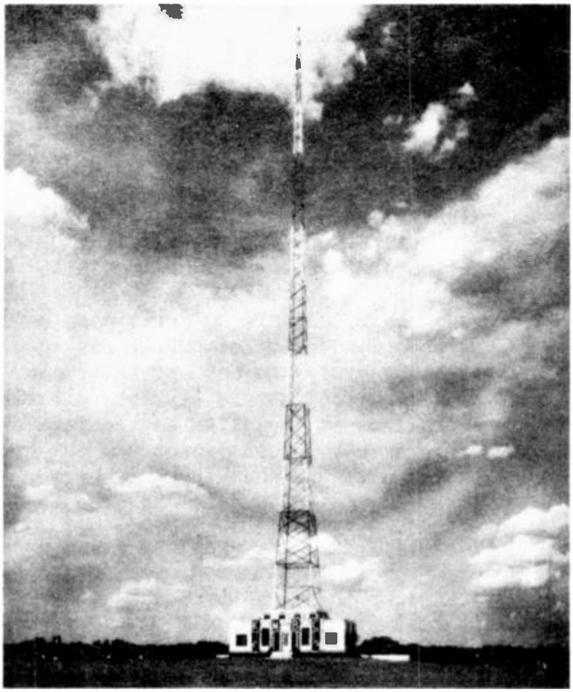


Fig.14 Photograph of KMBC broadcasting antenna.

Since the radiating tower at the broadcast station is insulated from ground, the modulated carrier wave may be fed from the transmitter directly into the tower. When this high frequency current flows in the tower, electric and magnetic fields are set up around it which cause the radio wave to be propagated into space in all

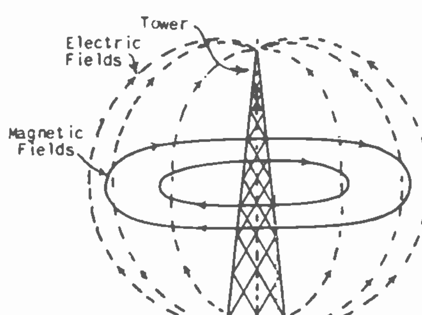


Fig.15 Drawing to show the electric and magnetic fields set up around a broadcasting antenna.

directions. Fig. 15 shows how these electric and magnetic fields exist around the tower when the radio carrier wave is being broadcast.

13. SPEED OF RADIO WAVES. A modulated carrier wave is propagated into space at a tremendous speed; in fact it travels at a speed the same as light, approximately 186,000 miles per second. At this rate, a radio wave can travel around the earth at the equator more than seven times in one second.

Regardless of the frequency (in kilocycles) of a radio wave, it will always travel through space at the speed of light. A 100 kc. radio wave travels at the same speed as a 300,000 kc. wave when radiated from an antenna. Thus, a radio wave arrives at your receiving antenna practically the same instant it is sent out from the transmitting station, regardless of how many miles the station is from your home.

I have given you a brief picture of what goes on at a radio transmitter. If you have found some of the terms and expressions used a little difficult to grasp, do not be greatly concerned about it at the present time. In your future lessons, all of this information will be repeated, and at that time each detail will be made very clear. For the present, I mainly want you to get a general idea of the subjects you will be studying. Later on, you will be able to read this lesson again and understand each term perfectly.

14. THE RECEIVING AERIAL. Transmitting a radio program over a carrier wave to our homes is indeed a most remarkable feat. Telephone circuits employ wires to carry the sound waves, but in radio an intangible electrical wave is used for the carrier. This, to most people is the mysterious thing about radio. After you learn about electrical and magnetic fields in future lessons, you will be able to understand how this "magic" act is performed. Now I know you are interested in learning how the modulated carrier wave is treated at the radio receiver in order to reproduce the original sound waves.

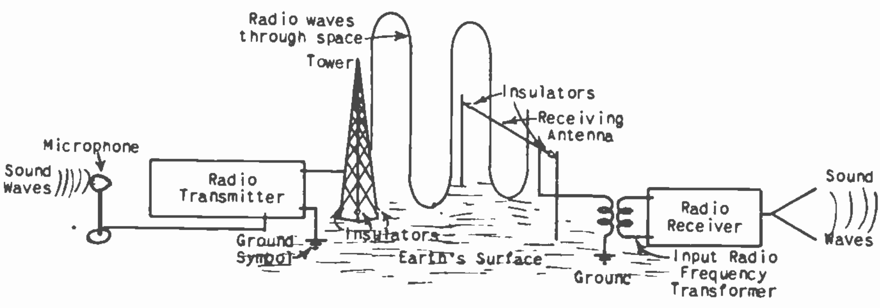
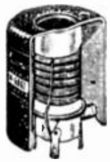


Fig.16 Illustrating the transmission of radio energy to a receiver.

In Fig. 16 you will see a drawing which illustrates the process of transmitting and receiving by radio. The radio waves travel through space and strike the receiving aerial wire. The aerial is insulated from ground, so very weak radio frequency voltages are produced in it. These voltages have exactly the shape or form as the passing radio wave. Assuming that the radio wave is a modulated carrier, the weak voltages in the aerial wire will cause weak radio frequency currents to flow through the aerial circuit from the elevated wire to ground. The ground (earth) serves as the return path for the radio energy from the receiver back to the radio transmitter.

Included in the aerial circuit is the primary winding of a radio frequency transformer. An RF (radio frequency) transformer is built differently from an audio transformer; however, its purpose in the circuit and its theoretical operation are the same. When drawing the symbol for an RF transformer, the center lines are omitted, indicating that no iron core is used in its construction. The core material for an RF transformer is air and the two coil windings are supported on a short, hollow tube of some non-metallic material such as cardboard, or bakelite. Fig. 17 at A is a photograph of a radio frequency transformer. You will probably find several such transformers inside the shield cans on your radio set.



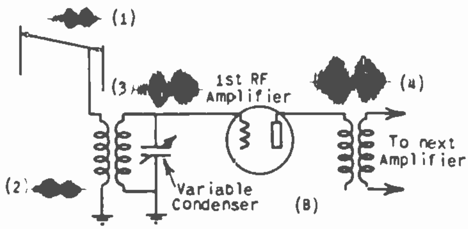


Fig.17 (A) Photograph of R.F. transformer. (B) Illustrating the reception and amplification of a radio wave at the receiver.

15. AMPLIFYING THE RECEIVED RADIO WAVE. Now we shall refer to B in Fig. 17 to see how the intercepted radio wave is conducted into the receiving set. The RF voltage in the aerial wire is represented by the small figure labeled (1). This is a modulated radio frequency voltage, and it causes a modulated radio frequency current to flow through the primary winding of the RF transformer to ground. The RF current through the primary is represented by the figure labeled (2). Notice that both (1) and (2) are small, indicating that the RF voltage and RF current in the aerial and primary coil are very weak. We would find them to be only a few microvolts and microamperes if we were to use sensitive instruments to measure the actual values.

When RF current passes through the primary of the transformer, an RF voltage is produced on the secondary side. We must now divert for a moment and explain the presence of a new piece of equipment. The new part is a variable condenser; it is connected across the secondary of the RF transformer. A condenser is an important piece of equipment in radio and electrical work because it is the only device which can store electrical energy. In nearly all radio circuits you will find many condensers used; some of them are fixed in size and some are variable.

The variable type of condenser is often called a "tuning" condenser because all radio receivers are tuned by varying the effective size of such a condenser. The tuning knob on your radio set is fastened to the shaft of one or more variable condensers. When you tune your set to receive different stations, notice that the flat metal plates of the condenser move in and out of mesh. This changes the effective size of the variable condenser and causes the tuning circuits in the set to respond to different incoming radio stations.

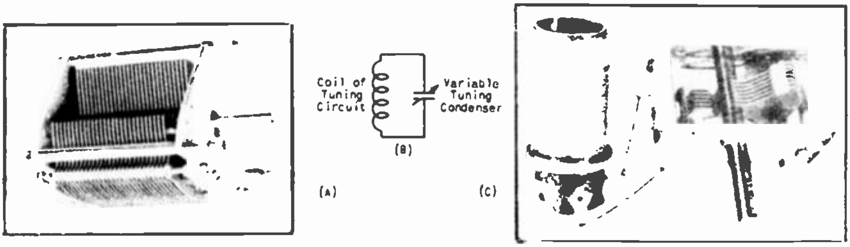


Fig.18 (A) Photograph of variable condenser. (B) Symbols to represent a tuning circuit. (C) Photo of tuning coil and condenser connected together.

A in Fig. 18 is a photograph of a variable tuning condenser. B in the same figure is a drawing to show with symbols how the tuning coil and variable tuning condenser are connected across each other. In practically all cases, the tuning coil is the secondary winding of an RF transformer as shown in Fig. 17. The photograph at C in Fig. 18 shows how the tuning circuit is connected. Try to locate these parts in your radio set.

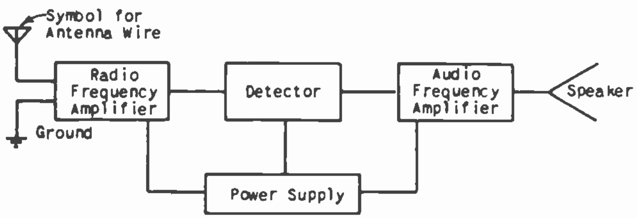


Fig.19 Block diagram of radio receiving set.

I cannot take the time now to tell you how a tuning circuit works. If you will look at the outline of your course, you will find that an entire lesson will soon be devoted to that subject. For the present, all I want you to remember is that such circuits are necessary in all radio sets so that they can be tuned from one radio station to another. Now we shall return to our discussion of B in Fig. 17.

The variable tuning condenser is rotated until the radio wave we want to receive is able to pass through the tuning circuit. When this is done, the RF voltages will be slightly amplified and applied to the grid of the first vacuum tube in the set. The drawing labeled (3) represents the modulated radio wave applied to the first RF amplifying tube. The radio wave is amplified by the vacuum tube, then delivered through a second RF transformer to a second amplifying tube. The drawing labeled (4) represents the amplified, modulated radio wave.

By using a sufficient number of amplifying tubes, the weak radio frequency voltage in the aerial wire can be made quite strong. Generally, amplification is continued until the signal is one volt or more. That part of the radio set which amplifies the modulated carrier wave is called the *radio frequency amplifier*. The block diagram in Fig. 19 shows the four important sections of all radio receivers; you can see that the radio frequency amplifier is the first section following the antenna. The power supply is merely for the purpose of supplying the necessary voltage and current for operating the vacuum tubes in the set.

16. THE DETECTOR AND AUDIO AMPLIFIER. Now we come to the interesting section of a radio receiver, the *detector*. You will recall that we used the high frequency wave generated by the transmitter only for the purpose of "carrying" the audio wave to the receiver. Up to this point in the receiving set, the high frequency carrier wave is still present. We must now separate the two, removing the carrier wave from the circuit, and feeding the audio wave into the audio amplifier.

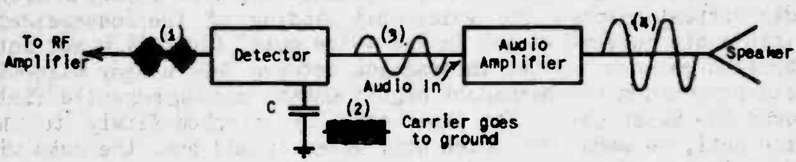


Fig.20 Illustrating how the detector removes the carrier wave.

A detector is a vacuum tube circuit carefully and precisely designed so as to perform this job. I know that when you study the lesson on detectors you will find it extremely interesting. Fig. 20 illustrates what happens; (1) shows the modulated carrier going into the detector; (2) shows the high frequency carrier being passed through the condenser C to ground; and (3) shows the removed audio wave going into the audio amplifier. The audio currents in the output of the detector have exactly the same form as the audio currents which were produced in the microphone circuit at the broadcast station.

In the receiver, we must now amplify these audio currents until they are strong enough to operate a loud speaker. Again one or more vacuum tubes are used and the result is that strong audio currents are fed into the windings of the loud speaker. Let us now see how the speaker operates, then our "bird's-eye" view of broadcasting and receiving will be complete.

17. THE POWER TUBE AND SPEAKER. The last tube in the audio amplifier is called the "power" tube. The reason is because it must deliver *audio power* (voltage and current) to the loudspeaker in order to make it operate. A in Fig. 21 shows how the loudspeaker is connected to the power tube and also shows an outline drawing of a typical speaker. By close inspection, you will see that a loudspeaker is constructed somewhat the same as a microphone. It contains a strong permanent magnet and a voice coil. The main difference is that a large paper cone is attached to the voice coil instead of a diaphragm.

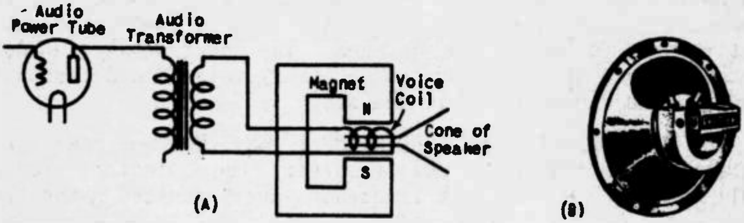


Fig.21 (A) Drawing to show how the power tube is connected to the loudspeaker. (B) Photograph of loudspeaker.

The amplified output of the power tube is passed through the primary winding of the last audio transformer in the set. The voltage produced in the secondary of the transformer then forces a strong audio current through the voice coil winding of the loudspeaker. As the audio current varies in the voice coil, the coil is set into vibration because of the interaction between the steady magnetic field produced by the permanent magnet and the varying magnetic field around the voice coil. The paper cone is attached firmly to the voice coil, so when the voice coil moves in and out, the cone vibrates in accordance to produce the sound waves.

The sound waves generated by the speaker cone are exact duplications of the electrical audio currents passing through the voice coil. Assuming that these currents have the same waveform (except that they are amplified) as the audio currents originally produced in the microphone circuit at the broadcasting station, the sound waves set up by the vibrating cone of the speaker are exactly the same as those which struck the diaphragm of the microphone. Thus, speech and music has been transmitted over many miles and reproduced in our homes by means of radio communication.

18. CONCLUSION. A complete radio communication system, including transmission and reception involves many, many different kinds of intricate circuits and component parts. Should any one circuit or any single part in this system fail to function properly, reception at the receiver will be either totally impossible or severe distortion will accompany the sound from the speaker. Radio operators, servicemen, and technicians must have a complete understanding of each and every circuit in the entire system if they are to be successful in constructing or maintaining the equipment. As you

study through your course of training, you will learn about these intricate circuits, one by one. Upon completion, you will have the necessary qualifications for one of the many prosperous jobs in the radio communication field.

I must again remind you that if you are to become an expert radio man, you cannot neglect to learn thoroughly the fundamentals of electricity in the next few lessons. These principles are all-important; you will not be able to comprehend the future lessons completely unless you have a working knowledge of the fundamentals.

In the brief outline of radio communication just given, I mentioned just one type of microphone, one design of phonograph pickup, one kind of loudspeaker, etc. In reality, there are many different ways of making each of these units and also, there are many types of radio circuits which I did not mention. You understand, of course, that it has been necessary for me to omit quite a lot in order to make a brief survey of such a broad field. If you now have a general insight on how radio programs are brought to your home, this lesson has fulfilled its purpose.

Later, I shall tell you in brief how television pictures are sent out over radio waves. You will be surprised when you learn that there is very little difference between broadcasting a television picture and broadcasting sound waves. The same underlying principles are used except that an "electric camera" is used instead of a microphone and a "reproducing screen" is used instead of a loudspeaker.

It is now time to begin studying some of the fundamental electrical laws and circuits. In the next lesson, I shall tell you about series circuits, parallel circuits, and Ohm's Law. These are three important subjects, very essential as a part of your basic knowledge.

When working with Ohm's Law, you will find it necessary to use simple arithmetic in solving some of the problems. I know you learned to use fractions in grade school several years ago, but I am going to help you recall the fundamental operations by reviewing them in the next few pages. Perhaps you have been using your arithmetic enough that you do not need the review; if so, just skip this material and proceed into the next lesson. At the end of Lesson 5, I will review the use of decimals for you.

Should you encounter difficulty in solving any of the problems or understanding any of the definitions, we advise that you secure the assistance of a friend who is capable of supplying the necessary detailed instruction. Private tutoring is the most satisfactory method of learning mathematics if no previous knowledge of the subject is possessed. Complete concentration and perseverance are necessary in order to master the subject of mathematics to the point where it is readily applicable when the occasion arises. The ability to apply mathematics to the study of Radio and Television is an unquestionable asset and every student should attempt to place himself in this desirable position.

COMMON FRACTIONS

1. DEFINITIONS.

A fraction is an indicated division, which expresses one or more equal parts into which a unit may be divided. Examples are: $\frac{1}{2}$, $\frac{5}{8}$, $\frac{1}{6}$, $\frac{161}{8}$, $\frac{3}{284}$, etc.

The number below the line in the fraction is called the denominator or the divisor of the fraction. The denominator shows into how many parts the whole is divided.

The number above the line in the fraction is known as the numerator or dividend of the fraction. The numerator shows how many of the parts, into which the whole is divided, are taken.

For example, suppose we divide an inch into eight equal parts and then take three of these parts. Eight would be the denominator of the fraction and three the numerator. We would then say we had $\frac{3}{8}$ of an inch.

The combination of a whole number and a fraction is called a mixed number. Examples are: $3\frac{3}{4}$, $2\frac{1}{8}$, $104\frac{4}{7}$, etc. Note that $3\frac{3}{4}$ means $3 + \frac{3}{4}$.

If the numerator is less than the denominator, it is said to be a proper fraction. Examples are: $\frac{1}{3}$, $\frac{3}{4}$, $\frac{4}{7}$, $\frac{64}{167}$, etc.

If the numerator is equal to or greater than the denominator, it is said to be an improper fraction. Examples are: $\frac{4}{4}$, $\frac{5}{4}$, $\frac{10}{3}$, $\frac{100}{25}$.

A proper fraction always has a value less than 1, while an improper fraction has a value equal to or greater than 1,

Two fractions which have their numerators and denominators respectively equal are equal to each other.

Of two fractions having equal denominators, the one with the larger numerator is the greater. Example: $\frac{5}{8}$ is greater than $\frac{3}{8}$.

Of two fractions having equal numerators, the one with the larger denominator is the smaller. Example: $\frac{5}{12}$ is less than $\frac{5}{8}$.

When two fractions have unequal numerators and denominators, comparison of their values is not so easy. For example, to compare $\frac{7}{10}$ and $\frac{8}{11}$, we must first change both fractions so that they have equal denominators. A method for doing this will be explained later.

2. FUNDAMENTAL PRINCIPLES.

(1) If we multiply or divide both numerator and denominator by the same number, we do not change the value of the fraction. For example, let us take $\frac{2}{3}$. If we multiply both numerator and denominator by 2, we will have $\frac{4}{6}$, which is equal to $\frac{2}{3}$. Or if we have $\frac{9}{3}$ and divide both numerator and denominator by 3, we will have $\frac{3}{1}$ or 3, which is equal to $\frac{9}{3}$.

(2) If we multiply the numerator or divide the denominator by a number, we multiply the fraction by that number. For example, we will take $\frac{2}{3}$. If we multiply the numerator by 3, we will have $\frac{6}{3}$, which is equal to 2, and this is three times $\frac{2}{3}$. Or if we use the same fraction and divide the denominator by 3, we will have $\frac{2}{1}$, or 2.

(3) If we divide the numerator or multiply the denominator by a number, we divide the fraction by that number. For example, using $\frac{3}{4}$, we will divide the numerator by 3; this will give us $\frac{1}{4}$, which is $\frac{3}{4}$ divided by 3. Or multiplying the denominator by 3 gives us $\frac{3}{12}$, which is equal to $\frac{1}{4}$.

3. REDUCTION OF A WHOLE OR MIXED NUMBER TO AN IMPROPER FRACTION.

Example (1). Reduce 3 to 4ths. Since $1 = \frac{4}{4}$, $3 = 3 \times \frac{4}{4} = \frac{12}{4}$ *Ans.* (By principle 2.)

Example (2). Reduce $8\frac{2}{3}$ to 3rds. Since $1 = \frac{3}{3}$, $8 = 8 \times \frac{3}{3} = \frac{24}{3}$. Therefore, $8\frac{2}{3} = \frac{24}{3} + \frac{2}{3} = \frac{26}{3}$ *Ans.*

Rule: To reduce a whole number to a fraction with a certain denominator, first change 1 to a fraction with this denominator and then multiply the numerator by the given whole number. If we have a mixed number, we must reduce the whole number to a fraction and then add to the numerator of this fraction the numerator of the fractional part of the mixed number.

4. REDUCTION OF AN IMPROPER FRACTION TO A WHOLE OR MIXED NUMBER.

Example (1). Reduce $\frac{28}{7}$ to a whole number. $\frac{28}{7} = 28 \div 7 = 4$ *Ans.*

Example (2). Reduce $\frac{21}{8}$ to a mixed number. $\frac{21}{8} = 21 \div 8 = 2\frac{5}{8}$ *Ans.*

Rule: To reduce an improper fraction to a whole or mixed number, divide the numerator by the denominator. The quotient[1] is the whole number. If there is a remainder, it becomes the numerator of the fractional part of a mixed number.

Exercises

1. Change the following numbers to fourths. 8, 11, 15. To sevenths. (*Answers:* $\frac{32}{4}$, $\frac{44}{4}$, $\frac{60}{4}$. $\frac{56}{7}$, $\frac{77}{7}$, $\frac{105}{7}$.)

2. Change the following mixed numbers to improper fractions. $8\frac{3}{7}$, $4\frac{1}{8}$, $12\frac{2}{9}$. (*Answers:* $\frac{59}{7}$, $\frac{33}{8}$, $\frac{110}{9}$.)

3. Change the following improper fractions to whole or mixed numbers. [illegible], [illegible], [illegible], [illegible], [illegible], [illegible], [illegible], [illegible]. (*Answers:* 9[illegible], 3[illegible], 42, 56, 29, 22[illegible], 13[illegible], 39[illegible].)

5. REDUCTION OF FRACTIONS TO LOWEST TERMS.

A fraction is in its lowest terms when the numerator and denominator are "prime"[2] to each other, or when there is no whole number that will exactly divide both of them.

Example. Reduce $\frac{60}{160}$ to its lowest terms. It is seen that 10 will exactly divide both 60 and 160. Therefore, we will have:

$$\frac{60 \div 10}{160 \div 10} = \frac{6}{16} \quad \text{(Principle 1)}$$

Again it is evident that 2 will exactly divide both 6 and 16. Therefore, we have:

$$\frac{6 \div 2}{16 \div 2} = \frac{3}{8}$$

which is the lowest terms, since there is no whole number, other than 1, which will exactly divide both 3 and 8.

Rule: To reduce a fraction to its lowest terms, divide both numerator and denominator successively by any whole number that will exactly divide both of them.

Exercises

Reduce the following fractions to their lowest terms.

1. [illegible], [illegible], [illegible]. Answer: [illegible], [illegible], [illegible].
2. [illegible], [illegible], [illegible]. Answer: [illegible], [illegible], [illegible].
3. [illegible]. Answer: [illegible].
4. [illegible]. Answer: [illegible].
5. [illegible]. Answer: [illegible].

[1] A quotient is the number obtained when a numerator is divided by a denominator.

[2] A number is said to be "prime" when it can be divided evenly only by itself and 1.

6. REDUCTION OF SEVERAL FRACTIONS TO FRACTIONS HAVING THE SAME DENOMINATOR.

Fractions which have the same denominator are said to have a common denominator.

Example (1). Reduce $\frac{1}{3}$ and $\frac{1}{4}$ to fractions which have 12 for a denominator. If we multiply both numerator and denominator of $\frac{1}{3}$ by 4, we obtain $\frac{4}{12}$. This will not change the value of the fraction. This multiplier is obtained by dividing 12 by 3. We have:

$$\frac{1}{3} = \frac{1 \times 4}{3 \times 4} = \frac{4}{12}$$

Likewise, to reduce $\frac{1}{4}$ to 12ths, we obtain the multiplier by dividing 12 by 4, which gives us 3. Therefore:

$$\frac{1}{4} = \frac{1 \times 3}{4 \times 3} = \frac{3}{12}$$

Example (2). Reduce $\frac{1}{2}$, $\frac{3}{5}$, and $\frac{2}{3}$ to 30ths.

Both terms of $\frac{1}{2}$ are multiplied by $30 \div 2 = 15$.
Both terms of $\frac{3}{5}$ are multiplied by $30 \div 5 = 6$.
Both terms of $\frac{2}{3}$ are multiplied by $30 \div 3 = 10$.

$$\frac{1}{2} = \frac{1 \times 15}{2 \times 15} = \frac{15}{30}$$

$$\frac{3}{5} = \frac{3 \times 6}{5 \times 6} = \frac{18}{30}$$

$$\frac{2}{3} = \frac{2 \times 10}{3 \times 10} = \frac{20}{30}$$

Rule: To reduce several fractions to fractions which have a common denominator, multiply both numerator and denominator of each fraction by a number found by dividing the common denominator by the denominator of that fraction.

To compare two fractions having unequal numerators and unequal denominators, they must first be reduced to fractions having a common denominator. Thus, to compare $\frac{4}{7}$ and $\frac{5}{8}$, we first reduce them to fractions having 56 as denominators. We obtain $\frac{32}{56}$ and $\frac{35}{56}$ respectively, from which it is easy to see that $\frac{5}{8}$ is greater than $\frac{4}{7}$.

7. LEAST COMMON DENOMINATOR.

In the preceding examples, we assumed a denominator and reduced the fractions to that denominator. Ordinarily, however, we are given several fractions which we must reduce to fractions having a least common denominator. This is abbreviated to L.C.D.

Sometimes the L.C.D. can be determined by inspection. Thus, the L.C.D. of $\frac{1}{4}$, $\frac{1}{6}$, and $\frac{1}{2}$ is 12. More often this is not the case and we can then use the following method:

Example (1). Find the L.C.D. of $\frac{8}{45}$, $\frac{8}{25}$, and $\frac{7}{30}$.

```
5/45, 25, 30
3/9,  5,  6
  3,  5,  2
```

L.C.D. $= 5 \times 3 \times 3 \times 5 \times 2 = 450$ *Answer.*

What we did was to write the denominators in a line and divide them by any number that would exactly divide two or more of them. In this case, it was 5. Then we divided the quotients by any number that would exactly divide two or more of them. The first quotients were 9, 5, and 6, and we see that 3 will exactly divide the 9 and the 6. We perform the divisions, bringing down the 5 since it is not divisible by 3. Our new quotients are 3, 5, and 2. We have continued the process as far as possible since there is no number that will exactly divide two or more of these numbers. The L.C.D. was found by multiplying together all of the divisors and the final quotients.

Rule: Divide the various denominators by a prime number that will divide two or more of them; then divide the remaining numbers and the quotients by a prime number that will divide two or more of them. Continue this as long as possible. The L.C.D. is the product of all the divisors and the quotients or numbers left.

Example (2) Find the L.C.D. of $\frac{[illegible]}{5}$, $\frac{[illegible]}{11}$, $\frac{17}{22}$, and $\frac{[illegible]}{44}$.

```
11/5, 11, 22, 44
 2/5,  1,  2,  4
   5,  1,  1,  2
```

L.C.D. = 11 × 2 × 5 × 2 = 220 *Answer.*

Exercises

1. Change $\frac{[illegible]}{7}$, $\frac{1}{10}$, and $\frac{4}{15}$ to 420ths. *Answer:* $\frac{[illegible]}{420}$, $\frac{42}{420}$, $\frac{112}{420}$.
2. Change $\frac{[illegible]}{[illegible]}$, $\frac{[illegible]}{7}$, and $\frac{[illegible]}{[illegible]}$ to 210ths. *Answer:* $\frac{42}{210}$, $\frac{[illegible]}{210}$, $\frac{[illegible]}{210}$.
3. Change $\frac{1}{2}$, $\frac{1}{4}$, and $\frac{1}{6}$ to 36ths. *Answer:* $\frac{18}{36}$, $\frac{9}{36}$, $\frac{6}{36}$.
4. Reduce the following to fractions having a L.C.D.:
   (A) $\frac{1}{2}$ and $\frac{2}{5}$. *Answer:* $\frac{5}{10}$, $\frac{4}{10}$.
   (B) $\frac{1}{[illegible]}$ and $\frac{[illegible]}{[illegible]}$. *Answer:* $\frac{[illegible]}{[illegible]}$, $\frac{[illegible]}{[illegible]}$.
   (C) $\frac{1}{10}$, $\frac{1}{[illegible]}$, and $\frac{1}{[illegible]}$. *Answer:* $\frac{[illegible]}{120}$, $\frac{[illegible]}{120}$, $\frac{[illegible]}{120}$.
   (D) $\frac{1}{7}$, $\frac{1}{[illegible]}$, and $\frac{1}{[illegible]}$. *Answer:* $\frac{[illegible]}{[illegible]}$, $\frac{7}{[illegible]}$, $\frac{[illegible]}{[illegible]}$.

8. ADDITION OF FRACTIONS.

We cannot add two fractions such as $\frac{1}{2}$ and $\frac{1}{3}$ directly, any more than we could add 2 apples and 3 oranges. We must first change the fractions into ones having a L.C.D. Thus:

$$\frac{1}{2} = \frac{1 \times 3}{2 \times 3} = \frac{3}{6}$$

$$\frac{1}{3} = \frac{1 \times 2}{3 \times 2} = \frac{2}{6}$$

Then to add the fractions, we add the numerators for a new numerator and use the L.C.D. as our denominator. Finally we reduce the sum to its lowest terms:

$$\frac{3}{6} + \frac{2}{6} = \frac{5}{6} \text{ Answer.}$$

(Examples follow)

Example (1). $\frac{1}{2} + \frac{2}{3} + \frac{1}{3} + \frac{1}{4} =$

$$\frac{6}{12} + \frac{8}{12} + \frac{4}{12} + \frac{3}{12} = \frac{21}{12} = 1\frac{9}{12} = 1\frac{3}{4} \text{ Answer.}$$

Example (2). Find the sum of $2\frac{2}{3} + 4\frac{5}{8} + 1\frac{1}{6} + \frac{5}{6}$. The whole numbers and the fractions may be added separately, and then these sums added to find the total. First, we will change these mixed numbers so that the fractional parts have a L.C.D.:

$$2\frac{16}{24} + 4\frac{15}{24} + 1\frac{4}{24} + \frac{20}{24} = 7\frac{55}{24} = 9\frac{7}{24} \text{ Answer.}$$

Rule: To add fractions that have equal denominators, add the numerators of the fractions and place the sum over the L.C.D. If this gives an improper fraction, it must be reduced to a whole or mixed number. If the fractions have unequal denominators, first reduce them to fractions with a L.C.D. To add mixed numbers, add the whole number and fractions separately and then add the sums.

Exercises

Add the following and express the sum in the simplest form.

1. $\frac{1}{2} + \frac{2}{3} + \frac{5}{12}$. *Answer:* $1\frac{7}{12}$.
2. $\frac{1}{7} + \frac{4}{9} + \frac{1}{3}$. *Answer:* $\frac{58}{63}$.
3. $\frac{5}{8} + \frac{5}{16} + \frac{3}{4}$. *Answer:* $1\frac{11}{16}$.
4. $1\frac{5}{8} + 3\frac{1}{12} + 4\frac{1}{2}$. *Answer:* $9\frac{5}{24}$.
5. $11\frac{1}{11} + 10\frac{1}{16} + 5\frac{1}{8}$. *Answer:* $26\frac{49}{176}$.
6. $\frac{1}{7} + 3\frac{1}{2} + \frac{1}{8}$. *Answer:* $3\frac{43}{56}$.

9. SUBTRACTION OF FRACTIONS.

Example (1). Subtract $\frac{3}{8}$ from $\frac{7}{8}$. $\frac{7}{8} - \frac{3}{8} = \frac{4}{8} = \frac{1}{2}$ *Answer.*

Since the fractions have a L.C.D., we find their difference by taking the difference of their numerators and using the L.C.D. as the denominator. If the fractions do not have a L.C.D., they must be reduced to fractions that do.

Example (2). Subtract $\frac{1}{4}$ from $\frac{5}{8}$. $\frac{5}{8} - \frac{1}{4} = \frac{5}{8} - \frac{2}{8} = \frac{3}{8}$ *Answer.*

Example (3). Subtract $2\frac{1}{2}$ from $5\frac{5}{8}$. $5\frac{5}{8} - 2\frac{1}{2} = 5\frac{5}{8} - 2\frac{4}{8} = 3\frac{1}{8}$ *Ans.*

Example (4). Subtract $3\frac{3}{4}$ from $7\frac{1}{3}$. First change the fractional parts into fractions that have a L.C.D.:

$$7\frac{1}{3} - 3\frac{3}{4} = 7\frac{4}{12} - 3\frac{9}{12}.$$

Notice that it is not possible to subtract the $\frac{9}{12}$ from the $\frac{4}{12}$. The easiest way out of this difficulty is to now change the mixed numbers into improper fractions and then subtract:

$$7\frac{4}{12} - 3\frac{9}{12} = \frac{88}{12} - \frac{45}{12} = \frac{43}{12} = 3\frac{7}{12} \text{ Ans.}$$

Rule: To subtract one fraction from another when they have equal denominators, find the difference of the numerators and write it over the L.C.D. If the fractions do not have equal denominators, reduce them to ones with a L.C.D. before subtracting. If the numbers are mixed numbers, subtract the fractional parts, then the whole numbers. If the fractional part of the subtrahend[1] is greater than the fractional part of the minuend[2], reduce the mixed numbers to improper fractions and then subtract.

[1] The number which is being subtracted is called the subtrahend.

[2] The number which is being subtracted from is called the minuend.

Exercises

Subtract the following and express the sum in the simplest form:

1. [illegible] - [illegible]. *Answer:* [illegible].
2. [illegible] - [illegible]. *Answer:* [illegible].
3. 3[illegible] - 1[illegible]. *Answer:* 2[illegible].
4. 4[illegible] - 2[illegible]. *Answer:* 2[illegible].
5. 2[illegible] - 1[illegible]. *Answer:* [illegible].
6. 5[illegible] - 3[illegible]. *Answer:* 1[illegible].

10. MULTIPLICATION OF FRACTION AND WHOLE NUMBER.

Example (1). Multiply $\frac{2}{3}$ by 5. By principle (2), multiplying the numerator of a fraction by a number multiplies the fraction by this number:

$$\frac{2}{3} \times 5 = \frac{10}{3} = 3\frac{1}{3} \textit{ Ans.}$$

Example (2). Multiply $\frac{2}{15}$ by 5. $\frac{2}{15} \times 5 = \frac{10}{15} = \frac{2}{3}$ *Ans.*

Rule: To multiply a fraction by a whole number or a whole number by a fraction, multiply the numerator of the fraction by the whole number, then reduce to lowest terms.

11. MULTIPLICATION OF A FRACTION BY A FRACTION.

Example (1). Multiply $\frac{2}{3}$ by $\frac{5}{7}$. $\frac{2}{3} \times \frac{5}{7} = \frac{10}{21}$ *Ans.*

Example (2). Multiply $\frac{3}{4}$ by $\frac{8}{9}$. $\frac{3}{4} \times \frac{8}{9} = \frac{24}{36} = \frac{2}{3}$ *Ans.*

Rule: To multiply a fraction by a fraction, multiply the numerators together for a new numerator, and the denominators together for a new denominator. Cancellation is always used in multiplication problems.

12. CANCELLATION.

In the solution of a problem, we often encounter a multiplication such as the following:

$$\frac{8 \times 3 \times 4 \times 16}{2 \times 4 \times 7 \times 8}$$

We could, of course, multiply together all the terms in the numerator and then divide this product by the product of the terms in the denominator. This would give us:

$$\frac{8 \times 3 \times 4 \times 16}{2 \times 4 \times 7 \times 8} = \frac{1536}{448} = 3\frac{192}{448} = 3\frac{3}{7}$$

However, we can save considerable time by a process known as cancellation. Let us solve the same problem by this method:

$$\frac{\cancel{8} \times 3 \times \cancel{4} \times \overset{8}{\cancel{16}}}{\cancel{2} \times \cancel{4} \times 7 \times \cancel{8}} = \frac{24}{7} = 3\frac{3}{7} \textit{ Ans.}$$

First, it is seen that 4 is found both above and below the line. We will draw a line through each of them and they are then said to be cancelled. We can do the same thing with the two 8's. Notice that the 16 above the line and the 2 below the line are both divisible by 2. We will draw a line through the 2 and also through the 16. Then we will write an 8 above the 16, which is the number of times that 2 is contained in 16. We now have left in the numerator 3 and 8, and in the denominator a 7. No further cancellation is possible; therefore, we multiply the 3 by the 8, which gives us $\frac{24}{7}$ or $3\frac{3}{7}$.

Example (1). $$\frac{4 \times 10 \times 2}{8 \times 30} = \frac{1}{3} \text{ Ans.}$$ (2 written below the 8, 3 below the 30)

First, we cancelled the 10 and 30, writing a 3 below the 30. Next, we cancelled the 4 and 8, writing a 2 below the 8. We now have left a 2 above the line and a 2 and 3 below the line; therefore, we can cancel the 2's. Now notice that every term above the line has been cancelled; we therefore retain one of the unit factors which we neglected to write when cancelling. This makes the numerator 1.

Rule: (1) Any factor[1] in the numerator may be divided into any factor in the denominator.

(2) Any factor in the denominator may be divided into any factor in the numerator.

(3) Any whole number which will exactly divide two numbers, one above and one below the line, may be divided into each.

(4) To obtain the answer, divide the product of the numbers remaining above the line by the product of the numbers remaining below the line. If no number remains above or below, use 1.

Note: This method cannot be used when there are indicated additions or subtractions in the problem.

Example (2). $$\frac{2 \times 4 + 3}{9 \times 7 - 8}$$

First, perform the multiplication, and we have:

$$\frac{8 + 3}{63 - 8}$$

Then perform the addition in the numerator and the subtraction in the denominator:

$$\frac{11}{55} = \frac{1}{5} \text{ Ans.}$$

Exercises

Use cancellation to find the results in the following:

1. $\frac{3 \times 4 \times 6}{2 \times 8 \times 16}$ *Ans.* $\frac{9}{32}$

2. $\frac{20 \times 35 \times 18}{24 \times 12 \times 7}$ *Ans.* $6\frac{1}{4}$

3. $\frac{144 \times 999 \times 121}{11 \times 333 \times 12}$ *Ans.* 396

[1] A factor of a whole number is any whole number that will exactly divide it. Thus, 2, 3, 4, and 6 are factors of 12.

4. $\frac{1320 \times 432 \times 660}{4400 \times 297 \times 288}$ *Ans.* 1

13. MULTIPLICATION OF MIXED NUMBERS AND WHOLE NUMBERS.

Example (1). Multiply $7\frac{3}{4}$ by 3.

$$7\tfrac{3}{4} \times 3 = \tfrac{31}{4} \times 3 = \tfrac{93}{4} = 23\tfrac{1}{4} \textit{ Ans.}$$

Example (2). Multiply $8\frac{1}{3} \times 2\frac{3}{4}$.

$$8\tfrac{1}{3} \times 2\tfrac{3}{4} = \tfrac{25}{3} \times \tfrac{11}{4} = \tfrac{275}{12} = 22\tfrac{11}{12} \textit{ Ans.}$$

Rule: To multiply two numbers, one or both of which are mixed numbers, change the mixed numbers to improper fractions and multiply the fractions according to the rule given in paragraph 11.

Exercises

Find the product of each of the following. Cancel where possible.

1. $\frac{7}{8} \times 3$.	*Ans.* $2\frac{5}{8}$.	5. $3\frac{1}{3} \times 4$.	*Ans.* $13\frac{1}{3}$.
2. $\frac{4}{5} \times 20$.	*Ans.* 16.	6. $5\frac{6}{7} \times 11$.	*Ans.* $64\frac{3}{7}$.
3. $\frac{2}{3} \times \frac{5}{7}$.	*Ans.* $\frac{10}{21}$.	7. $4\frac{2}{7} \times 2\frac{1}{4}$.	*Ans.* $9\frac{9}{14}$.
4. $\frac{3}{4} \times \frac{2}{3}$.	*Ans.* $\frac{1}{2}$.	8. $6\frac{1}{2} \times 4\frac{8}{11}$.	*Ans.* $30\frac{8}{11}$.

14. DIVISION OF FRACTIONS.

Example (1). Divide $\frac{4}{5}$ by 3. To divide $\frac{4}{5}$ by 3 is to find one of the 3 equal parts of $\frac{4}{5}$. Also, to take $\frac{1}{3}$ of $\frac{4}{5}$ is to find one of the 3 equal parts of $\frac{4}{5}$. To take $\frac{1}{3}$ of a number is to multiply that number by $\frac{1}{3}$. Therefore, we have:

$$\tfrac{4}{5} \div 3 = \tfrac{4}{5} \times \tfrac{1}{3} = \tfrac{4}{15} \textit{ Ans.}$$

The reciprocal of a number is 1 divided by that number. Thus $\frac{1}{3}$ is the reciprocal of 3; $\frac{4}{5}$ is the reciprocal of $\frac{5}{4}$; and 4 is the reciprocal of $\frac{1}{4}$. What we did in the above example was to multiply the dividend by the reciprocal of the divisor, where $\frac{4}{5}$ was the dividend and 3 the divisor.

Example (2). Divide 7 by $\frac{3}{4}$.

$$7 \div \tfrac{3}{4} = 7 \times \tfrac{4}{3} = \tfrac{28}{3} = 9\tfrac{1}{3} \textit{ Ans.}$$

Example (3). Divide $\frac{5}{9}$ by $\frac{2}{3}$.

$$\frac{5}{9} \div \frac{2}{3} = \frac{5}{\overset{3}{\cancel{9}}} \times \frac{\overset{1}{\cancel{3}}}{2} = \frac{5}{6} \textit{ Ans.}$$

Example (4). Divide $3\frac{2}{3}$ by $4\frac{1}{6}$.

$$3\tfrac{2}{3} \div 4\tfrac{1}{6} = \frac{11}{3} \div \frac{25}{6} = \frac{11}{\underset{1}{\cancel{3}}} \times \frac{\overset{2}{\cancel{6}}}{25} = \frac{22}{25} \textit{ Ans.}$$

The expression $\frac{1}{\frac{3}{4}}$ is equal to $1 \div \frac{3}{4} = 1 \times \frac{4}{3} = \frac{4}{3}$ *Ans.*

Also: $\dfrac{\frac{2}{3}}{4} = \frac{2}{3} \div 4 = \dfrac{\overset{1}{\cancel{2}}}{3} \times \dfrac{1}{\underset{2}{\cancel{4}}} = \dfrac{1}{6}$ *Ans.*

Likewise: $\dfrac{\frac{7}{8}}{\frac{3}{5}} = \frac{7}{8} \div \frac{3}{5} = \frac{7}{8} \times \frac{5}{3} = \frac{35}{24} = 1\frac{11}{24}$ *Ans.*

We shall have occasion to solve such problems as: $\dfrac{1}{\frac{1}{2} + \frac{2}{3} + \frac{1}{6}}$. This means that 1 is to be divided by the sum of the fractions $\frac{1}{2}$, $\frac{2}{3}$ and $\frac{1}{6}$. We therefore proceed to find the L.C.D. of these fractions, add them, and then divide 1 by this sum, as:

$$\frac{1}{\frac{1}{2} + \frac{2}{3} + \frac{1}{6}} = \frac{1}{\frac{3}{6} + \frac{4}{6} + \frac{1}{6}} = \frac{1}{\frac{8}{6}} = 1 \times \frac{6}{8} = \frac{6}{8} = \frac{3}{4} \textit{ Ans.}$$

Rule: To divide a whole number, or a fraction, by a fraction, or a whole number, invert the divisor and multiply it by the dividend. If either or both dividend and divisor are mixed numbers, first change to improper fractions.

Exercises

1. $\frac{2}{3} \div 6$.	*Ans.* $\frac{1}{9}$.	5. $1\frac{1}{2} \div 2\frac{1}{3}$.	*Ans.* $\frac{9}{14}$.
2. $4 \div \frac{1}{3}$.	*Ans.* 12.	6. $\frac{7}{9} \div \frac{9}{11}$.	*Ans.* $\frac{77}{81}$.
3. $\frac{5}{8} \div \frac{3}{4}$.	*Ans.* $\frac{5}{6}$.	7. $\frac{9}{10} \div \frac{1}{3}$.	*Ans.* $2\frac{7}{10}$.
4. $7\frac{3}{7} \div 2\frac{2}{5}$.	*Ans.* $3\frac{2}{21}$.	8. $\frac{4}{5} \div \frac{6}{7}$.	*Ans.* $\frac{14}{15}$.

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UNIT NO. 1

OHM'S LAW AND ITS APPLICATION

LESSON NO. 5

AMBITION

.....THE MOTIVE FORCE THAT DRIVES MEN TO SUCCESS!

This little story is a true recital of an incident that vividly portrays the reason why some men reach the depths of failure and despair, while others, who started life on an equal basis, climb steadily up the ladder of success.

Driving through an older section of the city one cold, disagreeable day, I was thinking about my comfortable home and other pleasant things, when suddenly, without warning, my car snorted a couple of times, jerked along and then stopped. We all know that a car will not run without gas, so with a muttered exclamation of disgust, I opened the door and clambered out into the cold. Gazing up and down the street in the hopes I would sight a filling station, my thoughts were interrupted by a shuffling sound at my back and a weak, watery voice that said, 'Mister, I'm cold. Got no place to go and I'm hungry. Won't you please stake me to a meal.' Turning around, I beheld the drooping figure of a man that was comparatively young.....a tragic face and a stooped, shriveled figure draped in rags which had once been a suit of clothes. As I looked into his pleading eyes, I could not help but wonder why there was such a difference in men that spelled either failure or success. So I decided to find out.

We went into a small restaurant. I bought him a plate of food and a steaming cup of coffee, and we talked. I discovered that this poor man had never had any particular ambition. He just kept hoping and hoping that some day he would get a 'lucky break' like 'other guys get'. He didn't believe in 'eddecation', had no objective in sight and was just sort of 'sittin' around in the same old place'.

Flash! It suddenly dawned on me that that was exactly what my car was doing....."sittin' in the same old place." And it was sitting there because there was no power to drive it to my destination. This decrepit, hopeless man lacked driving power, too.....ambition to make his 'energy engine' run. He was 'out of gas'. He would never have money in the bank, a happy home, a car nor any of life's luxuries. Poverty was his only future.

YOU WANT SUCCESS.....A BANK ACCOUNT.....A CAR..... A HAPPY HOME AND A REGULAR JOB WITH REGULAR, SUBSTANTIAL PAY CHECKS. SO FIRE YOURSELF WITH AMBITION, STEP ON THE STARTER AND KEEP DRIVING TOWARDS YOUR DEFINITE OBJECTIVE IN LIFE! NEVER 'RUN OUT OF GAS'!

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Lesson Five

OHM'S LAW and It's Application

A very interesting fact in the history of Radio and Television is that approximately a hundred years ago, a scientist named Georg Simon Ohm developed an electrical law which has stood without change down through the years. It is known as "Ohm's Law" and is considered as one of the fundamental laws in the applications of all Electrical, Radio and Television science.

It is imperative that you become thoroughly familiar with the use of this law and its applications. Bear in mind that there is nothing difficult in the study of this subject. Do not make this interesting and important subject hard work and drudgery, but rather approach the subject with an open mind and you will find it much easier than you anticipated.

1. DIRECTION OF CURRENT FLOW. It has been shown that it is impossible to establish an electron movement through a conductor without an electrical pressure or voltage applied across the conductor. Since electrons are negative particles of electricity, the electron moving force or voltage evidently causes the movement of electrons by the attraction and repulsion exerted on these tiny negative particles. The direction of the attraction and repulsion will be in accordance with the fundamental physical laws:

1. Like charges repel each other.
2. Unlike charges attract each other.

Every source of voltage, then, must have an attraction at one of its poles[1] and a repulsion at the other pole for the negative electrons in order to set them in motion. *The pole at which the attraction for the electrons exist is known as the "positive pole" of the voltage source, and the pole at which the repulsion for the electrons exist is known as the "negative pole" of the voltage source.*

We have all heard the expression "positive and negative poles of a battery" used, and at this time it is necessary to learn exactly what is meant by it. In a battery of any kind, the electrical pressure produced at its two poles or terminals is due entirely to a chemical reaction which occurs within the battery. The chemical reaction causes electrons to be taken from one pole of the battery and also causes electrons to be driven into the other pole of the

[1] The "pole" and the "terminal" of a battery mean the same.

battery. An expenditure of chemical energy is necessary in order to cause this electron displacement. The pole from which the electrons are taken is less negative than before and is called "positive" because of its electron deficiency. The pole into which the electrons are forced will be more negative than before; hence, it is called "negative" because of its excess number of electrons.

In an electrical generator, the expenditure of mechanical energy causes a similar electron displacement to take place by induction, and a "positive" and a "negative" pole are produced. The positive and negative poles of a generator likewise have a deficiency and excess of electrons respectively. (See Fig. 1.)

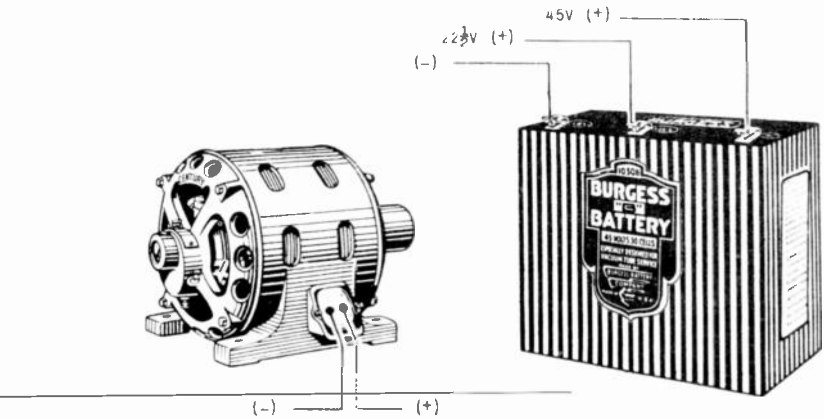


Fig.1 All devices, capable of producing a DC voltage, will have a positive terminal and a negative terminal. These terminals are marked on the battery and the generator shown above.

When the electrical pressure of a battery is applied across any complete circuit, the electrons in the atoms which are loosely held will be repelled from the negative pole of the battery and attracted to the positive pole, thus causing a drift or movement of the electrons from negative to positive. Previously, an electric current was defined as the rate of electron flow through a circuit. Hence, it follows that *the direction of current flow through an electrical circuit is from the negative pole to the positive pole of a voltage source.*

It is quite possible that the last statement in the preceding paragraph does not coincide with former theory which might have been learned by the student. Since the earlier experiments in electricity, around 1752, by Benjamin Franklin, it has been common to make the statement that "current flows from positive to negative". The two words "positive" and "negative" were selected arbitrarily by Franklin at the time of his experimentations merely because they have exactly opposite meanings. In his earlier experiments, he noticed that the actions occurring in an electrical circuit coincided in many ways with the flow of water through a pipe. Since the law of gravity demands that water flow from a high level to a low level and since the word "positive", at first thought, seems to denote high and the word "negative" seems to denote low, Franklin concluded (but with no substantial proof) that current flowed from positive to negative. Through the ensuing years, this same assumption has been taken for granted, and it was not until the adoption of the electron theory that Franklin's original idea was entirely disproved. It is now a well-known fact that current (rate of electron flow) is in the opposite direction to the first assumption. For several years, engineers have known this to be true; however, such a radical change in technical literature cannot be brought about in a short period of time. During the past few years, quite a number of the technical articles appearing in current magazines and several books written by engineer-authorities have adopted the newer and correct statement that *current flows from negative to positive.* (See Fig. 2.)

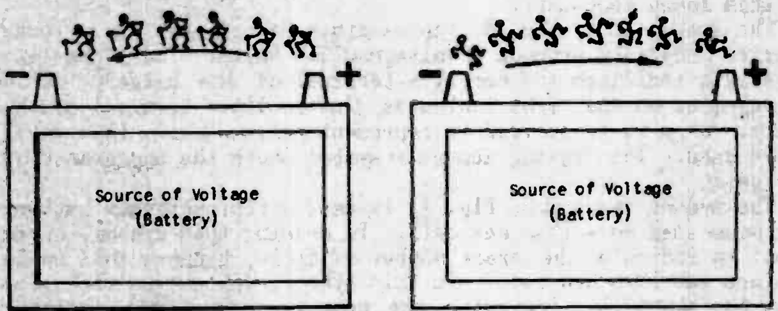


Fig. 2 The drawing on the left shows old men passing from the positive to the negative terminal of the battery. This is the direction in which the current was thought to flow before the electron theory. The drawing on the right shows active, young men passing from the negative to the positive terminal of the battery. This is the actual direction of current flow as proved by the electron theory.

Since it is our desire to train the student with a fundamental knowledge exact in every respect throughout our entire course of study, we are going to adopt the proper conception of the direction of current flow. Bear in mind that whereas other technical literature may state that current flows from positive to negative, there is really no purposely introduced dissention between our opinions. All engineers know that current flows from negative to positive, but due to the fact that the older expression has been used for such a long time, it is rather difficult to adopt the newer method of instruction and explanation.

We are of the opinion that if the student is properly trained with information that is exactly correct, the benefits derived therefrom in his future search for technical knowledge will warrant the slight difficulty encountered at the present time. It is not our purpose to ridicule those authors who make the statement that "current flows from positive to negative." We merely aim to make it clear that we are adopting the modern theory.

2. SYMBOLS USED IN WIRING DIAGRAMS. Before proceeding further, it will be necessary to learn several symbols which are used in Radio and Television work to represent various parts of electrical apparatus. Instead of showing a photograph of the piece of equipment, the engineer finds it much simpler to designate that piece of apparatus with a symbol. The symbols to be given are those commonly employed by all engineers. A wiring diagram, when drawn with symbols, is much more helpful to the engineer than an actual photograph of the equipment, because it shows exactly how the current flows through the entire circuit. A photograph would show the current coming up to the part, then leaving it, but would not show the path traveled through the inside of the part.

The symbols given here are those which will be used for our immediate study only. Other symbols will be given in following lessons when found necessary.

The symbol at A, Fig. 3, represents a dry cell battery. These batteries generally produce a voltage of 1.5 volts. The short line on the left indicates the negative terminal of the battery, while the long line on the right indicates the positive terminal of the battery. When it is desired to represent only one cell, the symbol at A is used. The drawing above the symbol shows the appearance of a dry cell.

The symbol shown at B, Fig. 3, is used to represent any battery which possesses more than one cell. In drawing this symbol, never attempt to indicate the exact number of cells, because this would sometimes run into hundreds. In this symbol, the same as with symbol A, the short line indicates the negative pole of the battery and the long line indicates the positive pole of the battery. The drawing above the symbol shows the appearance of a 3-cell car battery.

The symbol shown at C is used to represent a fixed resistance. The use of resistors is very common throughout all Radio and electrical work. Resistors are used to reduce voltage, to produce heat, or to prevent the short circuit of a voltage source. Resistors are manufactured by employing some special kind of wire, such as nichrome, manganin, constantin, etc. They are also made of carbon, since this material has a high resistance. These resistors may be purchased in nearly any size desired, from a fraction of an ohm to several megohms. The symbol for a fixed resistor does not indicate the size of the resistor in ohms, so it is necessary to print the number of ohms near the symbol if that information is necessary.

As well as fixed resistors, we also find that there are several needs for variable resistors. The symbol for a variable resistor (commonly known as a rheostat) is shown at D, Fig. 3. The arrow drawn through the symbol represents that its value is variable by changing the position of the sliding contact arm. From the photograph shown with this symbol, it can be seen that a rheostat has two external connections. One of the external connections is fastened internally to one end of the resistance wire or strip, and the other external connection is connected internally to the sliding contact arm. The other end of the resistance strip is left without

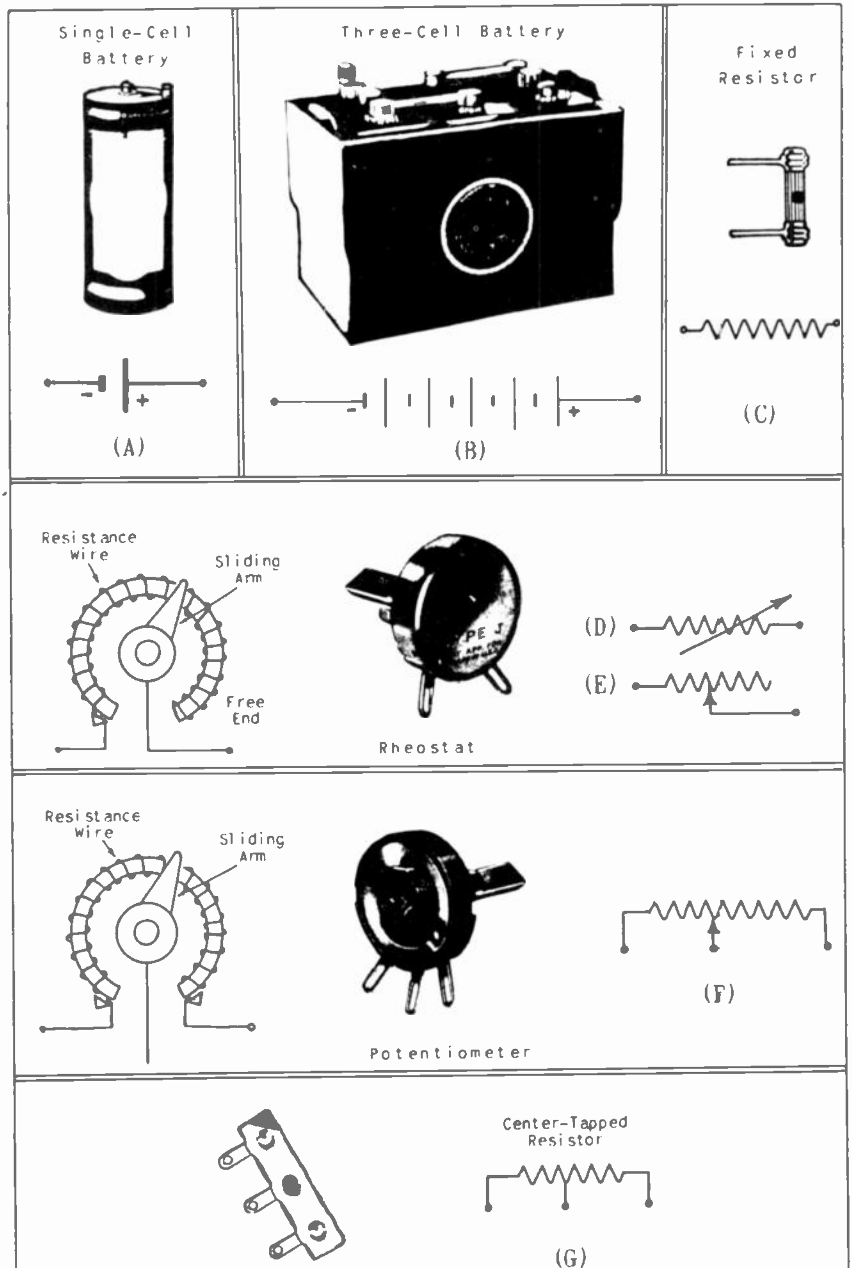

Single-Cell Battery
(A)
Three-Cell Battery
(B)
Fixed Resistor
(C)
Resistance Wire
Sliding Arm
Free End
Rheostat
(D)
(E)
Resistance Wire
Sliding Arm
Potentiometer
(F)
Center-Tapped Resistor
(G)

Fig. 3

any external connection. An outline drawing illustrating these internal connections is shown on the left side of the photograph.

The symbol shown at E represents the same piece of apparatus as the symbol at D. A rheostat may be represented on a wiring diagram with either of these symbols. There is no difference whatsoever in the piece of equipment itself; some engineers desire to represent this part with one symbol, while other engineers prefer the other symbol.

The symbol shown at F represents what is commercially known as a "potentiometer". A potentiometer is a variable resistance, the same as a rheostat; however, the potentiometer has a connection to both ends of the resistance wire or strip, as well as a connection to the sliding contact arm. As can be seen from the photograph of a potentiometer, it has three external connections. The only difference, then, between a potentiometer and a rheostat is that a potentiometer will be provided with three external connections, while a rheostat will have only two. There is nothing about the symbol of a rheostat or a potentiometer which tells the size in ohms, so if this information is necessary, it must be printed near the symbol.

Quite often we find it necessary to use a resistor that has a tap (extra connection) either at the center or near either end. If a fixed resistor has a tap at the exact center, it is commonly known as a "center-tapped resistor", but if the tap is nearer one end of the resistor than the other, it is known only as a "tapped resistor." The symbol and photograph of a center-tapped resistor is shown at G, Fig. 3.

The use of meters is very important in the theoretical and practical applications of electricity and Radio. By the use of meters, it is possible to measure the amount of current flowing through a circuit and to measure the electrical pressure or voltage applied to a circuit. If we desire to measure the current flowing through a circuit, an ammeter will be employed. The symbol for an

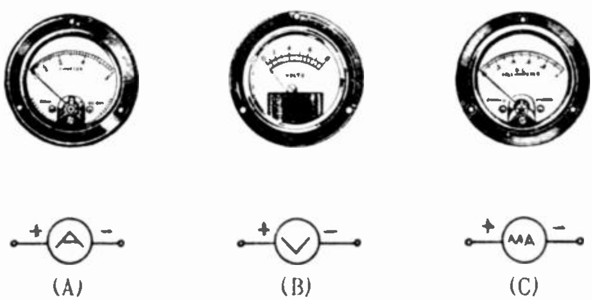


Fig. 4

ammeter is shown at A, Fig. 4. To measure the voltage applied to an entire circuit, or to measure the voltage across any part of a circuit, a voltmeter will be used. The symbol employed for a voltmeter is shown at B, Fig. 4. In most Radio work, the current flowing through the various circuits will be much lower than one ampere; hence, the more popular unit for measuring current in Radio circuits is the milliampere. Milliammeters, then, will be used more than ammeters for Radio and Television current measurements. (C, Fig. 4.) All meters used for DC[1] measurements will have a positive terminal and a negative terminal, so it is necessary to make certain that the meter is properly connected in the circuit to prevent damaging the instrument.

3. CONNECTING DC METERS. Before connecting a DC meter in a circuit to measure voltage or current, there are three things which must be taken into consideration:

1. The proper meter must be selected for the measurement to be made; that is, a voltmeter must be used for all voltage measurements, and a milliammeter or an ammeter must be used for all current measurements.
2. The range of the meter must be sufficiently high so that the meter will not be overloaded.
3. The meter must be connected in the proper direction.

The first consideration is important because if we do make the mistake of attempting to measure voltage with a milliammeter or an ammeter, the instrument is certain to be damaged. The reason for this will be illustrated with an example later in this lesson. The student must keep the fact firmly in mind that *an ammeter must never be used to measure voltage*.

No particular damage will result if a voltmeter is used to measure current; however, a correct indication of the current flowing through the circuit will not be obtained. It is very essential to always use a voltmeter for voltage measurements and an ammeter for current measurements.

It is possible to purchase meters with a wide variety of ranges. By the range of a meter, we mean the maximum current or voltage which it is capable of measuring. For example, if the range of a voltmeter is 0 - 50 volts, the design of the instrument is such that the maximum voltage which that instrument can measure is 50 volts. Likewise, if the range of a meter is 0 - 25 ma.,[2] then the maximum current which can be measured is 25 milliamperes. If we attempt to use that instrument for the measurement of a current higher than 25 ma., the meter will be damaged. It is very important to *always make certain that the current or voltage you desire to measure with a meter does not exceed the range of the instrument*. If you do not know approximately the voltage or current, always use the highest range available. If, by measurement, you find that a lower range will give a more accurate reading, then a lower range should be used. Overloading a voltmeter or an ammeter is just as apt to cause dam-

[1] "DC" are the letters used to abbreviate Direct Current. Quite often "DC" is used as a descriptive adjective. All batteries produce a DC voltage and a DC current.

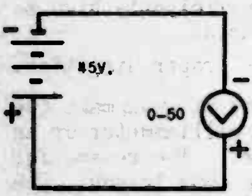
[2] "Ma." is often used as an abbreviation for milliamperes.

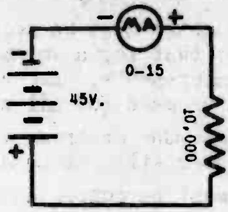
age as connecting it in the circuit improperly.

After making certain that the right type of meter is being used and that it will not be overloaded, we must next make certain that the meter is connected in the circuit in the proper direction. The negative side of the meter must always be connected toward the negative side of the source of voltage, and the positive side of the meter must always be connected toward the positive side of the source of voltage. This is true for both voltmeters and ammeters.

In Fig. 5, a voltmeter with a range of 0 - 50 volts is shown measuring the voltage of a 45 volt battery. It is safe to use a meter with a range of 0 - 50 volts because the maximum pressure of the battery is 45 volts. The negative side of the voltmeter is con-

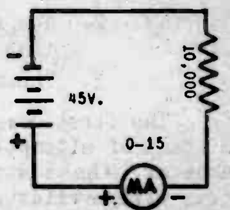
Fig.5 Showing a 0-50 voltmeter measuring the pressure of a 45-volt battery.





6 Showing a 0-10 milliammeter measuring the current through a resistor.

Fig.7 Same drawing as Fig.6, except the MA is in a different position.



nected to the negative terminal of the battery and the positive side of the voltmeter is connected to the positive terminal of the battery. If the battery is in good condition, the voltmeter will be reading 45 volts.

Fig. 6 shows the correct method of connecting a milliammeter in a circuit. The milliammeter cannot be placed directly across the 45 volt B battery without a resistor in series because it would be seriously overloaded. It will be found later in this lesson that by the use of Ohm's Law, we can calculate the amount of current flowing through this circuit. It will be 4.5 ma. Knowing that the current cannot exceed this value, it is safe to use a 0 - 10 milliammeter for the measurement. The negative side of the milliammeter must be connected to the negative terminal of the 45 volt battery and the positive side of the milliammeter must be connected toward the positive terminal of the 45 volt battery.

In Fig. 6, the positive side of the meter is not connected directly to the positive terminal of the battery; however, it is connected toward the positive pole. The meter must be connected in this manner because otherwise the current would flow through the meter in the wrong direction, causing the needle of the instrument to move in a counter-clockwise direction instead of clockwise. If this occurs, it is very likely that the needle-like pointer of the meter will be bent and that some of the fragile parts of the moving mechanism will be damaged.

The milliammeter could be moved from the position as shown in Fig. 6 to the position as shown in Fig. 7 and would still measure the current properly and would read the same value. In Fig. 7, the positive side of the meter is connected directly to the positive terminal of the battery and the negative side of the meter connected toward the negative terminal of the battery. This circuit is exactly the same as the circuit shown in Fig. 6 and the current measured will be exactly the same value.

It makes no difference in what part of the circuit the milliammeter is connected as long as the current flows through it in the proper direction.

4. SERIES AND PARALLEL CIRCUITS. When we speak of an electrical circuit, we mean a *closed path consisting of conductors through which an electrical current can flow under the pressure of an applied voltage.* All electrical circuits will consist of:

1. Apparatus for generating the electrical voltage.
2. Conductors for carrying the current.
3. A device for controlling the electrical energy.
4. A device for using or converting the electrical energy.

Some electrical circuits may be quite complicated; however, we shall start with the simplest type and build our knowledge from that.

In Fig. 8, we have a simple electrical circuit shown, consisting of a battery, an electrical bell, a switch and the connecting wires. In this electrical circuit, the battery is the source of pressure, the switch is the control device, the connecting wires conduct the current and the bell converts the electrical energy into mechanical energy.

A hydraulic circuit which can be compared to this is shown in Fig. 9. The water pump in this hydraulic circuit is the source of water pressure, the valve is the control device, the connecting pipes conduct the water and the revolution of the water wheel represents the conversion of hydraulic energy into mechanical energy.

The pressure produced by the water pump in Fig. 9 will cause a flow of water through the hydraulic circuit when the valve is opened, and in Fig. 8, the pressure of the battery will cause a flow of current through the electrical circuit when the switch is closed. It should be noted that there is a distinct similarity between the hydraulic and the electric circuit. The switch in the electrical circuit may be opened or closed to start or stop the flow of current the same as the valve in the hydraulic circuit may be opened or closed to govern the flow of water.

Electric circuits are constructed in several ways, all of which may be classified as: (1) a series circuit, (2) a parallel circuit, or (3) a series-parallel circuit.

A series circuit is properly defined as *a circuit through which all of the current leaving the negative pole of the battery must pass in order to return to the positive pole of the battery.* In a series circuit, there is only one path which the current can possibly take when passing from negative to positive. The diagram as shown in Fig. 8 would represent a true series circuit because all of the current that leaves the battery must pass through the switch (when it is closed) and the bell in order to return to the positive

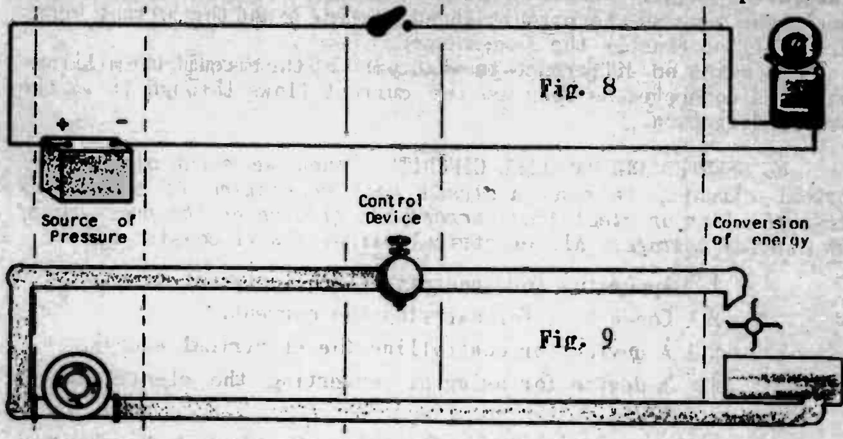


Fig.8 In this electrical circuit, the battery is producing the voltage, the wires are carrying the current, the switch is to control the electrical energy, and the bell is the device for converting the electrical energy into mechanical energy.

Fig.9 This hydraulic circuit corresponds to the electrical circuit in that the pump is producing the water pressure, the pipes are carrying the water, the valve is controlling the water flow, and the water wheel is set in motion as the water energy is converted into mechanical energy.

pole of the battery. Another illustration of a true series circuit is shown in Fig. 10. In this diagram, all of the current which leaves the negative pole of the generator must pass through each of the incandescent lamps in order to return to the positive terminal of the generator. An expression commonly used is that the "incandescent lamps are connected in series with each other." This means

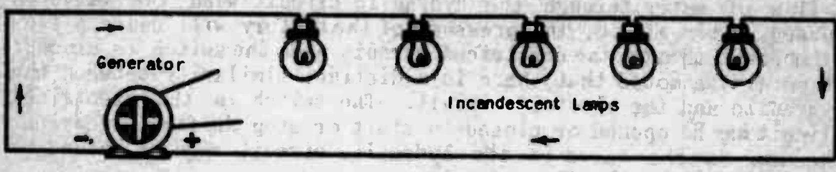


Fig.10 The incandescent lamps are connected in series across the generator. This is a true series circuit.

that they are connected so that the current which passes through one must also pass through the others in the circuit. If you were told to connect another lamp in series, it would be necessary to break the circuit at some point, then insert the lamp, connecting it in a manner similar to the others shown in Fig. 10.

In a parallel circuit, *the current may have two or more paths which it may take when flowing from the negative terminal of the* *voltage source back to the positive terminal of the voltage source.* Any number of paths may be provided for the current in a parallel circuit. In any parallel circuit, all of the current that leaves the negative pole of a battery does not have to pass through each individual part of the circuit to return to the positive pole of

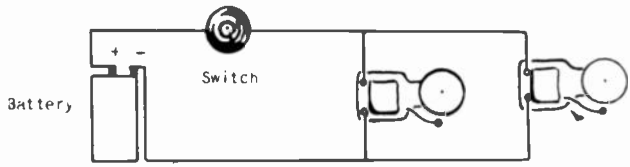


Fig. 11 The two electric bells are connected in parallel across the battery.

the battery. Two bells connected in parallel are shown in Fig. 11. Only two branches are provided in this parallel circuit; however, any number of bells could be connected in parallel. All of them would ring when the push button switch was closed.

Another example of a parallel circuit using incandescent lamps is shown in Fig. 12. Parallel circuits are used for all house wir-

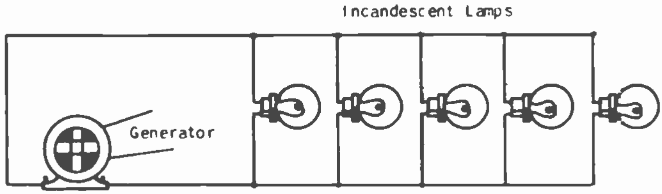


Fig. 12 The five incandescent lamps are connected in parallel across the generator. This is a true parallel circuit.

ing, which means that each of the 110 volt lamps and other electrical devices are connected in parallel across the supply line coming into your home. (Other voltages than 110 are sometimes used.)

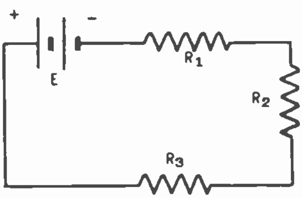


Fig. 13 The three resistors, R_1, R_2, and R_3, are connected across the battery E to form a true series circuit.

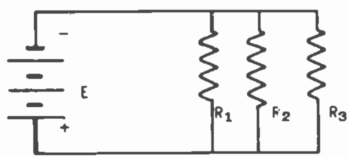
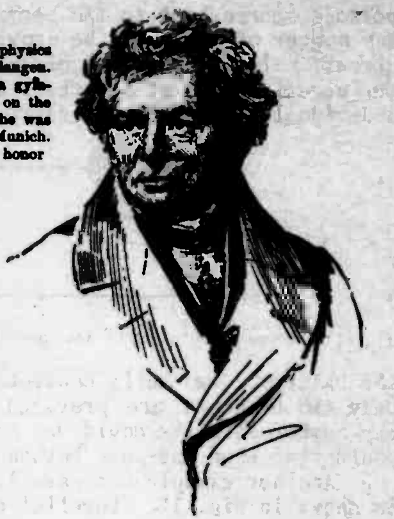


Fig. 14 The three resistors, R_1, R_2, and R_3, are connected across the battery E to form a true parallel circuit.

Now let us use the electrical symbols previously learned to illustrate series and parallel circuits. In Fig. 13, resistances

GEORG SIMON OHM (1787-1854)

German physicist and discoverer of the famous law in physics which bears his name. He was born and educated at Erlangen. It was in 1826, while he was teaching mathematics at a gymnasium in Cologne, that he published his famous paper on the experimental proof of his law. At the time of his death he was professor of experimental physics in the university at Munich. The ohm, the practical unit of resistance, is named in his honor



R_1, R_2 and R_3 are connected in series across the voltage E. All of the current which leaves the negative pole of the battery E must pass through R_1, R_2 and R_3 in order to return to the positive pole of the battery; hence, this is a true series circuit. In Fig. 14, the resistors R_1, R_2 and R_3 are connected in parallel across the supply voltage E, thus forming a true parallel circuit. The current which leaves the negative pole of the battery E will divide, a portion of it passing through R_1, a portion passing through R_2 and a portion passing through R_3. Then these three portions will unite and the total current will return back to the positive terminal of the battery.

5. **OHM'S LAW.** There is a very definite and important law governing the relationship between the voltage, current and resistance in an electrical circuit known as Ohm's Law. This law is extremely simple, but the simplicity of it does not in any way detract from its importance. Ohm's Law is the basic foundation of all electrical circuits and it is essential that every student of Electricity, Radio or Television become very familiar with it. It is essential that the student study the three equations of Ohm's Law as shown in Fig. 15 until it is thoroughly learned in each of its three forms.

It is easy to make mistakes when applying Ohm's Law unless certain precautions are observed. First, in all calculations, it is necessary that the voltage be substituted in the formula in volts, the current in amperes and the resistance in ohms. If the current is given in milliamperes (as is very often the case), it must be changed to amperes before using any one of the three Ohm's Law equations. Sometimes the resistance may be expressed in megohms, or the voltage in millivolts; in each case, the megohms or millivolts must be changed to ohms and volts.

Ohm's Law may be applied to an entire electrical circuit, or it may be applied to any portion or part of an electrical circuit. If it is applied to an entire circuit, then the current (in amperes) flowing through the entire circuit will equal the electrical pressure (in volts) applied to the circuit, divided by the resistance (in ohms) of the entire circuit ($I = E \div R$). If Ohm's Law is

Ohm's Law

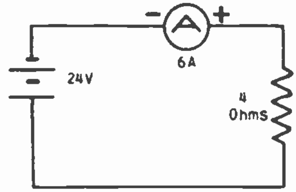
CURRENT =	$\frac{\text{ELECTROMOTIVE FORCE}}{\text{RESISTANCE}}$
$I = \frac{E}{R}$	AMPERES = $\frac{\text{VOLTS}}{\text{OHMS}}$
RESISTANCE =	$\frac{\text{ELECTROMOTIVE FORCE}}{\text{CURRENT}}$
$R = \frac{E}{I}$	OHMS = $\frac{\text{VOLTS}}{\text{AMPERES}}$
ELECTROMOTIVE FORCE =	CURRENT × RESISTANCE
$E = I \times R$	VOLTS = AMPERES × OHMS

Fig. 15

applied to a portion or part of a circuit, then the current through that part of the circuit will equal the voltage across that same part of the circuit divided by the resistance of that same part ($I = E \div R$). These statements should be learned very carefully because we have found that nearly all of the errors in applying Ohm's Law result from considering the voltage across one part of a circuit and the resistance or current of a different part, or vice versa.

As the first example, we shall apply Ohm's Law to the circuit shown in Fig. 16. In this circuit the electrical pressure is 24 volts, the resistance of the circuit is 4 ohms and the current flowing through the circuit is 6 amperes. These facts are proved by using the three equations of Ohm's Law shown directly below the figure. In this example, all three of the values were known for the circuit and Ohm's Law was used merely to prove the relationship existing between them.

Fig. 16 Circuit illustrating the use of Ohm's Law.



E = I × R = 6 Amps × 4 Ω = 24 V.
I = E ÷ R = 24 V. ÷ 4 Ω = 6 Amps
R = E ÷ I = 24 V. ÷ 6 Amps = 4 Ω

In Fig. 17, only two of the values are known. By using the proper equation of Ohm's Law, the unknown value may be found. The voltage is given as 100 volts and the resistance of the circuit is 10,000 ohms. The "unknown" in the circuit is the amount of current flowing. By inspection, it can be seen that the proper equation to use is I = E ÷ R. Since the voltage is 100 volts and the resistance is 10,000 ohms, then:

$$I = 100 \div 10{,}000 = .01 \text{ ampere}$$

When the current is less than 1 ampere, it is generally expressed in milliamperes. To change .01 ampere into milliamperes, we must multiply by 1,000. It will then equal 10 milliamperes. Therefore, the milliammeter in Fig. 17 should be reading 10 milliamperes.

Next, assume that the resistance of the circuit and the current flowing through the circuit are known, then proceed to calculate the electrical pressure in volts applied to the circuit. In Fig. 18,

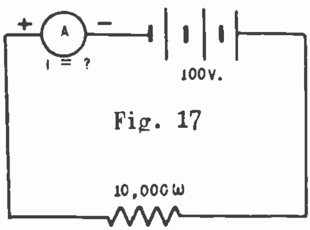


Fig. 17

Circuits illustrating the application of Ohm's Law to electrical circuits in which one value is unknown.

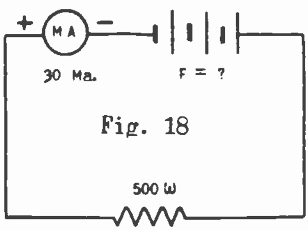


Fig. 18

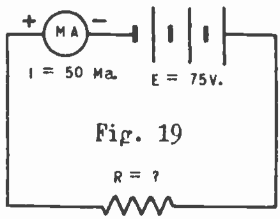


Fig. 19

the current is given as 30 ma. Before using this value of current in Ohm's Law, it will be necessary to convert it into amperes. To convert milliamperes to amperes, we must divide by 1,000. 30 ma. divided by 1,000 equals .03 ampere. Next, select the proper form of Ohm's Law to use for this calculation. By inspection, we find that the correct form is E = I × R. Substituting the known values in this equation, we have:

$$E = 500 \times .03 = 15 \text{ volts}$$

In the next example, we will consider that the resistance of the circuit is unknown and that the voltage and current are given. In Fig. 19, the voltage applied is 75 volts and the current flowing through the circuit is 50 milliamperes. Again we must change the 50 milliamperes into amperes by dividing 50 by 1,000. This gives .05 ampere. Next, selecting the proper form of Ohm's Law, which is R = E ÷ I, and substituting in this equation, we have 75 ÷ .05, or 1,500 ohms.

With these three examples, we have used Ohm's Law in its three forms for finding an unknown value in an electrical circuit.

As a more practical example of Ohm's Law, let us calculate the resistance in Fig. 20. By measurement with a voltmeter, we find

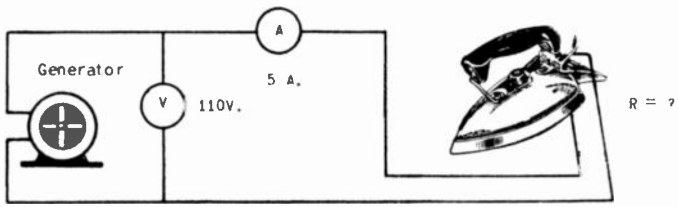


Fig. 20 The voltage applied to the iron and the current flowing through the iron can be measured with meters, then the resistance of the iron element calculated.

the voltage output of the generator to be 110 volts, and by placing the ammeter in series with the line, we find the current flowing through the electric iron to be 5 amperes. What is the resistance of the heating element in the iron? The proper form of Ohm's Law to use is R = E ÷ I. Substituting in this equation, we have:

$$R = 110 \div 5 = 22 \text{ ohms}$$

6. **RESISTORS IN SERIES.** *If two or more resistors are placed in series with each other (as shown in Fig. 21), the resistance of each will add to the resistance of the others and the total resistance of the combination will be equal to the sum of the individual resistances.* In Fig. 21, resistor A is 300 ohms, resistor B is 200 ohms and resistor C is 500 ohms. The total resistance from the left side of resistor A to the right side of resistor C will be 300 + 200 + 500 = 1,000 ohms. This rule is expressed as a formula in the following manner:

$$R_t = R_1 + R_2 + R_3 \ldots \text{etc.} \qquad (1)$$

Where: R_t is the total resistance.
R_1, R_2, R_3...etc., are the individual resistors.

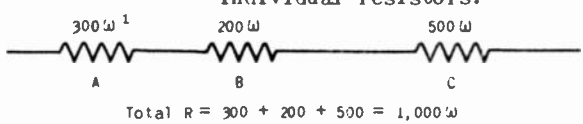


Fig. 21 The three resistors A, B, and C are connected in series; hence, their resistances add. The total resistance is 1,000 ohms.

[1] The Greek letter "ω" will be used throughout the entire course to symbolize "ohms". The capital of this sign "Ω" may be used in other writings to represent ohms.

Regardless of how many resistors are connected in series, the total resistance will always be equal to the sum of all the individual resistors.

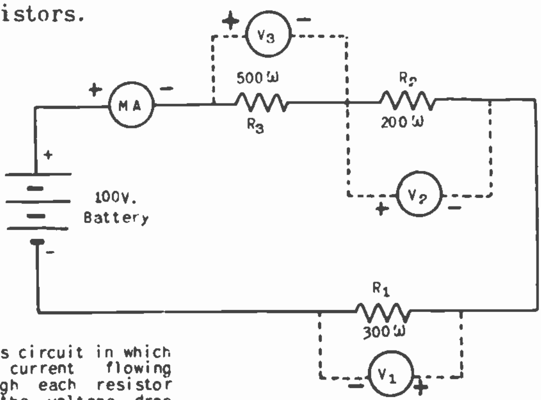


Fig. 22 Series circuit in which the current flowing through each resistor and the voltage drop across each resistor are unknown.

Now let us apply what · have learned about Ohm's Law and series resistors to the circuit shown in Fig. 22. By inspecting Fig. 22, it can be seen that all of the current which leaves the negative pole of the 100 volt battery must pass through resistors R_1, R_2, and R_3 and the milliammeter in order to return to the positive pole of the battery. Hence, this is a true series circuit and the resistors R_1, R_2 and R_3 are in series with each other. Since these three resistors are in series, the total resistance of the circuit will be 1,000 ohms (300ω + 200ω + 500ω = 1,000ω). The voltage across the entire circuit is 100 volts, so to find the current flowing through the circuit, Ohm's Law is applied:

Substituting: $I = E \div R$

$I = 100 \div 1{,}000 = .1$ ampere

If it is desired to express the current in milliamperes instead of amperes, multiply the .1 ampere by 1,000 and it will be 100 ma. It should be clear that the total current of 100 milliamperes must pass through all three resistors, R_1, R_2 and R_3 in completing the circuit.

At the beginning of the discussion on Ohm's Law, it was stated that Ohm's Law could be applied to any part or portion of a circuit the same as it could be applied to an entire circuit. As an example, suppose we apply Ohm's Law to resistor R_1 alone. We know that the value of resistor R_1 is 300 ohms and that the current flowing through the resistor is 100 ma. (.1 ampere). The unknown value is the voltage across resistor R_1, since we have both the resistance and current given. Using the form of Ohm's Law, $E = I \times R$, we find:

$$E = 300 \times .1 = 30 \text{ volts}$$

This 30 volts calculated across resistor R_1 is commonly known as a "voltage drop". The expression "voltage drop" will be used frequently throughout the remainder of this lesson and in lessons

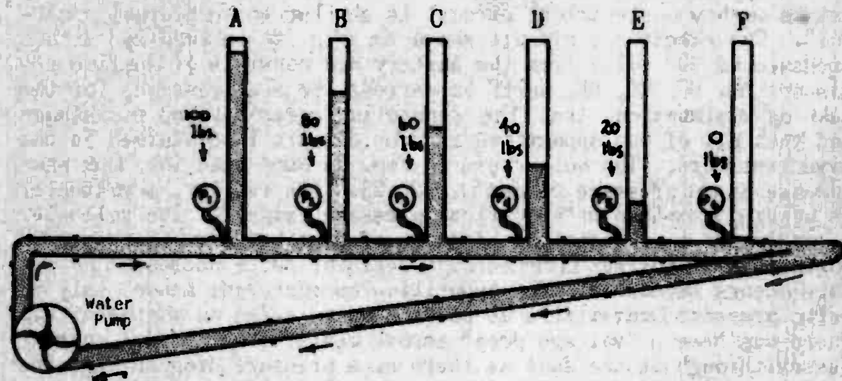


Fig. 23 A hydraulic circuit illustrating the definition of a "pressure drop". The gauges indicate a pressure drop as the water passes through the main line pipe.

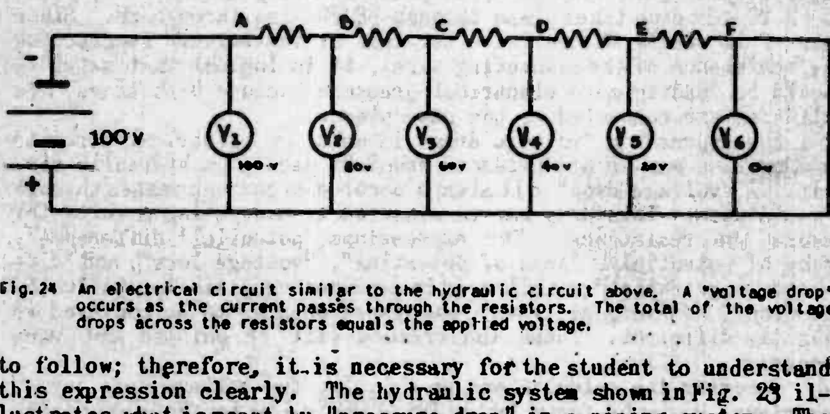


Fig. 24 An electrical circuit similar to the hydraulic circuit above. A "voltage drop" occurs as the current passes through the resistors. The total of the voltage drops across the resistors equals the applied voltage.

to follow; therefore, it is necessary for the student to understand this expression clearly. The hydraulic system shown in Fig. 23 illustrates what is meant by "pressure drop" in a piping system. The total pressure produced by the pump is 100 lbs. as read on pressure gauge P_1. (For explanation, neglect the pressure drop from the pump to gauge P_1.) As the water flows from the position of gauge P_1 to the position of gauge P_2, there is a pressure decrease of 20 lbs., due to the opposition offered by the main line pipe. The level of the water in standpipe B illustrates this drop in pressure. As the water continues to pass through the main line to gauge P_3, an additional pressure drop of 20 lbs. occurs; hence, gauge P_3 reads 60 lbs. and the level of the water in standpipe C is lower than the level in either A or B. A 20 lb. drop occurs from P_3 to P_4 and from

P_4 to P_5. The remaining 20 lb. drop occurs from P_5 to P_6. This results in no pressure being available to raise water in the standpipe F. From gauge P_6, the water passes into the drain pipe and back to the pump by gravity. This illustration should be studied until the expression "pressure drop" is clearly understood.

Keeping in mind that voltage is defined as "electrical pressure", let us see how an electrical circuit is similar to the hydraulic circuit. The electrical circuit shown in Fig. 24 is supplied with a pressure of 100 volts from the battery and consists of the five resistors AB, BC, CD, DE, and EF in series. We shall assume, for the sake of explanation, that the connecting wires have no resistance and that all of the opposition in the circuit is contained in the five resistors. The voltmeters in Fig. 24 are used for the same purpose as the pressure gauges in Fig. 23. (In reality, a voltmeter is nothing more than an "electrical pressure gauge.") The voltmeter V_1 indicates the electrical pressure of the battery; that is, 100 volts. As the current flows through resistor AB, a decrease in pressure occurs because of the opposition encountered; hence, only 80 volts pressure is available at point B as indicated on voltmeter V_2. There has been a "voltage drop" across resistor AB as the current passes through it the same as there was a pressure drop through the main line pipe in Fig. 23 between gauges P_1 and P_2. As the current passes through resistor BC in Fig. 24, another "voltage drop" occurs, resulting in only 60 volts pressure being available at point C. A 20 volt drop takes place through DE and also through EF. Since point F is really the positive terminal of the battery (neglecting the resistance of the connecting wire), it is logical that meter V_6 should be reading zero electrical pressure because both sides of the voltmeter are connected to the same place.

The expression "voltage drop" is used in electrical circuits in the same manner as "pressure drop" is used in a hydraulic circuit. A "voltage drop" will always occur when current passes through a resistance. This drop may be measured by connecting a voltmeter across the resistance. The expressions "potential[1] difference", "drop of potential", "loss of potential", "voltage loss", and "difference in potential" are all used in a manner very similar to "voltage drop"; however, at times, the exact meaning to be conveyed is slightly different. These differences will be pointed out when necessary.

Resuming the calculations on Fig. 22, the voltage drop across resistance R_2 can be found by applying Ohm's Law to that part of the circuit. It is known that the current through resistance R_2 is .1 ampere and that the size of resistance R_2 is 200 ohms. Applying Ohm's Law in the form $E = I \times R$, we have .1 ampere × 200 ohms, equals 20 volts. The voltage drop across resistance R_2, then, is 20 volts, and the voltmeter V_2, if connected as shown, should be reading 20 volts.

The last resistor through which the current must flow is resistance R_3. To calculate the voltage drop across resistor R_3, E = .1 ampere × 500 ohms = 50 volts. The voltmeter V_3 should be read-

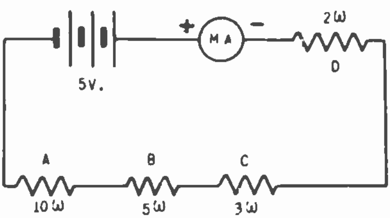
[1] The word "potential" is used frequently throughout electrical language instead of the word "voltage". The definition for "potential" is the same as the definition for "voltage"; hence, both words mean the same.

ing 50 volts. Now, adding the voltage drops across the three resistors, we have 30 volts across R_1, plus 20 volts across R_2, plus 50 volts across R_3 equals 100 volts, the total voltage drop across the three resistors. It should be noted that the entire pressure across the battery has been used to force the .1 ampere through the resistors R_1, R_2 and R_3. It is true that a very small fraction of the 100 volts total pressure is required to force the current through the connecting wires and the milliammeter, but since the resistance of these parts of the circuit is so extremely low, it is neglected in most practical problems.

In this example, we have proved a very important law of electrical circuits, which states: *The total voltage drop across a circuit external to a source of voltage is always equal to the voltage of the supply source.* When we speak of an "external circuit", we mean all of the electrical parts, connecting wires, meters, etc., which are connected between the positive and negative terminals of a source of voltage. The student should bear in mind that the expression "voltage drop" means the decrease or loss of electrical pressure which results when current passes through a resistance. The voltage drop across a resistance can always be measured by connecting a voltmeter in parallel with it.

Before leaving the simple series circuit, we shall work another example. The circuit to be used is shown in Fig. 25. In this cir-

Fig. 25 A true series circuit in which the current flowing through each resistor and the voltage drop across each resistor are unknown.



cuit, the resistors A, B, C, and D are all connected in series, so the total resistance of the external circuit (neglecting the resistance of the connecting wires and meter) is found by adding the separate resistances together. We find this to be:

$$R_t = 10 + 5 + 3 + 2 = 20 \text{ ohms}$$

Then, using the form of Ohm's Law, $I = E \div R$, and substituting:

$$I = 5 \div 20 = .25 \text{ ampere}$$

We find the current flowing through the series circuit to be .25 ampere or 250 milliamperes. This 250 ma. of current will leave the battery at the negative pole, pass through all four resistors, A, B, C, and D (and the milliammeter), then return to the positive pole of the battery. In order to calculate the voltage drop across resistors A, B, C, and D, it is necessary to take the current of 250 milliamperes through each resistance separately, such as:

Voltage drop across	A	= .25 ampere	×	10ω	=	2.5 volts
" " "	B	= .25 "	×	5ω	=	1.25 "
" " "	C	= .25 "	×	3ω	=	.75 "
" " "	D	= .25 "	×	2ω	=	.5 "
" " "	entire circuit	= .25 "	×	20ω	=	5.00 "

The total of voltage drops across resistors A, B, C, and D should equal the applied voltage of 5 volts. Adding the voltages, we find that the total is 5 volts, so our calculations are correct.

7. **RESISTORS IN PARALLEL.** The application of Ohm's Law to parallel circuits may seem a little difficult; however, if the sub-

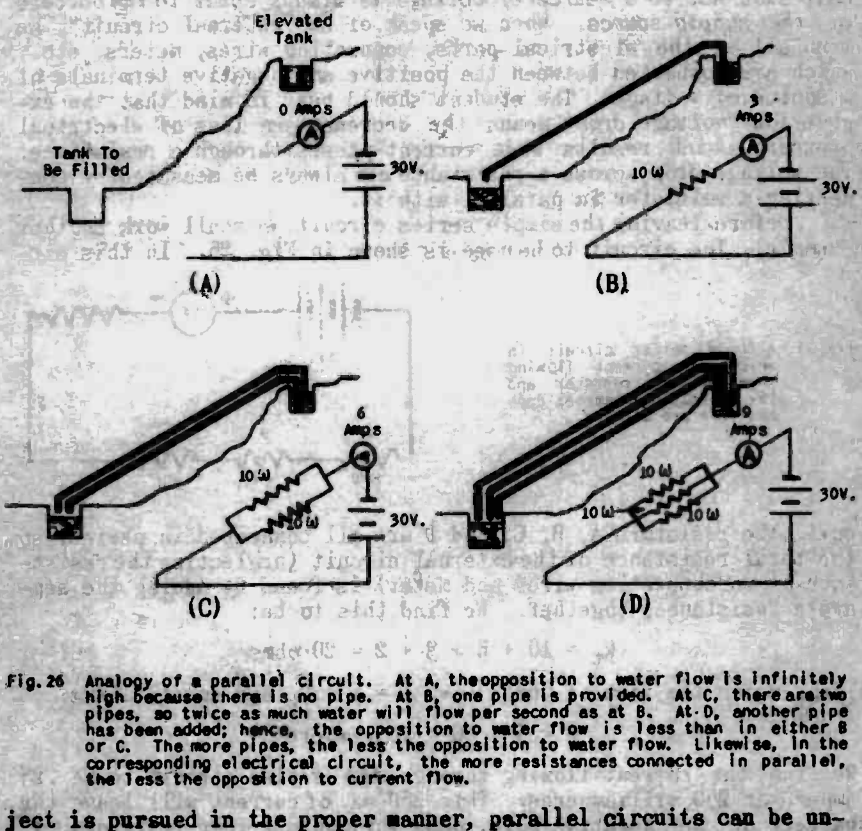


Fig. 26 Analogy of a parallel circuit. At A, the opposition to water flow is infinitely high because there is no pipe. At B, one pipe is provided. At C, there are two pipes, so twice as much water will flow per second as at B. At D, another pipe has been added; hence, the opposition to water flow is less than in either B or C. The more pipes, the less the opposition to water flow. Likewise, in the corresponding electrical circuit, the more resistances connected in parallel, the less the opposition to current flow.

ject is pursued in the proper manner, parallel circuits can be understood just as easily as series circuits. The important requisite is to obtain a good fundamental understanding of parallel circuits, then the problems dealing with these circuits become simple. An analogy between water and an electrical circuit has been found to be helpful in securing a basic understanding. We will begin at A, Fig. 26, with this analogy. Suppose a tank of water has been placed in an elevated position, such as at the top of a hill, above another tank, located at the bottom of the hill. As long as there is no connecting pipe between the tank at the top of the hill and the tank at the bottom of the hill, then naturally, no water can flow from the upper tank to the lower and the lower tank will not be filled. As a reason for the water not flowing from the upper tank to the lower tank, we might say that the opposition or resistance to the flow of water is infinitely high because there is no conducting pipe. Likewise, in the electrical circuit shown at A, Fig. 26, there will be no current flow from the negative to the positive terminal of the battery, because the circuit is incomplete; that is, no conducting path is provided. We can also make the statement that the opposition or resistance to the flow of current from the negative to the positive terminal of the battery is infinitely high, the same as the opposition to the passage of water from the upper tank to the lower tank is infinitely high.

At B, Fig. 26, one connecting pipe is shown from the upper to the lower tank of water. Let us assume that the water pressure in the upper tank and the size of the connecting pipe is such that 10 gallons of water will flow into the tank at the bottom of the hill each second. The rate of water flow then would be 10 gallons per second. The electrical circuit shown at B, Fig. 26, has been completed with a 10 ohm resistance, thus allowing current to flow from the negative terminal of the battery through the resistance to the positive terminal. By using Ohm's Law, we find that the current which flows through a 10 ohm resistance under a pressure of 30 volts is 3 amperes.

At C, Fig. 26, we have added an additional pipe connecting the upper tank to the lower one and assuming that the water pressure in the upper tank remains the same and the size of the second pipe is the same as the first, there will be 10 gallons per second passing through the second pipe also. Since we have 10 gallons per second through the first pipe and 10 gallons per second through the second pipe, the total rate of water flow from the upper tank to the lower tank will be 20 gallons per second. Notice that adding the second pipe has doubled the rate of water flow; hence, the opposition to the water flow has been cut in half. Now the electrical circuit shown at C is very similar to the water circuit. An additional 10 ohm resistance has been added between the negative and positive terminals of the battery. The same voltage is applied across the second 10 ohm resistance as across the first 10 ohm resistance; that is, 30 volts. With 30 volts applied across each of the two 10 ohm resistors, there will be a current flow of 3 amperes through each, or a total current flow from the negative terminal of the battery to the positive terminal of the battery of 6 amperes. Since more current is flowing through the circuit with the same applied voltage, it is quite evident (can be proved by Ohm's Law) that the resistance to the flow of current from one terminal of the battery to the other has been decreased.

Looking at this from another angle, we might say that the conductance of the electrical circuit at B is $\frac{1}{10}$ of a mho (resistance is 10 ohms) and the conductance of the electrical circuit shown at C is $\frac{2}{10}$ of a mho. The conductance of the circuit shown at C is found by adding the conductances of the two 10 ohm resistances; that is, $\frac{1}{10}$ mho + $\frac{1}{10}$ mho = $\frac{2}{10}$ mho. Since $\frac{2}{10}$ of a mho is larger than $\frac{1}{10}$ of a mho, it follows that the conductance of the circuit as shown at C is greater, which means that its resistance has decreased.

To carry this analogy one step farther, at D, Fig. 26, a third similar pipe has been added between the upper and lower tanks. Assuming the water pressure and pipe size to be the same, the third pipe will also carry 10 gallons of water per second, making a total of 30 gallons per second from the upper to the lower tank. The addition of the third pipe has increased the conductance to the flow of water from the upper tank to the lower one, or stated in other words, the addition of the third pipe has decreased the opposition to water flow from the top tank to the bottom one. The electrical circuit shown at D has been altered the same as the water circuit; that is, an additional 10 ohm resistance has been added. Since there are 30 volts applied across each of the three 10 ohm resistors, according to Ohm's Law, 3 amperes of current will be passing through each resistance; hence, the total current flow from the negative to the positive terminal of the battery is now 9 amperes. The reason for this increased current flow is that the resistance to the passage of current from one terminal of the battery to the other has been decreased because of the additional conducting path (10 ohm resistor). An increase in conductance or a decrease in resistance will always result in more current flowing through a circuit if the applied voltage remains the same.

After studying the foregoing examples very carefully, it should be quite evident that the more conducting paths provided between the two poles of a battery, the more current will flow from the battery. (As conductance increases, resistance decreases.) Remember that in a parallel circuit, the total current is not required to pass through each part of the circuit, but rather will divide, a portion of the total current passing through each of the branches provided.

The difficulty usually encountered when working with parallel circuits is understanding why the effective or equivalent resistance of the circuit decreases as additional resistance is added to the external circuit. This need not be confusing because the addition of a resistor in parallel is really providing another conducting path for the current, thereby increasing the total conductance and decreasing the total resistance[1] of the circuit. The addition of a resistor to a parallel circuit has exactly the opposite effect as does the addition of a resistor to a series circuit. When placed in series, the total resistance of the circuit will be increased, whereas when placed in parallel, the total resistance of the circuit will be decreased.

[1] The total resistance of a parallel circuit is often called the "effective resistance". This expression means "the actual resistance in ohms resulting from the effect of the parallel conducting paths". The expression "equivalent resistance" is also used for the same purpose.

Now refer to Fig. 27. Here resistors A and B are connected in parallel across the battery, which has a pressure of 100 volts. First, apply Ohm's Law to the individual parts of the circuit. There is a pressure of 100 volts applied across both resistors A and B. With 100 volts across resistance A, and since resistance A is 200 ohms, we find by Ohm's Law:

$$I = E \div R$$
$$I = 100 \div 200 = .5 \text{ ampere}$$

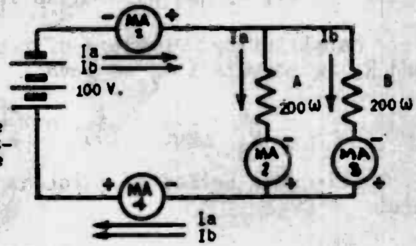


Fig. 27 Parallel electrical circuit. The current flowing through each resistance and the total resistance of the circuit are unknown.

Since we also have 100 volts applied across resistance B, and since resistance B is also 200 ohms, then we find there will be .5 ampere passing through resistance B. From these calculations, we know that MA_2 will be reading 500 milliamperes and that MA_3 will be reading 500 ma. The current passing through these two resistors must come from the negative terminal of the 100 volt battery. Since the total current will be passing through MA_1, there will be 500 + 500 or 1,000 ma. passing through MA_1. (1,000 ma. equals 1 ampere.) Likewise, after the current has passed through resistance A, it will unite with the current through resistance B; then the total current (1 ampere) will return to the positive terminal of the battery through MA_4. Consequently, MA_4 will be reading the total current of 1 ampere. If we have a total of 1 ampere flowing from the negative terminal and returning to the positive terminal, and if the pressure of the battery is 100 volts, then applying Ohm's Law to the entire circuit, we can find the equivalent or effective resistance of the entire circuit. This is found by:

$$R = E \div I$$
$$R = 100 \div 1 = 100 \text{ ohms}$$

Thus, when two 200 ohm resistors are connected in parallel, the equivalent or effective resistance of the combination is equal to 100 ohms.

We can also calculate this equivalent resistance for the parallel circuit in a different manner. Quite often the applied voltage will not be given, in which case it will not be possible to find the effective resistance of the circuit as was done in Fig. 27.

We know that the total conductance in a parallel circuit is equal to the sum of the separate conductances in each path. In other words:

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \text{...etc.} \qquad (2)$$

Where: $\frac{1}{R_t}$ is the total conductance in the circuit.

Or:

R_t is the total or effective resistance of the circuit.

And:

R_1, R_2 and R_3 are the individual resistances.

Substituting the values of resistors A and B in Fig. 27 for R_1 and R_2 in formula (2), we have:

$$\frac{1}{R_t} = \frac{1}{200} - \frac{1}{200}, \text{ or } \frac{1}{R_t} = \frac{2}{200}, \text{ or } R_t = 100\omega$$

This same method of solution is made easier by use of the formula:

$$R_t = \cfrac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\text{...etc.}} \qquad (3)$$

This equation is generally known as the "inverse formula". The reason for the word "inverse" is because of a certain operation which is performed in solving a problem of this kind. Understand, that this "inverse formula" is exactly the same as formula (2) except that it is given in a slightly different form to simplify the solution of such problems.

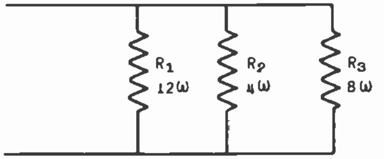


Fig. 28 Find the effective resistance of the combination by the use of formula (3).

Let us work a problem such as that shown in Fig. 28 using formula (3). Resistor R_1 is given as 12 ohms; R_2, 4 ohms; and R_3, 8 ohms. Substituting these values for R_1, R_2 and R_3 in formula (3), we have:

$$R_{eff} = \cfrac{1}{\frac{1}{12} + \frac{1}{4} + \frac{1}{8}} = \cfrac{1}{\frac{2 + 6 + 3}{24}} = \cfrac{1}{\frac{11}{24}}$$

Where: R_{eff} is the effective resistance of the parallel resistors.

We now have a problem in the simple division of fractions wherein we must invert the denominator, then multiply. (The inversion of the denominator at this time is the reason for calling this the inverse formula.) Continuing the solution, we have:

$$R_{eff} = 1 \times \frac{24}{11} = \frac{24}{11} = \text{approximately } 2.18 \text{ ohms}$$

Notice particularly that *the effective resistance of the parallel combination is less than the value of the smallest resistor in the parallel group.* It will be found that this is **always** true; regardless of the size or number of resistors connected in parallel, the effective resistance of the combination will always be less than the value of the smallest.

Another method of finding the effective resistance of a parallel combination when each branch has the **same resistance** can be stated as follows: *If all branches of a parallel circuit are equal, the effective resistance of the combination will be the value of one resistor divided by the number of resistors in the group.*

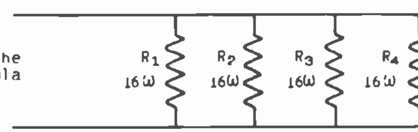
Expressed in a formula, this rule is:

$$R_{eff} = \frac{R_1}{R_n} \qquad (4)$$

Where: R_{eff} is the effective resistance of the group.
R_1 is the value of one resistor in the group.
R_n is the number of resistors in the group.

Applying this rule to the resistors shown in Fig. 29, divide 16 (the value of one resistor) by 4 (the number of resistors in the

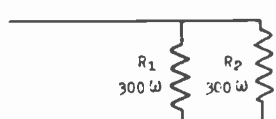
Fig. 29 Find the effective resistance of the combination by the use of formula (4) and formula (3).



group), thus obtaining an effective resistance of 4 ohms for the parallel combination. This same problem can also be calculated by use of the inverse formula (3). The student should work this problem using formula (3) to prove that this statement is true. This method is a short cut and can always be used when the parallel group consists of equal resistors, thus saving considerable time and calculation.

Using the formula (4) to calculate the effective resistance of

Fig. 30 Use formula (4) to find the effective resistance.



the circuit shown in Fig. 30, divide the value of one resistance (300 ohms) by the number of resistors in the group (2), thus obtaining an effective resistance for the combination of 150 ohms.

A third method for calculating the effective resistance of a parallel combination which can be applied to circuits where only two resistors are connected in parallel is given by the formula:

$$R_{eff} = \frac{R_1 \times R_2}{R_1 + R_2} \quad (5)$$

This formula is used only when two resistors are in parallel; it cannot be used for more than two resistors in parallel.

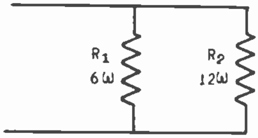


Fig. 31 Find the effective resistance by the use of formula (5).

Using formula (5), let us work out the effective resistance of the parallel combination shown in Fig. 31. R_1 is 6 ohms and R_2 is 12 ohms. Substituting these values for R_1 and R_2 in the formula (5), we have:

$$R_{eff} = \frac{6 \times 12}{6 + 12} = \frac{72}{18} = 4 \text{ ohms}$$

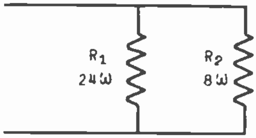


Fig. 32 Use formula (5) to find the effective resistance.

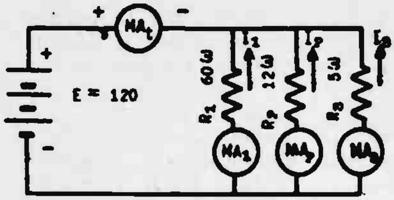
Solving the parallel resistors shown in Fig. 32:

$$R_{eff} = \frac{24 \times 8}{24 + 8} = \frac{192}{32} = 6 \text{ ohms}$$

This method for solving parallel combinations of resistors should always be used when two unequal resistors are in parallel. Notice that the effective resistance of each combination that has been solved is less than the value of the smallest resistor in the parallel group. This is always true. Formulas (4) and (5), used in solving these problems, can be verified by working the same problems with the general inverse formula (3). Of course, the answer secured should be the same regardless of the formula used.

The student should study all of the methods just given for the calculation of the effective resistance of parallel circuits when the voltage is unknown. Make sure that you understand the procedure and mathematics involved very thoroughly. Each of these three methods have applications to be found in some of the following examples:

In Fig. 33, a parallel circuit is shown consisting of three branches; R_1 is 60 ohms, R_2 is 12 ohms, and R_3 is 5 ohms. First, calculating the effective resistance of the combination by using the



Branch	E Volts	I Amperes
R_1	120	2
R_2	120	10
R_3	120	24
	I_t =	36

Fig.33 True parallel circuit. Find the effective resistance and the current through each resistor.

inverse formula (3), we find the resistance of the combination to be 3.33 ohms. Next, find the current which passes through each branch of the parallel circuit. Since we know there will be a voltage of 120 volts across each of the three resistors, to calculate the current through each branch, it is only necessary to divide the voltage (120 volts) by the resistance of each branch. Doing this, we find the current through R_1 equals 2 amperes, the current through R_2 equals 10 amperes and the current through R_3 equals 24 amperes. Now, adding these three currents together, we obtain a total current of 36 amperes, which will be drawn from and returned to the battery.

If we wish to verify our former calculation of the effective resistance of the circuit, we can now divide the voltage applied to the entire circuit by the current flowing through the entire circuit, or:

$$R_{eff} = 120 \div 36 = 3.33 \text{ ohms.}$$

If the method of solution for a parallel circuit is not entirely clear, you should make up a number of problems similar to that in Fig. 33 and attempt to find all of the unknown values, following the same procedure. You may check your own work by calculating the effective resistance of the combination using the inverse formula and by calculating the effective resistance, using Ohm's Law for the entire circuit. The two resistance values secured should be the same. If they are, your method of solution is correct and you have obtained the proper answers.

8. **SUMMARY OF SERIES AND PARALLEL CIRCUITS.** In a series circuit, the current flowing through the circuit remains the same in every part of the circuit and the total voltage applied to the circuit divides—or drops—across the various parts of the circuit, according to the value of each.

The total resistance of resistors connected in series is equal to the sum of the individual resistors.

In a parallel circuit, the voltage applied across every branch of the circuit is the same, and the current divides through the branches of the circuit according to the value of each.

The effective or equivalent resistance of a parallel combination can be found by:

1. Use of the inverse formula when three or more resistors of unequal sizes are in the combination.
2. If all resistors in the parallel group are the same value, divide the value of one resistor by the number of resistors in the group.

3. Where two resistors of different values are in parallel, the effective resistance may be found by dividing the product of the two resistors by the sum of the two resistors.

The sum of the voltage drops across the external circuit must always equal the applied voltage. This rule is particularly important in series circuits because the calculations in a series circuit can be checked by adding the voltages dropped across each resistance. They should equal the applied voltage.

In a parallel circuit, the sum of the currents through the individual branches must equal the total current.

9. CONNECTING BATTERIES IN SERIES AND PARALLEL. When two or more batteries are connected in series, the total voltage produced across the series combination will be equal to the sum of the voltages of the individual batteries. In Fig. 34A, the voltage produced across the two 4½-volt series batteries will be 9 volts.

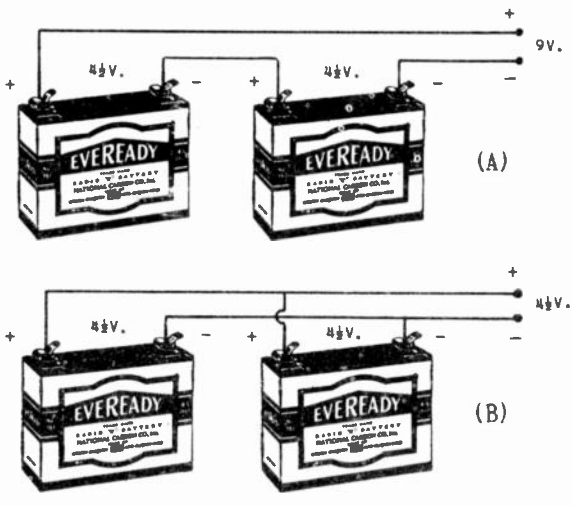


Fig.34 When batteries are connected in series as at A, the voltages will add together, and when equal batteries are connected in parallel as shown at B, the voltage output of the combination will be the same as one battery alone. The current drain from the parallel batteries will be one-half the current drain from the series batteries.

If the same two batteries are connected in parallel[1] as shown in Fig. 34B, the voltage produced across the combination will only be equal to the voltage of one 4½-volt battery.

The advantage of connecting batteries in series is to secure

[1] In Fig. 34B, this indicates that the wires are not connected together at this point.

a higher voltage than one battery can produce. The advantage of connecting batteries in parallel is to provide a greater current capacity than one battery can produce.

When batteries are in series, the current flowing through the external circuit will be supplied by each of the series batteries. The voltage output of series batteries will be greater, but the maximum current which can be supplied to the external circuit (without damage to the battery) will be limited by the battery in the series group which has the smallest current delivering capacity.

With parallel batteries, the current supplied to the external circuit is divided between the individual batteries. If two equal batteries are connected in parallel, half of the current flowing through the external circuit will be supplied by one battery and the other half of the current by the other battery. When three equal batteries are in parallel, one-third of the total current will be supplied by each battery, etc. The voltage output of the combination will be equal to the voltage of one battery.

Batteries having unequal voltages may be connected in series, but not in parallel.

10. **PROBLEMS.** It is suggested that the student work the following group of problems to make certain that he clearly understands the various forms of Ohm's Law and the rules governing series and parallel circuits.

Problem 1: A short circuit is a path for current which has an extremely low resistance. A short circuit can be made by placing a wire with .001 ohm resistance across a 110 volt line. If the pressure is maintained at 110 volts, what current would flow through the short circuiting wire? *Answer:* 110,000 amperes.

(A current of this value passing through the wire would immediately melt it because of the tremendous heat produced.)

Problem 2: The field coils of a certain motor are to be used on a 110 volt line. How much resistance must they have if the current through them is to be 2.18 amperes? *Answer:* 50.5 ohms.

Problem 3: The average resistance of the human body is 10,000 ohms. About .1 ampere through the body is usually fatal. What is the lowest voltage that would ordinarily kill a person?

Answer: 1,000 volts.

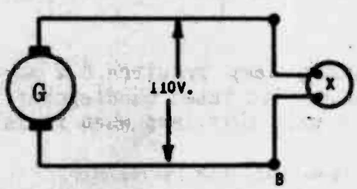


Fig.35 If X is a voltmeter, it will measure the voltage output of the generator, but if it is an ammeter, it will quickly burn out, because AMMETERS MUST NOT BE CONNECTED IN PARALLEL.

Problem 4: In Fig. 35, a pressure of 110 volts is maintained between points A and B by generator G. An electrical measuring instrument marked X is connected across A and B. If the instrument X is a voltmeter of 150,000 ohms resistance, how much current will flow through it? *Answer:* .000733 ampere.

If the instrument X were a 0-10 milliammeter having only .005 ohm resistance, how much current will flow through it? Assume that the pressure of 110 volts is maintained across A and B.

Answer: 22,000 Amperes.

(From this problem, it can be seen why an ammeter should not be placed across a source of voltage. In this case, the milliammeter is overloaded 2,200,000 times).

Problem 5: Find the current passing through each resistance and the voltage drop produced across each resistance in Fig. 36. (The answers are given in the chart on the right side of the figure).

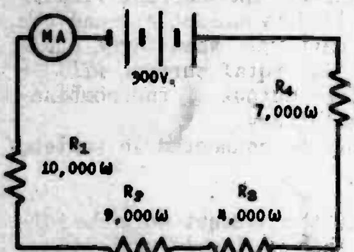


Fig.36 Series circuit.

Resistor	E Volts	I Amperes
R_1	100	.01
R_2	90	.01
R_3	40	.01
R_4	70	.01

Total R of Circuit = 30,000Ω
Total I of Circuit = .01 A. or 10 Ma.

Problem 6: Find the current through each resistance and the voltage drop across each resistance in the circuit as shown in Fig. 37. (The answers are given in the chart on the right side).

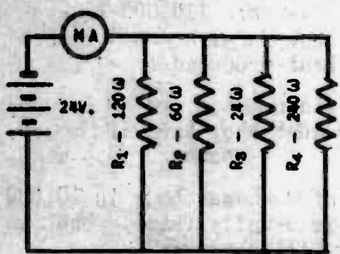


Fig.37 Parallel circuit.

Resistor	E Volts	I Amperes
R_1	24	.2
R_2	24	.4
R_3	24	1.
R_4	24	.1

Effective R of circuit = 14.11Ω
Total I through circuit = 1.7 Amps

Problem 7: A certain series tungsten lamp requires 6.2 amperes at 90 volts pressure to operate at its rated candlepower. What resistance must be placed in series with this lamp when it is used on the 112-volt line?

Hint: The voltage must be dropped from 112 to 90 volts with the resistor.

Problem 8: What voltage will be required to force a total current of 12 amperes through a parallel combination consisting of 14 ohms, 15 ohms, and 8 ohms? *Answer:* 45.6 Volts.

Hint: The voltage drop across a parallel circuit is equal to the effective resistance of the parallel circuit times the total current passing through all the branches.

Problem 9: Three lamps of equal resistance are placed in parallel across a 112-volt line and the current taken by the entire combination is 2.4 amperes. What is the resistance of each lamp?

Answer: 140 ohms.

Problem 10: A certain vacuum tube has 15,000 ohms resistance between the filament and plate. If a plate voltage of 300 volts is applied, how much plate current will flow?

Answer: 20 Ma.

In the last lesson, I briefly reviewed the operations of fractions for you. While studying this lesson on Ohm's Law, you undoubtedly have found it necessary to use decimals to work the problems. In the event that you need a review of decimals, I suggest that you study the material on this and the following pages. If you desire additional assistance on arithmetic, do not hesitate to ask for it on your Midland Consultation Service sheets.

DECIMAL FRACTIONS

1. DEFINITIONS.

Any fraction which has 10 or a multiple of ten as the denominator is called a decimal fraction. Examples are: $\frac{3}{10}$, $\frac{7}{100}$, $\frac{523}{1000}$, $\frac{1723}{100000}$. It is more convenient, in writing the above fractions, to use a notation peculiar to decimals. This involves the use of a period called the decimal point. Rewriting the above fractions in decimal notation, we have .3, .07, .523, .01723! These are read three-tenths, seven-hundredths, five hundred twenty-three-thousandths, and one thousand, seven hundred twenty-three-hundred thousandths.

Each figure to the right of the decimal point occupies a decimal place. The examples above are, respectively, one, two, three, and five place decimals. The value of a decimal depends upon the number of decimal places. For example:

$.0007 = \frac{7}{10000}$ = 7 ten-thousandths.
$.007 = \frac{7}{1000}$ = 7 thousandths.
$.07 = \frac{7}{100}$ = 7 hundredths.
$.7 = \frac{7}{10}$ = 7 tenths.
$7. = 7 = 7.$
$70. = 70 = 70.$

Rule: To change a decimal to a common fraction, write the number in the decimal as the numerator; for the denominator, write 1 followed by as many zeros as there are decimal places.

2. MIXED NUMBERS.

When there are figures written to the left as well as to the right of the decimal point, the combination is known as a mixed number. Examples are: 12.3, 124.42, 9.063! The figures written to the left of the decimal point is the whole number, while those written to the right is the fractional part. These mixed numbers are read twelve and three-tenths, one hundred twenty-four and forty-two-hundredths, and nine and sixty-three-thousandths.

Occasionally we find a zero written to the left of the decimal point, such as 0.3! This zero merely indicates that there is no whole number. The number is read three-tenths, just as if the zero were not present.

3. NUMERATION OF DECIMALS.

The following table shows the relation between whole numbers and decimals.

Hundreds of millions	Tens of millions	Millions	Hundreds of thousands	Tens of thousands	Thousands	Hundreds	Tens	Units	Decimal point	Tenths	Hundredths	Thousandths	Ten-thousandths	Hundred-thousandths	Millionths	Ten-millionths	Hundred-millionths
9	8	7	6	5	4	3	2	1	.	1	2	3	4	5	6	7	8

In reading a decimal, the numerator is read first as if it were a whole number, and then the denominator is stated. Example: .631 is six hundred thirty-one-thousandths.

In writing a decimal, the number which indicates the numerator is written, and the decimal point is then placed so that there will be as many decimal places as there are zeros in the denominator. This is called pointing off the decimal. Example: Express twenty-one-ten-thousandths as a decimal. The numerator is 21 and the denominator 10,000. We first write 21 and then place the decimal point so that there will be four decimal places, corresponding to the four zeros in 10,000. Thus, .0021

4. FUNDAMENTAL PRINCIPLES CONCERNING DECIMALS.

(1) Placing zeros to the right of a decimal or removing zeros from the right of a decimal does not change its value. Example: .4, .40, and .400 are all equal, since $\frac{4}{10} = \frac{40}{100} = \frac{400}{1000}$.

(2) Inserting a zero between the decimal point and the first figure of the decimal will divide the decimal by 10. Examples:

$$.3 \div 10 = .03$$
$$.03 \div 10 = .003$$

We may restate this principle as follows: If we move the decimal point to the left, we divide the number by 10 for each place that we move the point.

(3) Removing a zero from the left of a decimal multiplies the decimal by 10. Examples:

$$.0004 \times 10 = .004$$
$$.004 \times 10 = .04$$

Or we may say that moving the decimal point to the right multiplies the number by 10 for each place that we move the point.

Exercises

Express the following as decimals:

1. Ninety-two-hundredths. *Ans.* .92
2. Three and three-thousandths. *Ans.* 3.003
3. Fifty-two-millionths. *Ans.* .000052
4. Three hundred ten hundred-thousandths. *Ans.* .00310

Read the following:

5. .000371 *Ans.* Three hundred seventy-one millionths.
6. 85.0027 *Ans.* Eighty-five and twenty-seven-ten-thousandths.
7. .921 *Ans.* Nine hundred twenty-one-thousandths.
8. .0000067 *Ans.* Sixty-seven ten-millionths.

5. ADDITION OF DECIMALS.

Example: Add 22.33, 156.007, 410., and .00004

```
 22.33
156.007
410.
   .00004
588.33704
```

Rule: Arrange the numbers one under another so that the decimal points fall in a vertical line directly under each other. Add as with whole numbers and place the decimal point in the sum directly under the other decimal points.

Exercises

Add the following:

1. 31.2 + 324. + 1.006 + .3712 + 6 *Ans.* 362.5772
2. .22 + .3345 + 3276. + .00007 *Ans.* 3276.55457
3. 75. + 2.34 + 6. + .0023 + 121.002 *Ans.* 204.3443
4. 2. + .2 + .03 + .0056 + 81 *Ans.* 83.2356

6. SUBTRACTION OF DECIMALS.

Example (1). Subtract .073 from .0983

```
.0983 minuend
.073  subtrahend
.0253 difference
```

Example (2). Subtract .002 from 18

```
18.000 minuend
   .002 subtrahend
17.998 difference
```

Rule: Write the subtrahend under the minuend so that the decimal point of one falls directly under the decimal point of the other. Subtract as with whole numbers, placing the decimal point in the difference so that it falls directly below the others. Add zeros to the right of the minuend if necessary.

Exercises

Perform the indicated subtractions.

1. 82.25 - 17.003 *Ans.* 65.247
2. 1. - .0067 *Ans.* .9933
3. 12.342 - .6 *Ans.* 11.742
4. 113.4 - .007 *Ans.* 113.393

7. MULTIPLICATION OF DECIMALS.

To multiply decimals, we write the right-hand figure of the multiplier[1] under the right-hand figure of the multiplicand[1] without regard to the positions of the decimal points.

Example (1). Multiply 2.22 by .003

```
  2.22 multiplicand
  .003 multiplier
.00666 product
```

The product will have as many decimal places as the sum of the decimal places in the multiplicand and the multiplier. In the example, the multiplicand has two decimal places and the multiplier three. Therefore, the product has 2 + 3 or five decimal places.

Example (2). Multiply 18.23 by .0756

```
   18.23 (two decimal places)
   .0756 (four decimal places)
   10938
   9115
  12761
1.378188 Ans. (six decimal places)
```

Rule: Write the multiplier under the multiplicand without regard to the position of the decimal points. Multiply as with whole numbers, and then point off in the product, beginning from the right, as many decimal places as there are in the multiplicand and multiplier combined, adding zeros to the left of the product if necessary.

Exercises

Multiply the following:

1. 37.23 × 1.6 *Ans.* 59.568
2. .003 × .0025 *Ans.* .0000075
3. 260 × .43 *Ans.* 111.8
4. 2.1 × 3.4 *Ans.* 7.14

[1] In a multiplication problem, the multiplier is that number by which a number is multiplied; the multiplicand is that number which is multiplied by the multiplier.

8. DIVISION OF DECIMALS.

Division of decimals consists of writing the divisor to the left of the dividend and then proceeding as with whole numbers.

Example (1). Divide .12558 by .46

```
              .273 Quotient
Divisor .46).12558 Dividend
              92
              335
              322
               138
               138
```

The number of decimal places in the quotient is equal to the number of places in the dividend minus the number of places in the divisor. In the example, the dividend has 5 decimal places and the divisor 2. Therefore, the quotient has 5 - 2 or 3 decimal places.

Example (2). Divide .0025 by 1.25

```
                             .002  (3 decimal places)
(2 decimal places)  1.25).00250  (5 decimal places)
                             250
```

In this example, it was necessary to add a zero to the right of the dividend; this, however, does not change its value. (Principle 2.)

Usually, division does not come out even; that is, there is a remainder. It is common practice to add zeros to the right of the dividend and continue the division until there are two or three decimal places in the quotient. Then a plus sign (+) may be added to the right of the quotient to indicate that the division may be carried further.

Example (3). Divide 167 by .32

```
                   521.87  (2 places)
(2 places)  .32)167.0000  (4 places)
                160
                  70
                  64
                   60
                   32
                   280
                   256
                    240
                    224
                     16
```

Rule: Write the divisor to the left of the dividend and proceed with the division as with whole numbers. The number of decimal places in the quotient is equal to the number of decimal places in the dividend minus the number of decimal places in the divisor. If the division is not exact, add zeros to the right of the dividend and continue the division until the quotient contains two or three decimal places. Before dividing, it may be necessary to annex zeros to the right of the dividend so that the number of decimal places in the dividend will be equal or greater than the number of places in the divisor, or so that the dividend will be large enough to contain the divisor.

Exercises

Perform the following divisions:

1. $.000768 \div .024$ *Ans.* .032
2. $309.6 \div 4.3$ *Ans.* 72.
3. $.002 \div 25$ *Ans.* .00008
4. $67. \div .018$ *Ans.* 3722.22+

9. REDUCTION OF COMMON FRACTIONS TO DECIMALS.

Often it is convenient to change common fractions into decimals. This is done by dividing the numerator by the denominator. Usually this division does not come out even, in which case we carry out the division until the quotient contains two or three decimal places.

Example (1). Change $\frac{1}{6}$ to a decimal.

$$6\overline{)1.000} = .166+ \quad \textit{Ans.}$$

Example (2). Change $\frac{1}{4}$ to a decimal.

$$4\overline{)1.00} = .25 \quad \textit{Ans.}$$

Suppose we encounter a problem such as:

$$\frac{1}{1.2} + \frac{2}{2.3} + \frac{1}{5.4}$$

It is, of course, possible to find the L.C.D. of these fractions, change them to fractions having this common denominator and then add, finally reducing the answer to a decimal fraction. It is usually much easier, however, to reduce each of these fractions to a decimal fraction by dividing the numerators by the respective denominators and then adding, as with ordinary decimal fractions. For example:

$$\frac{1}{1.2} + \frac{2}{2.3} + \frac{1}{5.4} = .833 + .869 + .185 = 1.887 \quad \textit{Ans.}$$

Likewise, a problem, such as:

$$\frac{1}{\frac{1}{2.1} + \frac{1}{.7} + \frac{1}{3}}$$

is best solved by reducing each of the fractions to a decimal, adding these decimals together and then dividing 1 by this sum. For example:

$$\frac{1}{\frac{1}{2.1} + \frac{1}{.7} + \frac{1}{3}} = \frac{1}{.476 + 1.428 + .333} = \frac{1}{2.237} = .447 \quad \textit{Ans.}$$

Rule: Divide the numerator by the denominator and continue the process until the quotient contains two or three decimal places, if the division is not exact.

Exercises

Change the following common fractions into decimals:

1. $\frac{7}{13}$ *Ans.* .538
2. $\frac{3}{8}$ *Ans.* .375
3. $\frac{3}{4}$ *Ans.* .75
4. $\frac{5}{6}$ *Ans.* .833

Notes

(These extra pages are provided for your use in taking special notes)

Notes

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The text of this lesson was compiled and edited by the following members of the staff:

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UNIT NO. 1

FUNDAMENTAL ALTERNATING CURRENT

LESSON NO. 6

BENJAMIN FRANKLIN

.....THE FIRST GREAT AMERICAN.

Benjamin Franklin was born in Boston in the year 1706. His father, a soap and candle maker, apparently was not a believer in education, for when Ben was ten years of age, he insisted that he give up his reading and studies and select a trade. Although he visited the shops of the various tradesmen, he could find nothing that appealed to him, so became his father's apprentice, and toiled at the hateful task of candle and soap making. Finally he decided that he would like to become a printer and was "bound over" to his oldest brother James for nine years.

Although James may have been an able printer, he had an evil temper and made life miserable for poor Ben. As a result, Ben slipped away to New York and finally, after enduring great hardships, he reached Philadelphia. Here he worked hard, studied and often went without food so that he might add to his education and save a little money.

When he reached the age of twenty, he was the owner and publisher of a successful paper, the "Pennsylvania Gazette", and later published "Poor Richard's Almanac", a book that enjoyed great popularity over a period of twenty-five years. Other noteworthy accomplishments were the founding of the first public library, a police movement that was the forerunner of our present police system, a society that now stands as the University of Pennsylvania, and the first public hospital in the United States.

His ever-active mind continued to work overtime and finally turned to the field of science. He was positive that the phenomena of lightning and thunder was caused by the presence of electrical currents in the air. Men of standing and much knowledge laughed at him, but he refused to be discouraged. Then that epochal day arrived when Benjamin Franklin actually drew electricity from the clouds with the aid of a silk kite, a hemp string, and a door key, and it became his turn to laugh. His name was now placed along with those of other great scientists......something that pleased him immensely. In his later life, he served his country well and faithfully and became a great historical figure whom Americans and people the world over revere and respect.

How the "wise men" who laughed at Ben would have laughed at you had you lived in that day and been able to tell them about the many uses to which electricity would be put in the future. Even today, well-meaning people laugh at their fellow men who, like Ben, have faith in a new idea or a new development such as Television. YOUR eventual success will not be gauged by the amount of money you have now. Instead, it will be determined by the extent of your ambition and determination! Opportunity exists today more than ever before, and the specialized training that you are receiving from Midland can do much to place those opportunities within your reach. You are just as good as the other fellow.....YOU, TOO, CAN MAKE GOOD!

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Lesson Six

FUNDAMENTAL ALTERNATING CURRENT

"This lesson is going to bring to you another very important study of electrical phenomena. If there is a question in your mind as to why you should study so much about electricity when your chief desire is to learn Radio and Television, let me assure you that without a proper fundamental knowledge of electricity, it is impossible to progress to any extent in the study of Radio and Television.

I am sure you will find the study of alternating current exceptionally interesting. Bear in mind that without alternating current, we would not have many of our present day industries, nor would Radio and Television be possible or practical."

1. FORMS OF CURRENT. Up to the present time, we have been dealing with one form of current flow only; that is, direct current. Direct current is often abbreviated DC. There are two other fundamental forms of current flow with which it will be necessary to become familiar in order to understand the fundamental electrical phenomena. These are pulsating direct current and alternating current (often abbreviated AC). All three of these forms of current flow are used to a large extent throughout Radio and Television work. Some branches of electricity deal only with DC or pulsating DC, while other branches deal almost entirely with AC. However, in the specialized study of Radio and Television, all three forms of current are encountered continually.

2. PURE DIRECT CURRENT. In a previous lesson, it was stated that an electrical voltage may be generated by: (1) friction; (2) application of heat to the junction of two dissimilar metals; (3) through the process of induction; (4) by a chemical reaction; (5) light falling on a photosensitive substance. Since the generation of an electrical voltage by friction is of no commercial value, it is not necessary to take this method into consideration. The voltage produced by the application of heat to the junction of two dissimilar metals, by a chemical reaction and by a steady source of light falling on a photosensitive substance always results in the production of a direct voltage. This means that the voltage gener-

ated will always force current through a circuit in one direction only, such as in the circuits used for explanation in the preceding lessons.

It was stated that a battery has a positive pole and a negative pole and it must be understood that the positive pole always remains positive and the negative pole always remains negative as long as the chemicals within the battery are capable of producing a voltage. Since the voltage of a battery is always in one direction, the current flow through an electrical circuit connected across its terminals will always be in the same direction. The current which flows under the pressure of a steady DC voltage is known as a pure direct current. *If the voltage does not change and if the resistance in the external circuit remains constant, the current flow through the circuit will always be the same value and will always flow in the same direction. This is known as a pure direct current.*

3. **PULSATING DIRECT CURRENT.** *Pulsating direct current will always flow in the same direction through a circuit; however, it will be changing in value.* In order to explain this definition, let

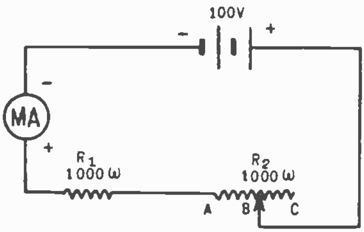


Fig.1 DC circuit. Varying the position of the movable arm B on the potentiometer changes the current flowing through the circuit.

us refer to Fig. 1. Since a battery is used in Fig. 1 as the source of voltage for the circuit, we know that the current will always flow through the circuit from the negative pole of the battery, through the milliammeter, through resistance R_1, through R_2 and back to the positive terminal of the battery. In all cases where the current flows in one direction through the circuit, it should be properly called a DC circuit. In order to calculate the amount of current flowing through the circuit, it is necessary to know the exact amount of resistance between points A and B on rheostat R_2. The portion of the rheostat between B and C is not in the electrical circuit. That part of the rheostat between A and B will be in series with R_1; hence, to calculate the current flowing through the circuit, it is necessary to add these two values together, then divide the sum into the applied voltage. Suppose that the moving contact arm on the rheostat was set for a resistance of 500 ohms between A and B. Then, the total resistance in the circuit would be 1,500 ohms (R_1 plus the resistance between A and B). When divided into 100 volts, this gives a current flow through the circuit of $66\frac{2}{3}$ ma. If the movable contact arm B were moved toward C, thus introducing more resistance in the circuit, the current flowing through the circuit would decrease. If B were moved completely to the right (at point C), there would be 2,000 ohms of resistance in the circuit and the current flow through the circuit would be 100 ÷ 2,000 ohms or 50 milliamperes. If, on the other hand, the movable arm B were moved completely to the left, thus making contact at point A, we would have only 1,000 ohms of resistance in the circuit, and the current flowing through the circuit would be 100 ÷ 1,000 or 100 milliamperes. Thus, it can be seen that the DC current flowing through the circuit can be varied from 50 milliamperes to 100 milliamperes by changing the position of the movable contact arm B.

Even though the value of the current flowing through the circuit may be changed in this manner, the direction of flow is not altered; that is, current will always be flowing from left to right through resistance R_1 and from left to right through whatever resistance is inserted by the rheostat between A and B.

Now, suppose that the arm B on the rheostat were rapidly moved back and forth between positions A and C on the rheostat. It is quite evident that the current flowing through the circuit would not remain at a steady value, but rather would change with the resistance change. As more resistance was inserted, the current would decrease and as less resistance was inserted, the current would increase. Since the current flowing through the circuit does not remain at a constant value, we cannot call it a pure direct current, so this form of current flow is known as a pulsating direct current.

In order to obtain a clear distinction between a pure direct current and a pulsating direct current, let us refer to Fig. 2. In

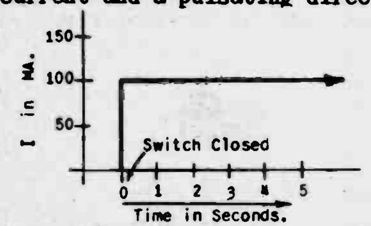


Fig.2 Illustrating that a pure DC current flows always in one direction at a constant value. Current flow is steady because the resistance and voltage are constant.

this figure, we have shown the conditions existing in a DC circuit if the resistance of the circuit remains constant. When the switch in the circuit was closed at the instant designated on the diagram, the current immediately rose to a certain value (100 ma.) and then remained constant. The current continues to flow at a value of 100 ma. throughout the time the switch is closed. The time specified on this diagram is in seconds; however, it could just as well have been in minutes or hours. This is a pure DC current.

In Fig. 3, the same circuit is being considered; however, af-

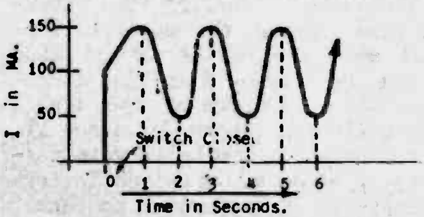


Fig.3 Illustrating that a pulsating DC current flows always in one direction, but changes in value. Current flow varies because the resistance is changed with the voltage remaining constant.

ter the switch is closed, the resistance of the circuit is being changed, thus causing the current flowing through the circuit to vary in accordance. The resistance of the circuit is being decreased in the time specified from 0 to 1 second, thus causing the current to rise. During the interval of time between 1 and 2 seconds, the resistance of the circuit is being increased, thus causing the current to decrease to a lower value. From 2 to 3 seconds after the switch is closed, the resistance of the circuit is again being decreased, allowing the current to rise. From 3 to 4, the resistance is being increased again, thus causing the current to drop back to 50 ma., etc.

It should be seen from this illustration that as the resistance of the circuit changes, the current will pulsate; that is, increase and decrease in value, but will always flow in one direction (from negative to positive of the voltage source). This represents a pulsating DC current.

4. **ALTERNATING CURRENT.** *An alternating current is one which changes not only in value, but also in its direction of flow.* This means that an alternating current will flow through the circuit first in one direction, then in the opposite direction, and at the same time, will be continuously changing in value.

Let us first illustrate what is meant by a change in the direction of current flow through a circuit. We shall use a battery as our source of voltage and a double pole - double throw switch (abbreviated D.P.D.T.) to reverse the direction of current through a single resistance. This circuit arrangement is shown in Fig. 4.

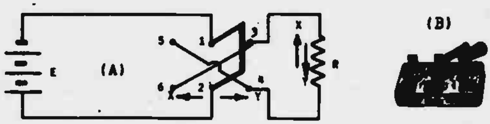


Fig. 4 (A) Double pole-double throw (abbreviated DPDT) switch circuit in which the direction of the current through resistor R may be changed by throwing the arm of the switch.

(B) Picture of a DPDT switch. The symbol for this switch is shown in the center of (A).

The picture of a D.P.D.T. switch is shown to the right in Fig. 4 and the symbol for this switch is shown in the center of the circuit diagram. In Fig. 4, when the arm of the D.P.D.T. switch is thrown to the right (in the direction as shown by the arrow marked Y), current will flow from the negative side of the battery to terminal 1 on the switch, through the upper connecting blade of the switch to terminal 3, then to the top of the resistor R, down through the resistor to the terminal 4 on the switch, through the lower blade of the switch to terminal 2, then back to the positive terminal of the battery. Notice that when the switch was in this direction, current passed through the resistance R in the direction as shown by the arrow Y. Now, throw the arm of the double pole switch to the left (in the direction as shown by arrow X). Current now flows from the negative terminal of the battery to terminal 1 on the switch, across the upper blade of the switch to terminal 5, then to terminal 4, up through the resistance R to terminal 3 of the switch, over to terminal 6, through the lower blade of the switch to terminal 2, then back to the positive terminal of the battery. With the switch thrown in this direction, notice that the current passed through the resistor R in the direction of the arrow X.

This action illustrates what is meant when it is said that the current flow through a circuit changes in direction. In this example, the current flow through the resistor R (which may represent any electrical circuit) was first in one direction, then in the opposite direction, depending on the position of the double pole arm of the switch. If we would rapidly swing the arm of the switch back and forth between the terminals 3-4 and 5-6, then the current flow through the resistor R would be rapidly reversed.

From the definition of an alternating current, we know that it acts in a manner very similar to the current reversals through the resistance R as illustrated in Fig. 4. The only difference is that the current reversals through the resistance R were rather abrupt, because of the rapid making and breaking of contact when the switch arm was thrown, whereas a commercial alternating voltage goes through these reversals in a very smooth and even manner. When speaking of these current reversals in an alternating circuit, the words "positive" and "negative" are generally used. These two words are used merely to designate the opposite directions of the current flow. As an example, in Fig. 4, the current flow up through the resistance R in the direction of the arrow X may be called the positive direction; then the current flow in the direction of the arrow Y would be called the negative direction. It must be thoroughly understood that these two terms, "positive" and "negative", were arbitrarily chosen for the sole purpose of designating opposite directions. The word "negative" is not to be interpreted as meaning "below zero", but to mean the opposite direction of flow.

For commercial purposes, an alternating voltage is generated by an AC generator. An illustration of the voltage output as pro-

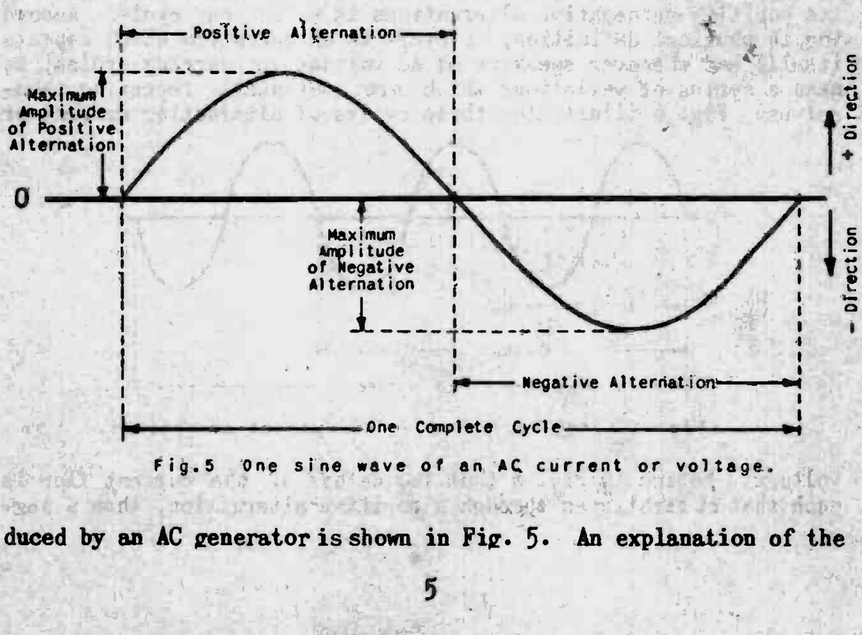


Fig.5 One sine wave of an AC current or voltage.

duced by an AC generator is shown in Fig. 5. An explanation of the operation of this type of generator will be explained in Lesson 13. The smooth voltage output of an AC generator as shown in Fig. 5 is commonly called a "sine wave" or a "sinusoidal wave". We shall not attempt to explain why this wave is called a "sine wave" or a "sinusoidal wave" at the present time; however, the student should remember this term.

Before continuing further, it is necessary to learn the meaning of several words which are used when speaking of alternating current. As can be seen from Fig. 5, the nature of an alternating current or voltage is such that it starts from zero and rises to its maximum value in the positive direction, then gradually recedes to zero. The alternating current or voltage then reverses its direction and rises to a maximum value in the negative direction, then gradually recedes to zero. The change from zero to maximum and back to zero in the positive direction is called one alternation, and the change from zero to maximum and back to zero in the negative direction is also called one alternation. In order to distinguish these two alternations from each other, the change in the positive direction is called the positive alternation and the change in the negative direction is called the negative alternation. *An alternation, then, is defined as a change in alternating voltage or current from zero to maximum and then back to zero.*

The word amplitude is frequently used when speaking of AC and is also used when speaking of pulsating DC. *The word amplitude means the value to which the voltage or current rises with respect to zero.* Referring to Fig. 5, the maximum amplitude of the positive alternation means the maximum value to which the AC voltage or current rises on the positive alternation, and the maximum amplitude of the negative alternation means the maximum value to which the AC voltage or current rises on the negative alternation.

The complete change of the AC voltage or current through both its positive and negative alternations is called one cycle. According to physical definition, a cycle is an operation which repeats itself, and whenever speaking of AC voltage or current cycles, we mean a series of variations which are continually repeating themselves. Fig. 6 illustrates three cycles of alternating current or

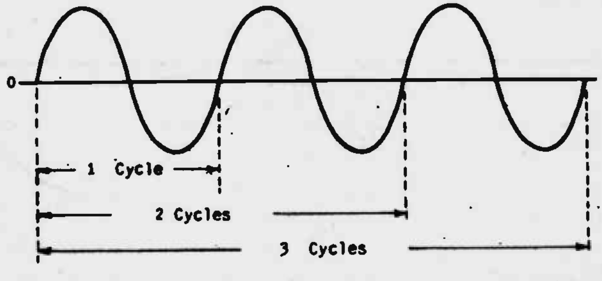


Fig.6 Three cycles of an AC current or voltage.

voltage. Notice in Fig. 6 that the nature of the current flow is such that it first goes through a positive alternation, then a negative alternation, then another positive alternation, etc. In other words, the variations are continually repeating themselves in alternate directions. One cycle will always consist of two alternations, a positive alternation and a negative alternation. When defining one cycle of alternating voltage or current, we should state that it consists of the *variations starting from zero, rising to its maximum amplitude in the positive direction, then returning to zero, after which it rises to its maximum amplitude in the negative direction and then again returns to zero.* Two such complete changes constitute two cycles and three such complete changes constitute three cycles, etc.

The diagrams shown in Figs. 5 and 6 may be used to represent either alternating voltage or current. Instead of definitely stating it is an alternating voltage or an alternating current, we often use the expression "AC wave", which means that the diagram shown may be representative of either an AC voltage or an AC current.

If the AC wave increases and decreases evenly and if the positive alternation is exactly the same shape as the negative alternation, it is called a "sine wave".

5. HYDRAULIC ANALOGY OF DC, PULSATING DC AND AC. In order to clarify the definitions of DC, pulsating DC and AC, a hydraulic analogy illustrating these three terms is advisable. Fig. 7 shows

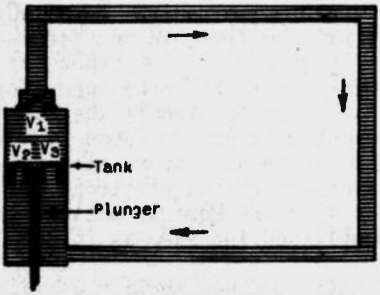


Fig. 7 Hydraulic circuit used for explanation of pure DC and pulsating DC.

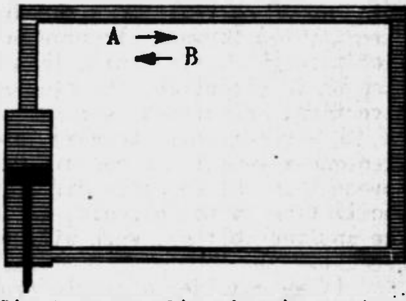


Fig. 8 Hydraulic circuit used for explanation of AC.

a closed pipe circuit containing a tank, a pump and valves so arranged that water will flow through the pipes in one direction only, independent of the direction of piston motion. This arrangement may be used as a water analogy for a DC system. The connecting pipe is analogous to the wire in an electrical circuit, and the piston (pump) is analogous to the source of electrical pressure. If the piston or plunger of the pump in Fig. 7 is moved from the bottom of the tank to the top of the tank, the pressure of the water will open the valve V_1 at the top of the tank and allow a current of water to flow around through the connecting pipe. The space at the bottom of the tank will fill as the plunger moves up. This single motion of the plunger represents the nature of a current flow in a pure DC circuit; that is, the water flow will be at a constant rate of flow (amperes in an electrical circuit) and in one direction.

We can use the same hydraulic system shown in Fig. 7 to represent pulsating direct current, because, due to the action of the valves, regardless of which direction the plunger is moved, there will be a flow of water in one direction only through the connecting pipe. Suppose, for example, that we move the plunger from the bottom to the top of the tank. Then, water will flow in the direction indicated by the arrow. Now as the plunger is moved down from the top to the bottom of the tank, the valves V_2 and V_3 will open, permitting the plunger to descend, but there will be no movement of water through the pipe because the valve V_1 will close. A continued movement of the plunger up and down in the tank results in a flow of water only as the plunger goes up through the tank; hence the water flow will be pulsating through the pipes and always in one direction. This is analogous to a pulsating DC electrical circuit.

The hydraulic system shown in Fig. 8 is similar to that shown in Fig. 7 except that the valves have been removed. As the piston in the tank is moved from its mid-position to the top, water will flow through the pipe in the direction as shown by the arrow A. Then, as the plunger is moved from the top to the bottom of the tank, water will be forced around through the pipe in the direction of the arrow B. It may be easily seen that as the plunger is rapidly moved up and down, the water will flow through the connecting pipe first in one direction and then in the other. This oscillating[1] movement of the water corresponds to the manner in which an AC current flows through an electrical circuit. In an AC circuit, the forward electron movement will be first in one direction through the circuit; then as the pressure of the generator changes in direction, the electron movement will be in the opposite direction. Electrical work will be done in an AC circuit the same as in a DC circuit, because just as much work can be done by an electron movement in one direction as can be done by an electron movement in the opposite direction. Even though the electrons are oscillating in the circuit, as long as they are kept in motion by the applied voltage, work will be accomplished the same as in a DC circuit.

If we consider a single drop of water in any section of the piping in Fig. 8, as the plunger of the pump is moved up and down, that drop of water will never move very far from its original position, yet it will be constantly in motion. The single drop of water oscillating (swinging back and forth) in a section of the piping corresponds to an electron oscillating in a portion of an AC electrical circuit. As the electron oscillates, the "impulse" created by its every motion is transmitted very rapidly from atom to atom throughout the entire circuit.

An AC circuit (containing a pure resistance) having a voltage applied of 10 volts with a current flow of 1 ampere produces an electrical power of 10 watts ($W = E \times I$). Likewise, a DC circuit which has 10 volts applied with 1 ampere of DC current flowing through it also produces 10 watts of electrical power.

6. **FREQUENCY**. The word "frequent" as used in ordinary conversation means "to repeat a certain action quite often" such as "fre-

[1] The word "oscillate" means "to swing back and forth".

quently indulging in a sport", or "frequently visiting a friend". The word "frequent" is used in exactly the same manner when speaking of electrical circuits; that is, it denotes the recurrence of a particular action. It may be said that the cycles of AC current flowing through a circuit repeat themselves quite frequently. The word "frequency" is used to specify exactly how frequently or rapidly these cycles repeat themselves. It is necessary to employ a unit of time for this measurement, so the second has been adopted. If 1 second of time were required for an AC current to complete one cycle, then the occurrence would be expressed as "one cycle per second". If, however, the cycles occurred more frequently, such as being speeded up until two cycles were completed in one second of time, then we would use the expression, "a frequency of two cycles per second". The definition of frequency, then, when applied to an AC circuit, is the *number of cycles per second.* Since the second is always used as the unit of time, we usually omit the time factor and merely say "the frequency is 1 cycle", or "the frequency is 2 cycles", etc. The only reason that it is permissible for us to use the shortened expression is because the second is universally adopted as the time factor when speaking of frequency. Some special problems may involve the use of a different time factor, in which case, it must always be given; such as "the frequency is 4 cycles per minute", or, "the frequency is 25 cycles per hour", etc. Unless otherwise specified however, the second is always considered to be the time factor. In Fig. 9, we have 10 cycles occurring in 1 second of time.

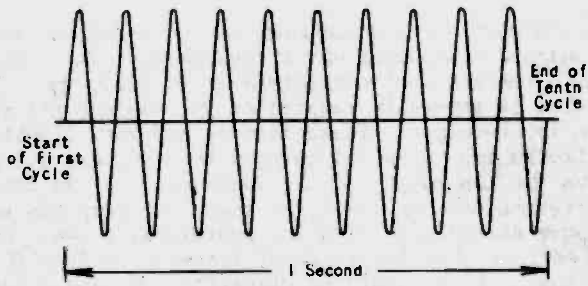
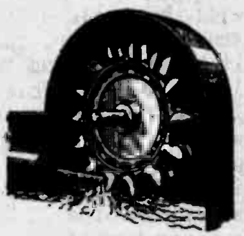


Fig.9 Illustration of 10 cycles of an AC current.

For the measurement of the revolution of mechanical bodies, the minute is nearly always employed as the unit of time. For example, when speaking of the speed at which a wheel revolves, we generally say, "10 revolutions per minute", or "900 revolutions per minute", etc. (See Fig. 10.) Revolutions per minute is often ab-

Fig.10 Diagram illustrating the mechanical revolutions per minute (r.p.m.) of a water wheel.



breviated "r.p.m." and cycles per second is often abbreviated "c.p.s." The small symbol ∿ is quite often used in electrical diagrams to represent the expression, "cycles per second."

The frequency of an AC generator may be anywhere from a fraction of a cycle per second to millions and millions of cycles per second. Mechanical generators of an AC voltage are limited to a frequency of around 20,000 cycles per second; however, vacuum tubes may also be made to generate an AC voltage, in which case the frequency may be made extremely high, quite often extending above 100,000,000 cycles per second. Frequencies from the very lowest to the very highest are used throughout all Radio and Television work. For convenience, we have three general divisions in this wide range of frequencies; namely, power frequencies, audio frequencies, and radio frequencies.

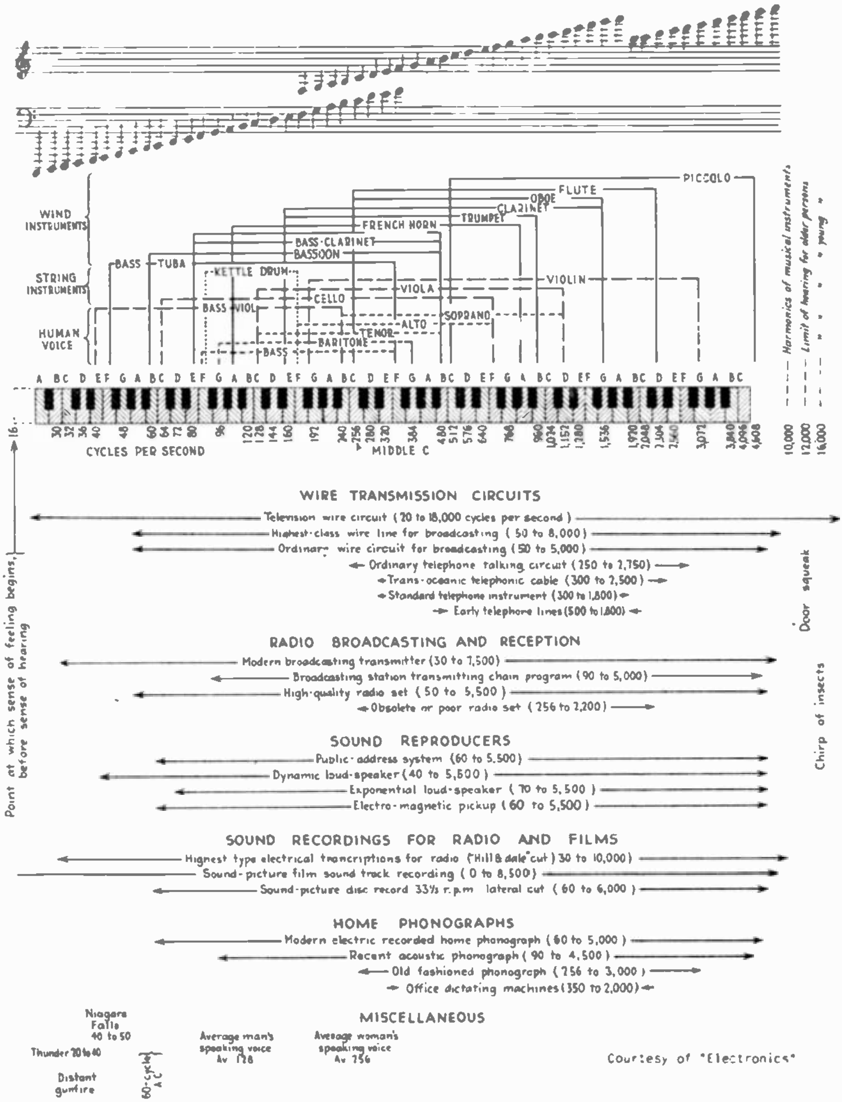
Power frequencies are defined as those used for power distribution work, such as 25 cycles or 60 cycles. All electrical power which is transmitted over any appreciable distance is transmitted in the form of AC, since it is much more economical than attempting to transmit power in the form of DC. In some localities of the United States, such as in the region of Niagara Falls, electrical power is distributed to homes at 25 cycles. Most modern, electrical generators, however, generate a 60-cycle voltage for power distribution and it will be found that this frequency is more popular at the present time than the formerly preferred 25-cycle voltage. Nearly all 32-volt Delco power plants used on farms generate a DC voltage.

Audio frequencies are defined as those which, when passed through a pair of headphones or a loudspeaker, will produce sound waves through the air that are audible to the human ear. This range of frequencies is generally considered to include all frequencies from 16 to 16,000 c.p.s. These figures may vary slightly in different textbooks and technical information, because all authors do not agree as to the range of the human ear. It is true that the range of frequencies to which the human ear responds varies with different persons and also with an individual's age. However, we are of the opinion that the range of frequencies from 16 to 16,000 cycles are those which should be classified as audio frequencies. It will be noticed that the audio frequency range also includes the two commonly used power frequencies of 25 and 60 cycles; so, when considering a frequency of 25 cycles or a frequency of 60 cycles, bear in mind that it may be called either a power frequency or an audio frequency.

In order to become familiar with the various audio frequencies, we suggest studying the chart shown on page 11. On this chart it will be noticed that the frequencies below 16 cycles affect the sense of feeling, rather than the sense of hearing. By actual test, it has been found that the average person cannot hear frequencies less than 16 cycles. Also, the chart shows that a frequency of 16,000 cycles is the upper limit of hearing for younger persons, while that of older persons is approximately 12,000 cycles. It is also interesting to note that the average frequency of a man's speaking voice is 128 cycles, while the average frequency of a woman's speaking voice is 256 cycles. These frequencies may be struck on a piano keyboard to obtain an idea as to where they lie in the aud-

Electronics' Chart of

Sound Frequency Characteristics



Courtesy of "Electronics"

ible spectrum.

The range of alternating currents called *"radio frequencies" extends from the upper limit of audio frequencies (approximately 16,000 cycles) to the extremely high frequency of 3,000,000,000 cycles.* It may seem rather out of reason that the AC current in a circuit can undergo 3,000,000,000 complete cycles in one second of time. However, such ultra-high frequencies have been generated and used for radio communication purposes. To obtain an idea of how rapidly the current must change in a circuit when the frequency is this high, the student might visualize 3,000,000,000 complete changes occurring during the time required for an ordinary pocket watch to tick three times.

As may be seen from the definition of radio frequencies, this band is many thousands of times wider in range than the band of frequencies occupied by audio frequency currents. The broadcasting of all radiotelephone and radiotelegraph signals is carried on in this band of radio frequencies. The Commercial Broadcast band occupies a small portion of this entire radio-frequency spectrum; namely; from 550,000 cycles to 1,600,000 cycles per second. The Federal Communications Commission has complete authority in assigning the various frequencies to broadcast, aviation, police, amateur, etc., radio stations. According to the present plan, Television broadcasting is carried on at frequencies extending from 42,000,000 to 90,000,000 c.p.s., with the band from 56,000,000 to 60,000,000 cycles excluded for amateur purposes.

The figures we have been using to designate the various frequencies in the radio-frequency spectrum are rather large, so for convenience, we will use the prefixes defined in an earlier lesson. Since the prefix "kilo" means 1,000 times, 1 kilocycle would be 1,000 cycles. The prefix "mega" was defined as meaning 1,000,000 times; hence, 1 megacycle would be 1,000,000 cycles. Examples of the use of these new terms would be as follows:

550,000	cycles	=	550	kilocycles[1]	=	.55 megacycle[1]
1,000,000	"	=	1,000	"	=	1. "
1,600,000	"	=	1,600	"	=	1.6 "
60,000,000	"	=	60,000	"	=	60. "
3,000,000,000	"	=	3,000,000	"	=	3,000. "

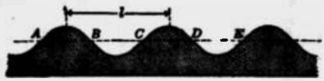
The expression "a broadcasting station is operating on a frequency of 800 kilocycles", means that the frequency of the alternating current which is being sent up into the broadcasting antenna is 800,000 cycles per second. Likewise, if the frequency of a broadcasting station is said to be 1500 kilocycles, it means that the frequency of the alternating current sent into the antenna of the broadcasting station is 1,500,000 c.p.s.

7. WAVELENGTH. *A wave of any kind may be defined as a vibration or a mode of motion.* Since all electrical waves and sound waves are invisible, it is advisable to select a suitable analogy in order to understand the meaning of the term "wavelength". Water

[1] Kilocycle is often abbreviated with the letters "KC", and megacycle is often abbreviated "MC".

waves can be seen, so an analogy of this kind should be enlightening. When a stone is dropped into a smooth pond, a disturbance is produced which extends over the surface of the water in circles, centered at the place where the stone struck. The water is pushed down and aside by the stone forming a circular ridge, which expands into a larger circle and is followed by a second circular ring, which expands, etc. The result is that the surface is soon covered with a series of circular crests which are separated by circular troughs, all moving away from the center of disturbance. The cross section of a water wave may be represented by a diagram as shown in Fig. 11. The "wavelength" of this water wave is measured horizon-

Fig.11 Cross-sectional view of a water wave to illustrate wavelength.



tally from any point on one wave to the corresponding point on the next wave. Thus, the wavelength is the distance between points A and C, between B and D, C and E, or the distance between the two successive crests marked "*l*". The amplitude of the water wave is half the vertical distance between the trough and crest, which is the same as saying that the amplitude is the distance from the dotted line through the center to the crest of the wave or the distance from the dotted line to the trough of the wave.

The same method of measuring the wavelength of a water wave is used to measure the wavelength of electrical waves; that is, *the wavelength of an electrical wave (audio-frequency or radio-frequency) is the horizontal distance from any point on one wave to the corresponding point on the next wave.* In order to express this wavelength, it is necessary to select a unit of measurement. When speaking of audio-frequency waves, the unit of measurement is the foot, and when speaking of radio-frequency waves, the unit of measurement is the meter. (1 meter = 39.37 inches.)

If an audio-frequency current is passed through a loudspeaker or a pair of headphones, the vibrations of the sound reproducing device causes the emission of "sound waves". The sound waves traveling from the cone of the speaker are similar to the sound waves shown when traveling outward from the ringing bell in Figure 12.

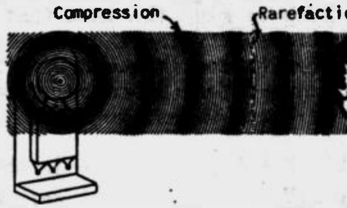


Fig.12 Diagram illustrating the passage of sound waves through the air. The compression and rarefaction of the air molecules are indicated by the heavy and light lines respectively.

Sound waves consist of the alternate compression and rarefaction[1] of air molecules at regular intervals. A cross-sectional view of the vibrating air molecules would appear similar to the water waves

[1] "Rarefaction" means to decompress or make less dense. It is the opposite of compression.

as shown in Fig. 11. The speed at which these vibrating air molecules travel through the air at a temperature of 68 degrees Fahrenheit is approximately 1130 feet per second. Since 68 degrees Fahrenheit is an average temperature, we may consider the speed or velocity of sound waves as being 1130 feet per second for practical applications.

Knowing the velocity (in feet per second) of a sound wave and the number of sound waves generated in a second of time (frequency), it will be possible to calculate the distance between the waves. This, of course, is the wavelength. The symbol generally used for wavelength is λ. This relationship may be expressed by the following formulas:

$$V = F \times \lambda$$

$$\lambda = \frac{V}{F}$$

$$F = \frac{V}{\lambda}$$

Where:
- V is the velocity of the sound wave in feet per second. (This is 1130 at 68° F.)
- F is the frequency of the sound wave in c.p.s.
- λ is the wavelength of the sound wave in feet.

For example, if the frequency of a sound wave is 500 c.p.s., then the wavelength of this sound wave may be found by dividing the 500 c.p.s. into the velocity of 1130 feet per second. This results in a wavelength of 2.26 feet. If the wavelength of a sound wave is known to be 9 feet, then the frequency of the sound wave may be calculated by dividing the 9 feet into the velocity of 1130 feet per second. This gives a frequency of approximately 125.5 c.p.s. In any case, if the frequency or the wavelength of a sound wave is known, the other may be found by dividing into 1130.

The wavelength of a radio-frequency wave is calculated in much the same manner as was done with an audio-frequency wave. However, there is a considerable difference in the velocity or speed. It has been definitely determined that a radio-frequency wave, when emitted from a broadcasting antenna, travels outward from the antenna at a velocity of 300,000,000 meters per second. This velocity is the same as that of light. A speed of 300,000,000 meters per second corresponds to approximately 186,000 miles per second. From this it can be seen that a radio wave would travel around the surface of the earth at the equator about 7 times in one second. This tremendous speed should be remembered, because it is quite important to keep in mind the fact that a radio wave travels with an almost unbelievable velocity. The formulas used for the calculation of wavelength and frequency for radio-frequency waves are the same as those used for the calculation of wavelength and frequency for audio or sound waves; that is:

$$V = F \times \lambda$$

$$\lambda = \frac{V}{F}$$

$$F = \frac{V}{\lambda}$$

Where:
- V is the velocity of the radio wave in meters per second. This is 300,000,000.
- F is the frequency of the radio wave in c.p.s.
- λ is the wavelength of the radio wave in meters.

Hence, if we know the frequency of a radio wave to be 1,000

KC, we may convert this into cycles (1,000,000 cycles), then divide it into 300,000,000 meters (the velocity of a radio wave), thus obtaining a wavelength of 300 meters. This means that the actual distance measured from any point on one radio wave to a corresponding point on the next radio wave is 300 meters.

As another example, suppose that we know the wavelength of a radio-frequency wave to be 200 meters and it is desired to find the frequency. By dividing 200 meters into the velocity of 300,000,000 meters per second, we obtain a frequency of 1,500,000 cycles, or 1,500 KC.

Since nearly all radio-frequency measurements are made in kilocycles, we very often reduce the number corresponding to velocity to 300,000; then whenever dividing the wavelength into this number, we will obtain the frequency directly in kilocycles. Likewise, by dividing the frequency in kilocycles into 300,000, we will obtain the wavelength in meters. This is merely for convenience and the answer secured will be just as correct as when dividing cycles into 300,000,000 to obtain meters, or when dividing wavelength into 300,000,000 to obtain cycles.

When dealing with some of the ultra-high radio-frequencies, the frequency is generally expressed in megacycles, in which case, to find wavelength, the frequency is divided into 300, or to find the frequency in megacycles, the wavelength is divided into 300. These relationships are given in the following formulas:

$F = \frac{300,000}{\lambda}$ or $\lambda = \frac{300,000}{F}$ Where: F is in kilocycles. λ is in meters.

And:

$F = \frac{300}{\lambda}$ or $\lambda = \frac{300}{F}$ Where: F is in megacycles. λ is in meters.

The conversion table shown in Fig. 13 shows the relationship between the frequency in kilocycles and the wavelength in meters for various frequencies in the commercial broadcast band and in the short-wave band.

The student should work out several examples from the Conversion Table to make certain that he understands the exact relationship between frequency and wavelength. By studying the table, it can be seen that the higher the frequency of a radio wave, the shorter the wavelength will be. The expression "short-wave" means a high-frequency radio wave. Generally, all frequencies above the commercial broadcast band (1600 kilocycles) are called "short-waves." A short-wave station will be any radio station which uses a transmitting frequency higher than 1600 KC. A "long-wave" station is the name generally applied to those stations using frequencies lower than 550 kilocycles. "Ultra-high-frequency" stations are those operating on frequencies above 30,000 KC (30 MC).

CONVERSION TABLE

FREQUENCY TO WAVELENGTH or WAVELENGTH TO FREQUENCY

$$\left.\begin{array}{c}\text{Wavelength}\\ \text{in}\\ \text{Meters}\end{array}\right\} = \frac{300{,}000}{\text{Frequency in Kilocycles}} \quad \text{or} \quad \frac{300}{\text{Frequency in Megacycles}}$$

Wavelength Meters	Frequency Kilocycles	Wavelength Meters	Frequency Kilocycles	Wavelength Meters	Frequency Kilocycles	Wavelength Meters	Frequency Kilocycles
20,000	15	1,132	265	411	730	139.5	2,150
15,000	20	1,111	270	405	740	136.4	2,200
12,000	25	1,091	275	400	750	133.3	2,250
10,000	30	1,071	280	394.8	760	130.4	2,300
8,570	35	1,053	285	389.6	770	127.7	2,350
7,500	40	1,035	290	384.6	780	125.0	2,400
6,670	45	1,017	295	379.8	790	122.5	2,450
6,000	50	1,000	300	375.0	800	120.0	2,500
5,450	55	968	310	370.4	810	117.7	2,550
5,000	60	938	320	365.9	820	115.4	2,600
4,620	65	909	330	361.4	830	113.2	2,650
4,290	70	882	340	357.1	840	111.1	2,700
4,000	75	857	350	352.9	850	109.1	2,750
3,750	80	833	360	348.8	860	107.1	2,800
3,529	85	811	370	344.8	870	105.3	2,850
3,333	90	790	380	340.9	880	103.5	2,900
3,158	95	769	390	337.1	890	101.7	2,950
3,000	100	750	400	333.3	900	100.0	3,000
2,857	105	732	410	329.7	910	85.7	3,500
2,727	110	714	420	326.1	920	75.0	4,000
2,609	115	698	430	322.6	930	66.7	4,500
2,500	120	682	440	319.1	940	60.0	5,000
2,400	125	667	450	315.8	950	54.5	5,500
2,308	130	652	460	312.5	960	50.0	6,000
2,222	135	638	470	309.3	970	46.2	6,500
2,144	140	625	480	306.1	980	42.90	7,000
2,069	145	612	490	303.0	990	40.00	7,500
2,000	150	600	500	300.0	1,000	37.50	8,000
1,935	155	588	510	285.7	1,050	35.29	8,500
1,875	160	577	520	272.7	1,100	33.33	9,000
1,818	165	566	530	260.9	1,150	31.58	9,500
1,765	170	556	540	250.0	1,200	30.00	10,000
1,714	175	545	550	240.0	1,250	20.00	15,000
1,667	180	536	560	230.8	1,300	15.00	20,000
1,622	185	526	570	222.2	1,350	12.00	25,000
1,579	190	517	580	214.4	1,400	10.00	30,000
1,538	195	509	590	206.9	1,450	8.57	35,000
1,500	200	500	600	200.0	1,500	7.50	40,000
1,463	205	492	610	193.5	1,550	6.67	45,000
1,429	210	484	620	187.5	1,600	6.00	50,000
1,395	215	476	630	181.8	1,650	5.45	55,000
1,364	220	469	640	176.5	1,700	5.00	60,000
1,333	225	462	650	171.4	1,750	4.62	65 000
1,304	230	455	660	166.7	1,800	4.29	70,000
1,277	235	448	670	162.2	1,850	4.00	75,000
1,250	240	441	680	157.9	1,900	3.75	80,000
1,225	245	435	690	153.8	1,950	3.53	85,000
1,200	250	429	700	150.0	2,000	3.33	90,000
1,177	255	423	710	146.3	2,050	3.16	95,000
1,154	260	417	720	142.9	2,100	3.00	100,000

8. **HEATING AND MAGNETIC EFFECTS.** Whenever current passes through a conductor, it is always accompanied by two effects:

(A) The production of heat.
(B) The establishment of electromagnetic lines of force around the conductor.

A detailed discussion pertaining to the magnetic effect of current flow will be given in Lesson 9. At the present time, we will concern ourselves with the heating effect only. (See Figs. 14 and 15.)

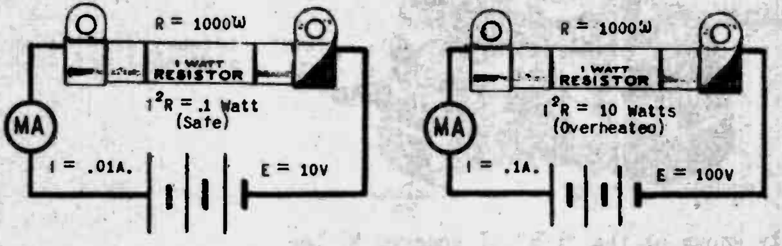


Fig.14 Circuits to illustrate the I^2R Law.

It is known that whenever water passes through a pipe, there will be friction between the water molecules and the inside surface of the pipe. This friction retards the movement of water through the pipe, thus constituting opposition to the water flow. Resistance in an electrical circuit is likewise due to friction, because when the electrons are moving through a conductor, they are continually colliding with the atoms of the metal in that conductor. Friction of any kind always results in the production of heat. In the case of the water pipe with friction between the pipe surface and the water molecules, the heat is easily carried away by the flow of the water and no noticeable temperature increase results. However, in an electrical circuit, the friction between the moving electrons and the atoms is not dissipated as readily, and as a result, the temperature of the conductor will rise. The increase in temperature of the conductor will depend upon the amount of current passing through it and its resistance. The greater the current flowing (in amperes), the greater will be the heat produced, and the more the resistance of the conductor, the greater will be the heat produced.

Heat is a form of energy and the heat produced by an electric current can be made to do work. The rate at which work is done by the heat in an electrical circuit is electrical power; hence, it may be expressed in "watts". We have previously defined electrical power as the rate at which work can be done in an electrical circuit and the unit for measuring this power is the "watt".

The relationship between the power, current and resistance in an electrical circuit can be expressed in the formula:

$$W = I^2R$$

Where: W is the power in watts.
I is the current in amperes.
R is the resistance in ohms.

Interpreting this formula, we find that the heat in watts will increase as the square[1] of the current and will increase directly as the resistance. In other words, the higher the resistance of the circuit and the more current passing through this resistance, the greater will be the heat in watts produced. This formula is gener-

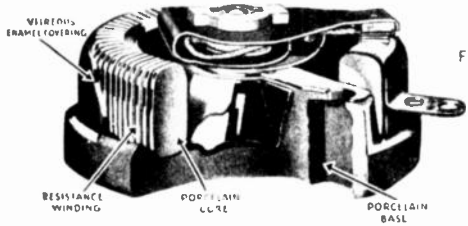


Fig. 15 Cutaway drawing of a 25-watt rheostat.

ally known as the "I^2R" (I squared R) Law.

This formula for finding the heat in watts has been secured directly from two fundamental formulas previously given. These are:

$$W = E \times I \quad \text{and} \quad E = I \times R$$

By substituting $I \times R$ for E in the formula $W = E \times I$, we have:

$$W = (I \times R) \times I, \quad \text{or} \quad W = I^2R$$

In some electrical circuits, the production of heat is very essential and in others it is desired to keep the heat produced to a minimum. In electrical devices such as irons, percolators, stoves, etc., the heat is desirable and is made to do actual work; whereas, in other types of electrical circuits, any heat that is generated in the circuit represents a loss of electrical energy and should be prevented as much as possible. Electrical power is required to overcome the resistance of a wire and force a current through it. This lost power appears in the form of heat generated in the wire. Likewise, mechanical power must be used to overcome the friction of a bearing on a motor and the lost mechanical power appears in the form of heat generated in the bearing. A mechanical engineer tries to reduce the amount of mechanical power wasted in heat by reducing the friction of the bearings, and likewise, an electrical engineer tries to reduce the electrical power wasted in the form of heat by reducing the resistance of the wire used to transmit or

[1] The square of a number means that number multiplied by itself, such as: the square of 8 is 8 × 8 or 64.

carry a given current.

Since the production of heat by electricity is a very important item in all electrical circuits, it is advisable to work out a few examples using the formula, $W = I^2R$.

Example 1: How many watts of heat energy will be used by an electric iron if the current drawn by the iron is 5 amperes and the resistance of the element in the iron is 20 ohms? In solving this problem, we must first square the amount of current flowing through the iron, that is, $5 \times 5 = 25$, then multiply this by the resistance of the iron's element, 20 ohms. $25 \times 20 = 500$ watts of heat energy.

Example 2: What is the amount of heat generated when 100 ma. passes through a resistance of 10,000 ohms? To solve this problem, it is first necessary to convert the 100 ma. into amperes. (100 ma. equals .1 ampere.) Squaring the current in amperes, we have $.1 \times .1 = .01$. Then, multiplying 10,000 ohms by .01, we have 100 watts of heat energy.

Example 3: The average resistance of a cigarette lighter in an automobile is .2 ohm. How much heat energy will be produced if the car battery measures 6 volts? It will first be necessary to find the amount of current drawn from the battery by the cigarette lighter. Using Ohm's Law, we find the current to be 30 amperes ($I = E \div R = 6 \div .2 = 30$). Then using the I^2R Law, we have $30^2 \times .2 = 900 \times .2 = 180$ watts of heat energy.

All resistor manufacturers rate their resistors in so many ohms and also give the wattage rating. (See Fig. 16.) For example, you may purchase a 1,000 ohm resistance which has a wattage rating of 1 watt, or you may purchase a 1,000 ohm resistance which has a wattage

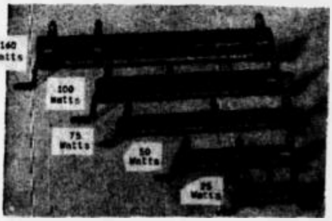


Fig.16 Photographs of 25, 50, 75, 100 and 160-watt resistors. All of these resistors have the same number of ohms; the only difference is in the wattage rating.

rating of 10 watts, etc. The resistance rating given by the manufacturer specifies the number of ohms possessed by the resistor and the wattage rating determines the maximum amount of current which can be passed through the resistance without causing the production of more heat than the element or wire can safely stand without melting. When purchasing a resistor, one should always take both of these things into consideration. First, determine the number of ohms of resistance needed in the circuit, then determine the maximum amount of current which will pass through the resistor. By using the I^2R Law, the maximum amount of heat in watts produced may be found, then purchase a resistor which will safely stand this amount of heat. In all cases, it is advisable to add approximately 25% as a safety factor. If a 25% safety factor is allowed, the resistor is not likely to burn out if more current than originally planned passes through it for a short while.

The text of this lesson was compiled and edited by the following members of the staff:

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UNIT NO. 1

VACUUM TUBE THEORY

LESSON NO. 7

DETERMINATION

.....SEE THAT YOUR DETERMINATION IS PROPERLY APPLIED.

Determination is an element of human nature that can be either an asset or a liability. To clarify this statement for you, we will cite two typical examples: young men, both of whom were determined. For the sake of convenience, we will call them John and James.

John had great visions of success. He basked in the radiance of his dreams that depicted him as a man of influence and means. Yet, he had no definite idea or plan as to just how he was going to make his dreams come true. When his parents suggested that he devote his spare time to training which would prepare him for a worth while future, he simply scoffed at the idea. As time went on and John's parents and close friends continued to make suggestions that he do something to insure his future, he became more and more determined that he would NOT do as they suggested. He would do as HE WANTED TO DO. He had a mind of his own and he would use it as he saw fit.

The years slipped by and John's determination remained as fixed as ever. His pocket book also remained as slim as ever and his future just as vague. John's misdirected determination had simply robbed him of money, promotion, and the respect of his friends, who whispered, 'John is so determined. He just won't take advice.' THIS KIND OF DETERMINATION IS A LIABILITY!

James also had great visions of success. He, too, dreamed of his future just as John did. He developed a strong desire to establish himself in an industry that offered young men a future. When one of his friends suggested that he get into Radio, James listened intently. Then he investigated the possibilities of Radio and became so enthusiastic that he determined to secure the necessary training even though his finances were extremely limited.

He DID get the training, and he DID become a success in his chosen field. His bank account increased rapidly. He married, had a home and car of his own and won the admiration of his many friends, who whispered, 'James is so determined. He just won't permit himself to become discouraged.' THIS KIND OF DETERMINATION IS AN ASSET!

Determination will fire you with the energy and equip you with the bull-dog tenacity that will make you 'stick to what you start' regardless of the obstacles which may confront you. Success is grand.....you want success.....YOU ARE DETERMINED TO HAVE IT AND YOU CAN HAVE AND ENJOY IT IF YOU PROPERLY DIRECT YOUR DETERMINATION!

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Lesson Seven

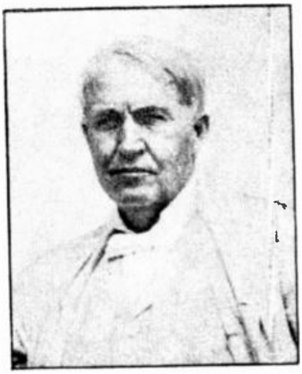
VACUUM TUBE THEORY

"Here is the lesson for which you have been waiting. It is your first actual introduction to a subject pertaining directly to Radio. I want you to remember this: *The vacuum tube is the foundation for the study of modern Radio and Television!* Without the vacuum tube, there would be no Radio industry for you to enter.

"The information given in this lesson is extremely important and I am sure you will find it easy to understand. However, even though the subject is easy, be sure to devote a sufficient amount of time to its study so that you will have all of the facts firmly fixed in your mind. Remember, this lesson will be the basis for all of your future vacuum tube studies."

1. **THE USE OF VACUUM TUBES.** The invention and development of the vacuum tube has probably been the greatest forward step in the history of Radio and Television, because without it, the Radio art as we know it today could not exist. Vacuum tubes are used in the design of a Radio or Television broadcasting station just as they must be used in the design of a Radio or Television receiving set. Vacuum tubes are employed to amplify the weak output of the microphone in the broadcasting studios. They are also used to generate the high-frequency alternating voltage necessary for Radio and Television transmissions. They are necessary to amplify the extremely weak currents produced in a receiving antenna, thus making it possible for these currents to operate the loudspeaker, after passing through the necessary conversions. Vacuum tubes also make it possible to operate a Radio receiver from the AC power supply lines, thus eliminating the use of batteries, as was required several years ago. The "shooting of a picture" by Television also depends entirely upon the function of several vacuum tubes, and likewise the transmission of Television signals, the reception of Television signals and the reproduction of a Television picture would not be possible without the use of vacuum tubes developed to the degree of efficiency as we know them today.

As well as being responsible for the modern art of Radio and Television, vacuum tubes are also employed quite extensively in the commercial field, especially by the telephone industry. Without



THOMAS A. EDISON

An American investigator and inventor in the field of electricity. Invented the incandescent lamp, the phonograph, discovered the "Edison effect", etc.

the use of vacuum tube amplifiers, long-distance telephone communications would not be possible. Vacuum tubes are employed in commercial power distribution to control large amounts of electrical power. They measure all sorts of quantities, convert electrical energy for high voltage transmission, etc.

The exact number of uses to which the vacuum tube may be applied is unknown and newer developments appearing every day make the fact more apparent that the vacuum tube is one of the most useful tools in the modern electrical industry. Because of this, it is quite necessary for anyone entering the Radio-Television field to become very familiar with the operation of a vacuum tube so that he may understand the performance of present-day circuits and also secure for himself a foundation in order to understand future developments as they appear.

2. **HISTORICAL DEVELOPMENTS OF THE VACUUM TUBE.** The earliest experiments which contributed to the basic knowledge of the vacuum tube were performed between 1873 and 1889 by Guthrie, Elster and Geitel. The experiments performed by these scientists pertained mostly to the conductivity of gases at different pressures near heated solids and flames. During the process of their experimentation, they actually used a piece of apparatus which was a two-element vacuum tube. It consisted of a straight, electrically heated filament of carbon or metal, located inside a bulb and directly below a cold plate sealed into the top of the bulb. Since they were interested only in the scientific side of their experiments, they did not mention the possibilities of this device as a rectifier of alternating current. At the present time, this is one of the most important applications of a two-element vacuum tube; that is, rectifying an alternating current into a direct current.

With apparently no knowledge of the experiments of Guthrie, Elster and Geitel, Thomas A. Edison made what he considered a very important discovery in 1883. The apparatus with which he was experimenting coincided very closely to that used by the other three scientists. At the time, Edison was experimenting with the incandescent lamp, which he had recently invented. He noticed that some of the carbon filaments of the incandescent lamp developed "hot spots" at certain points. These spots not only shortened the life of the lamp, but caused the bulbs to blacken, due to the carbon particles projected in straight lines from these spots and deposited on the inside of the glass bulb. To investigate this phenomenon, he sealed into the bulb a plate, situated between the legs of the horseshoe-shaped filament. Then he discovered that a galvanometer (current measuring device), connected between the plate and the positive end of the filament, would indicate a current, although no current flowed when the connection was to the negative end of the filament instead of the positive end. (See Figs. 1 and 2.) He concluded that in the first case, the current had evidently passed through the space between the plate and the filament. This was very outstanding in Edison's estimation because here was **current flowing with apparently no conductor.** This phenomenon has since been known as **the Edison effect** and is probably the actual starting point of the modern vacuum tube.

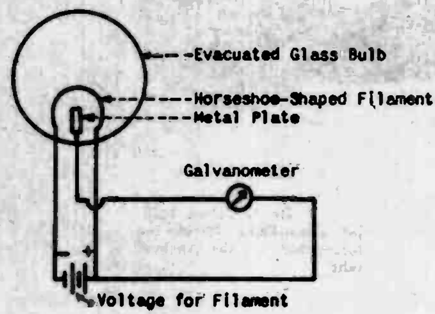


Fig. 1 Original setup used by Edison. Current flows through the galvanometer when connection is made to the positive side of the filament battery.

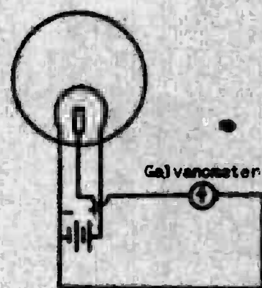
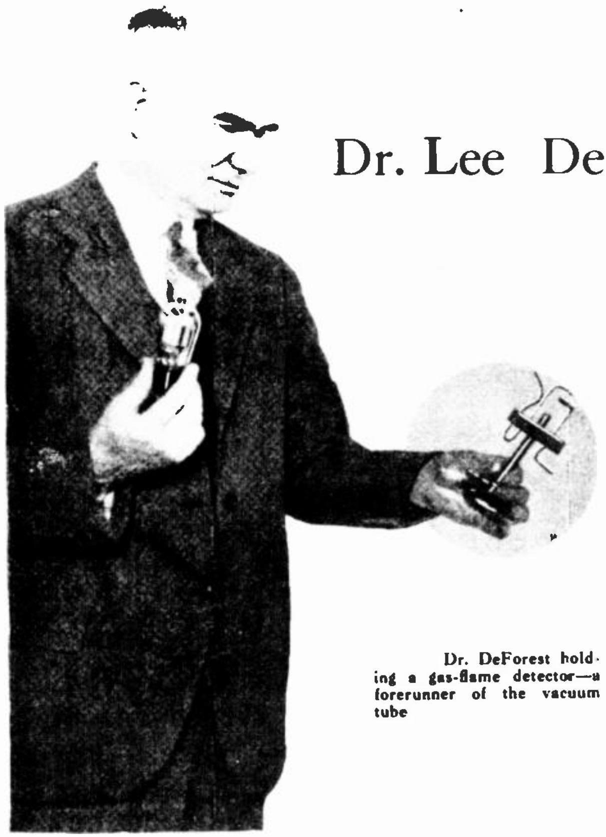


Fig. 2 Same as Fig. 1, except connection is made to the negative side of the filament battery. No current flows.

In the years 1884–1885, Preece made a more thorough study of the *Edison effect*. Preece proved that the kind of metals used for the plate had no influence upon the effect, but that the current was greatly influenced by the distance between filament and plate, the temperature of the filament and the voltage difference between the plate and filament. Having no suitable answer for the current flow across the space, he assumed that the current was carried by negatively charged particles of carbon, shot out in straight lines from the filament. Preece's conception of this action is very close to the actual explanation.

J. J. Fleming of England was the next scientist who conducted a series of experiments on the *Edison effect* between 1889 and 1896. Fleming was the first to suggest the use of this device for rectifying an alternating current into a direct current and secured pat-

Dr. Lee De Forest



Dr. DeForest holding a gas-flame detector—a forerunner of the vacuum tube

ents in Great Britain, United States and Germany, covering the use of the "oscillation valves", as he called the device. Our modern vacuum tube, consisting of an electrically heated filament and a cold plate sealed in an evacuated bulb, is a two-electrode tube, corresponding very closely to Fleming's original developments, but, of course, not as crude in construction. The two-electrode tube is often called a "Fleming valve".

As previously stated in our study, J. J. Thomson introduced the electron theory in 1897. The electron theory supplied the true explanation for the *Edison effect*. By using the electron theory, it is clearly shown that the current of electricity is not carried through the space between the filament and the plate by charged particles of carbon, but by the minute particles of negative electricity called **electrons**, which are emitted by the hot filament and attracted to the positively charged plate.

After Thomson proved this action, a number of outstanding experimenters turned their efforts toward the development of the two-element tube. Among the most prominent, deserving of mention in this early work, are Richardson, Wehnelt and Langmuir. The larger part of their work consisted of attempting to secure a greater electron emission from various materials when used as the filament of the tube. Also, these men are credited with the introduction of various gases in the tube, which since has led to the development of our modern mercury vapor rectifiers.

In 1907, Dr. Lee DeForest made an original and radical improvement in the vacuum tube by introducing a third electrode called the grid, between the filament and plate. This third electrode is situated in a position so as to control the flow of electrons from the filament to the plate. This "controlling action" of a three-element tube possesses tremendous advantages over the two-element tube. Whereas the two-element tube could be used only as a rectifier, with the introduction of the third electrode, the vacuum tube acquired new properties which opened up a tremendous field for commercial use. Under proper conditions, the three-element tube may be made to amplify a voltage; that is, a small voltage applied to the grid circuit of a tube will appear in the plate circuit greatly magnified.

For a brief period of time after DeForest's original invention, various experiments were performed on the three-element tube to improve its amplifying ability; then the vacuum tube was made available to the commercial world. Such a device had been needed for several years by the telephone and wireless industry; hence, it was immediately put into use and in a short time was considered indispensable. The widespread use of the vacuum tube amplifier naturally led to additional experimentation, out of which has grown our modern Radio and Television industry. (See Fig. 3.)

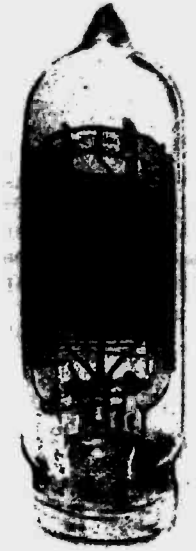
The importance of DeForest's invention of the three-element tube is recognized by scientists over the entire world and it is realized that through his efforts, our present telephone, Radio and Television industries have been made possible. For this reason, DeForest is often called the "Father of Radio". Dr. DeForest is still living at the time of this writing and is actively engaged in Television research work in California.

3. **THEORY OF THE TWO-ELEMENT VACUUM TUBE.** Since the two-element tube was the first form of a vacuum tube, it is well that we begin our study of this important device with this type. After securing a knowledge of the operation of the two-element tube, it will then be possible to add additional elements, one at a time, until we reach the final design of our modern multi-element tube.

A two-element (often called two-electrode) vacuum tube consists of a filament and a plate. The purpose of the filament in the tube is to supply a source of free electrons which may be attracted to the plate of the tube, when the plate is made positive with respect to the filament. A detailed description of the electron emission from the filament of the tube is first necessary.

First vacuum tube detector with a control element in the form of a plate

The first vacuum tube with the control element in the form of a grid



An improved audion with the first grid completely surrounding the filament

An audion used by the Navy. This tube had the first welded grid

Storage battery tube similar in general characteristics to present design

A three-element tube using high-output long-life oxide-coated filament

Fig. 9

By the emission of electrons is meant the expulsion or "giving off" of electrons by a solid or liquid body, usually not spontaneously, but as a result of the action of certain physical agencies. There are three important ways by which electrons are caused to be emitted:

1. Increasing the temperature of a body.
2. Bombardment of a body by rapidly moving ions, electrons or atoms.
3. Radiations of sufficiently short wavelength falling upon a body.

Electrons are spontaneously emitted from radioactive substances, but this form of emission is too weak to be of any importance as a source of free electrons for vacuum tubes, so it will not be considered further. The three types of emission just classified above according to the causes of emission are called, respectively:

1. Thermionic emission.
2. Secondary emission.
3. Photoelectric emission.

All three of these types of emission will be found to be of considerable importance in our study of Radio and Television. At the present time, however, we are mainly concerned with the emission of electrons due to the increase in temperature of a body; that is, the thermionic emission.

We have previously learned that every atom in any type of matter is composed of one or more planetary electrons revolving around a central nucleus. We have also learned that under ordinary conditions of temperature, the electrons in the atoms of a substance are in a constant state of motion and possess some energy due to this motion. Now if there were no restraints for these electrons at the surface of the conductor, all of them meeting the boundary of the conductor and having a normal component of velocity would escape, thus giving an enormous emission of electrons from all bodies, even at a normal temperature. It is necessary, therefore, in order to explain this phenomenon, to imagine a surface restraint or barrier through which only those electrons having a greater force or velocity than normal can penetrate and pass through the boundaries of the conductor. This surface restraint is thought to be due to the electrical attraction of the surface for the emerging electrons and may be likened to the surface tension of a liquid. In order for an electron to penetrate this surface barrier, it is necessary for it to possess kinetic[1] energy at least sufficient to overcome the restraining force. Now as the temperature of a conductor is increased, the velocity of some of the planetary electrons in the conductor increases, and these electrons possess a velocity sufficient to carry them through the surface barrier. The electrons which are emitted from the conductor charge the outside space negatively, leaving the conductor or body positively charged; hence, there will exist an attraction between the emitted electron and the conductor which tends to pull the electron back toward the conductor. This electron, when attempting to fall back into the conductor, will be

[1] Pertaining to motion.

repelled by other electrons which have later been emitted from it. At any given temperature of the conductor, an equilibrium is established when just as many electrons attempt to return to the body as escape in any given interval of time. Thus, a cloud of electrons will be formed outside of this conductor, having a density and occupying an area dependent upon the temperature. Now, if some external body is made positive with respect to this cloud of free electrons, the positive charge being sufficient to draw the electrons across the space between them, then an electron flow will result from the heated conductor to the positively charged body. The electrons which are drawn away from the cloud of free electrons surrounding the heated conductor will be replenished by additional electrons being emitted from the conductor.

Applying this emission theory directly to the operation of a two-element tube, let us refer to the circuit as shown in Fig. 4.

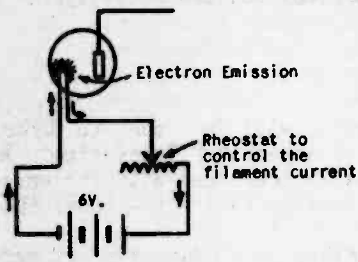


Fig.4 Two-element tube. The current flows through filament circuit as indicated by arrows.

Here we have a six-volt battery connected to the filament of a two-element tube with a rheostat in series to control the amount of current flowing through the filament wire. We know from previous study if a current passes through a conductor, the conductor will become heated, the heat generated being in proportion to the I^2R Law.

When the temperature of the filament wire becomes sufficiently high, the velocity of the electrons within the filament will overcome the surface restraint, thereby flying out from the filament and forming a cloud of negative electrons around the filament wire. This cloud of negative electrons is generally called the "space charge". It will not spread out over the inside of the evacuated glass or metal tube because of the attraction which the filament wire has for these electrons after they have been emitted from it. (The filament wire will be positive with respect to its previous condition after the electron emission.)

It is necessary to enclose this heated filament in a nearly evacuated bulb or space, because if the filament were heated to such a high temperature in open air, oxygen would combine with it, causing it to burn. It is possible to increase the temperature of any body to a much higher degree in an enclosed space where nearly all of the oxygen has been removed than it is to increase the temperature of the same body in air, without the body becoming disintegrated by burning. The space enclosed by the glass or metal tube in a so-called vacuum tube has had nearly all of the air and other gases pumped from it and therefore can be called an evacuated space. It should be understood that this space is not a complete vacuum, but the oxygen and other gas content is so exceedingly low that the heated filament will not become damaged.

4. **FILAMENT CONSTRUCTION.** Due to the difference in atomic structure of various conductors, some of them will emit electrons more readily than others when the temperature is increased by the passage of a current through them. It has been found that the metals, thorium, barium, calcium and strontium, will emit a more abundant supply of electrons at relatively low temperatures than other materials of reasonable cost; hence, they are used more commonly in vacuum tubes to produce electron emission. None of these metals, however, is sufficiently strong mechanically to be made into a self-supporting filament. Hence, these metals are generally mixed with or coated on some other metal that has the necessary property of mechanical strength, such as tungsten, nickel or platinum. Tungsten, nickel and platinum are all capable of withstanding a very high temperature without melting. Hence, they may be employed to carry the necessary current and to act as a rigid support for the electron-emitting material.

One of the common types of filaments is the thoriated tungsten filament. This filament consists of a mixture of tungsten and thorium, the tungsten being used for mechanical support and electrical conductivity, while the thorium is employed for the electron emission. Oxide coated filaments are also popular in modern vacuum tubes. These types of filaments consist of a wire of tungsten, nickel, or platinum which has been coated with barium or calcium oxide. In this construction, the oxide is merely coated on the outside of the wire instead of being actually mixed with the wire as are thoriated tungsten filaments. Pure tungsten is also used as the electron emitter in some of the large transmitting tubes.

As a comparison between these three types of filaments with regard to their electron emitting ability, for a given emission, the thoriated tungsten filament requires about one-half of the electrical heating power required by a pure tungsten filament, and an oxide-coated filament requires less than one-half the electrical heating power required by a thoriated filament. Thus, it can be seen that for a given electron emission, the oxide-coated filament requires the least electrical power, the thoriated tungsten is next and the pure tungsten filament requires the greatest amount of electrical heating power.

Regardless of the type of filament construction used, it is always employed solely for the purpose of producing a negative cloud of electrons around the heated filament wire. As stated before, this cloud of negative electrons is known as the "space charge". Bear in mind that the space charge is always negative because it consists of a quantity of negative electrons.

5. **THE PLATE OF THE TUBE.** The second electrode in the two-element tube is called the "plate". It consists of a circular or rectangular piece of metal, spaced from the filament. The plate is not in contact with the filament wire. If a voltage is applied to

the plate in such a direction as to make the plate positive with respect to the heated filament, an electron flow will be established between the heated filament and the plate, due to the attraction which the positive plate has for the electrons in the space charge. The plate is made positive with respect to the filament as shown in Fig. 5. The current which flows across the space inside of the tube

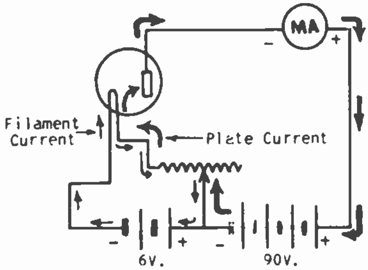


Fig. 5 Two-element tube showing filament and plate circuit. Small arrows indicate filament current. Large arrows indicate plate current.

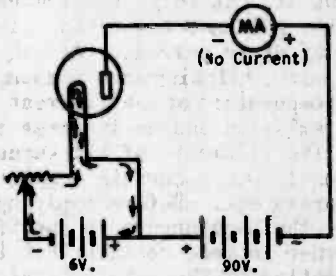
between the filament and plate starts from the negative side of the 90-volt battery shown in Fig. 5. The current flows through the connecting wire to the rheostat, through the rheostat, through one leg of the filament, from the filament across the gap to the plate, through the milliammeter connected in the plate circuit, then returns to the positive terminal of the 90-volt battery. The milliammeter in this circuit will indicate the amount of current flowing. This circuit is called the **plate circuit**. The path of the plate current in Fig. 5 is shown by the heavy arrows. *The proper definition for the plate circuit of a vacuum tube is that portion of the tube's circuit through which the plate current flows.*

The filament circuit of the tube consists of that portion of the tube's circuit through which the filament current flows. In Fig. 5, this is shown by the light arrows. The filament circuit consists of the filament of the tube, the rheostat, the connecting wires and the filament battery. The filament current leaves the negative side of the 6-volt battery, passes through the filament wire inside the tube, through the rheostat, then returns to the positive terminal of the 6-volt battery. Notice how the plate circuit overlaps into a portion of the filament circuit. The rheostat and the connecting wires on the right side of the filament circuit serve as a portion of both the plate and the filament circuit. The rheostat could just as well have been connected between the negative side of the 6-volt battery and the filament, because it is merely a series resistor used for the purpose of limiting the current through the filament circuit. Likewise, it is immaterial as to which side of the 6-volt battery the negative terminal of the 90-volt plate battery is connected. As long as the negative terminal of the 90-volt battery is connected to some point in the filament circuit, a return path will be provided for the current flow through the plate circuit. If this connection were not made, there would not be a complete circuit and it would be impossible for plate current to flow.

The importance of the heated filament wire must be realized, because were it not for the current passing through the filament, causing its temperature to rise to the point where emission occurs, there would be no electrons available in the space surrounding the filament that could be attracted to the plate of the tube; hence, there could not be a plate current flow.

The flow of plate current is made possible by the electron emission from the heated filament (supplying a source of free electrons) and the attraction exerted by the positive plate. Suppose that the connections to the 90-volt battery were reversed as shown in Fig. 6. In this diagram, filament current will flow through the

Fig. 6 Two - element tube circuit with plate battery reversed. No plate current flows because the plate is negative with respect to the filament.



filament circuit as shown. Since the plate of the tube is made negative with respect to the filament (due to the reversed connections of the 90-volt battery), there will be no flow of current through the plate circuit. The reason for no plate current flow can be seen by realizing that the space charge surrounding the heated filament consists of negative electrons which can be attracted only to an object which is positive. Since the plate of the tube is negative, there will be a repulsion against the electrons in the space charge instead of an attraction. If no electrons can pass across the space between the filament and the plate, the plate circuit is incomplete (equivalent to opening a switch in any electrical circuit) and no plate current will flow. The fact that plate current will flow when the plate of a tube is made positive, but will not flow when the plate is made negative represents one very important application of a modern vacuum tube—its use as a rectifier[1]. This was the only application of the two-element tube before 1907.

6. **CHARACTERISTICS OF A TWO-ELEMENT TUBE.** In all vacuum tube operations, we are primarily interested in a control of the current in the plate circuit. In a two-element tube, let us see what factors will affect this current flow.

[1] A rectifier is a device for changing AC to pulsating DC.

First, let us see how a change in the temperature of the filament will affect the plate current. As previously stated, the temperature of the filament (within limits) will determine the electron emission from the filament. The number or quantity of electrons in the space charge will, in turn, control the total number of electrons per second which pass to the plate of the tube; hence, the plate current will be affected by the temperature of the filament. The temperature of the filament depends on the current passing through it and its resistance (I^2R Law). Assuming that the resistance remains constant, the current passing through the filament will be responsible for the filament temperature and the amount of current flowing in the plate circuit. The filament current can be varied by changing the movable arm on the rheostat in the filament circuit. If the rheostat is adjusted to reduce the filament current, there will be a weak electron emission from the filament and the plate current will be practically zero. If the filament voltage is cut off entirely, the temperature of the filament will drop below the point necessary for electron emission and there will be no flow of plate current. As the resistance of the series rheostat is decreased, allowing more current to flow through the filament circuit, the temperature of the filament will rise, giving an increased electron emission and an increase in plate current.

The filaments of all vacuum tubes are designed to operate efficiently at a certain temperature, beyond which they are apt to be burned out. Before applying a voltage to the filament of any tube, the manufacturer's specifications should always be consulted in order to make certain that the voltage applied does not exceed the rating of the tube. Burning out the filament wire will render the tube useless.

If the voltage applied to the filament is set to the value recommended by the manufacturer, a variation in plate voltage will change the plate current. To vary the plate voltage applied to the tube, let us use the circuit arrangement as shown in Fig. 7. A

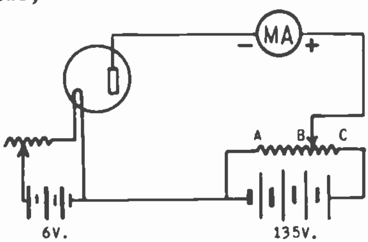


Fig.7 Illustrating how the plate voltage may be varied by changing the position of the movable arm B on the potentiometer.

potentiometer is connected across the 135-volt battery. If the movable arm (B) of the potentiometer is at the left of the potentiometer (A), the plate of the tube will be connected directly to the negative side of the 135-volt plate battery and there will be no voltage difference between the plate and the negative side of the filament. As the movable arm (B) of the potentiometer is moved to the right (toward C), the voltage applied between the plate and negative side of the filament will be increasing. Upon reaching the extreme right side of the potentiometer (C), the maximum plate voltage of 135 volts will be applied between plate and filament. By varying the position of the movable arm (B), it will be possible to change the plate voltage applied to the tube from 0 to 135 volts.

Assuming that the temperature of the filament remains steady, there will be a constant supply of electrons around the heated filament wire. If the plate voltage is reduced to zero, there will be no attraction for the electrons from the space charge to the plate; hence, the milliammeter connected in the plate circuit will be reading zero. As the plate voltage is gradually increased, the attraction of the plate for the negative electrons will be increasing, resulting in an increased number of electrons passing to the plate of the tube; hence, a greater flow of plate current will be indicated on the milliammeter. The plate current will continue to rise as the plate voltage is made higher and the maximum plate current will be obtained with this arrangement when the plate voltage is 135 volts.

The plate current in a given two-element tube will depend upon the voltage applied to the plate and the voltage applied to the filament. Since a variation of either filament voltage or plate voltage will affect the number of electrons passing from filament to plate, it would not be correct to state that the plate current depends upon either one of these alone, but upon the combined effect of the two. It should be remembered that **any alteration whatsoever that changes the number of electrons passing from the filament to the plate will affect the plate current in any vacuum tube.**

The student will recall that the current flow is always in the same direction as the electron flow, because it has been proved that a current flow actually consists of an electron movement. Other sources of technical information may state that the plate current flows from the plate to the filament in a vacuum tube. This conception of the direction of plate current flow is in keeping with the old conventional idea that current flows from positive to negative. The modern and correct direction of current flow has been adopted in this course and all explanations are based thereon; in other words, we shall always say that plate current flows from the filament to the plate.

There is a definite limit as to the maximum plate voltage which may be applied to a given tube, the same as there is a limit to the filament voltage. These voltages are all specified by the manufacturer of the tube and are dependent entirely upon the design of the tube itself. We will later find that the increases of plate current are not always in direct proportion to the increases of filament or plate voltage. These problems will be discussed in detail and graphs will be plotted to show the exact relationship between the filament voltage and plate current; also, between the plate voltage and plate current. This work is done in Lesson 12.

7. THE THREE-ELEMENT TUBE. The introduction of the grid between the filament and the plate constitutes what is known as a **three-element tube.** The grid is generally in the form of a metallic mesh or a coil of wire with wide spacing between the turns. A cross-sectional view showing the location of the elements in a three-element tube is shown in Fig. 8. The symbol used in wiring diagrams for the three-element tube is shown in Fig. 9 and a bottom view of

the tube's base, showing to which prong the various elements are connected is shown in Fig. 10.

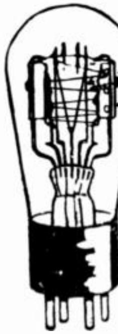


Fig. 8

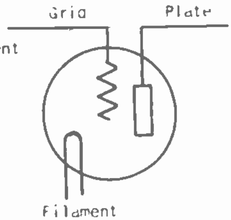


Fig. 9

Fig. 10

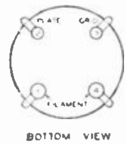


Fig. 8 Cutaway drawing of a three-element tube showing filament, grid and plate.

Fig. 9 Symbol for three-element tube as used on wiring diagrams.

Fig. 10 Bottom view of tube base indicating the respective prongs. The filament prongs are always larger than the grid and plate prongs.

The construction of the three-element tube is such that the filament is in the exact center, surrounded by the open grid wires, which, in turn, are enclosed by the thin, solid, metal plate. The electrons emitted from all sides of the filament are attracted by the plate. In order to reach the plate they must pass through the open spaces in the grid winding or mesh. Since the electrons must pass through the grid windings in order to reach the plate, if a voltage is applied to the grid which is either positive or negative with respect to the negative side of the filament, the stream of electrons to the plate will be affected by the grid voltage. If, however, the grid of the tube is connected directly to the negative side of the tube's filament, the grid will be at the same potential as the filament and will have no effect whatsoever upon the electron stream. The ability of the grid to affect the passage of electrons from the filament to the plate is responsible for the amplifying ability of a three-element tube; hence, a detailed discussion as to the manner of this control is necessary.

8. THE ACTION OF THE GRID. In Fig. 11, we have shown a circuit similar to that in Fig. 5, except for the addition of the C battery and the grid of the tube. Notice that the plate and filament circuits in Fig. 11 are the same (except that the filament control rheostat is in the negative lead); hence, if the filament or plate voltage is varied, the plate current will be changed. Now let us assume that the rheostat in the filament circuit is adjusted until there are exactly 250 ma. (.25 ampere) flowing through the filament wire. This amount of current will be sufficient to secure the necessary electron emission. Also, let us assume that a fixed

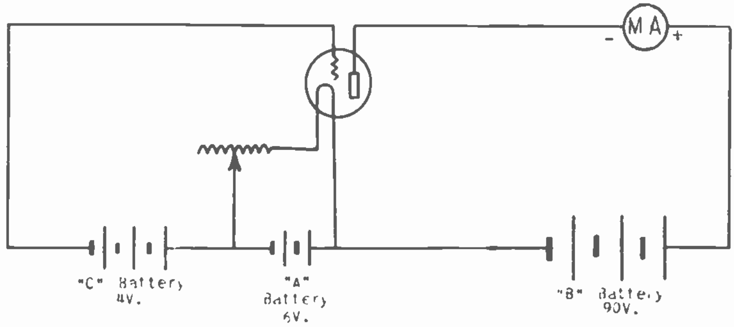


Fig.11 Three-element tube circuit. C battery is connected so as to make the grid negative with respect to the negative side of the filament.

voltage of 90 volts is applied between plate and filament by the B battery; then a certain amount of current will be flowing through the plate circuit as read on the milliammeter. Now, let us examine the effect of the C battery and the grid of the tube on the plate current flow. Notice that the positive terminal of the C (grid) battery has been connected to the negative side of the A (filament) battery and that the negative terminal of the C battery is connected directly to the grid of the tube. Since the C battery produces 4 volts of electrical pressure, the **grid of the tube will be negative with respect to the negative side of the filament by an amount equal to 4 volts.** The potential (voltage) of the electrons in the space charge surrounding the heated filament is always considered to be the same as the negative side of the filament; hence, the grid of the tube will be negative with respect to the electrons in the space charge. This will cause a **repulsion** to exist between the grid and the negative electrons in the space charge. If the attraction which the plate has for the space charge electrons is not sufficiently great to overcome this repulsion, there will be **no electron flow through the grid to the plate** of the tube. In modern tubes, a negative potential of 4 volts on the grid will not be sufficient to entirely prevent the passage of electrons to the plate; however, it will cause a considerable reduction. Many more electrons will pass to the plate if the grid is not made negative. If the voltage of the C battery is reduced, for example, to 2 volts, then there will be **less repulsion** against the electrons when they attempt to pass through the grid wires to the plate, resulting in a greater electron flow and **more current** indicated by the milliammeter in the plate circuit. On the other hand, if the voltage of the C battery is increased to, say, 6 volts, the grid of the tube will be made more negative than before, causing a **greater repulsion** against the negative electrons, thus allowing fewer of them to pass to the plate and there will be **less current** flowing in the plate circuit. By increasing the voltage of the C battery to a sufficiently high value, it will be possible to produce such a tremendous repulsion against the electrons in the space charge that the passage of electrons to the plate is entirely stopped, thus reducing the plate current completely to zero. This condition is possible regardless of the fixed positive voltage applied to the plate.

As stated before, if the grid were connected directly to the negative side of the filament, there would be no effect whatsoever on the electron passage from filament to plate. A circuit illustrating this connection is shown in Fig. 12. Since the potential

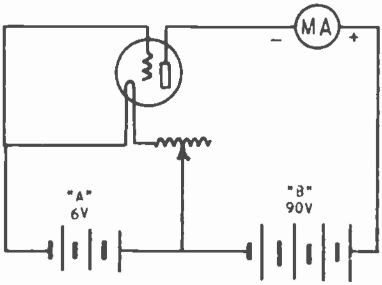


Fig.12 Three-element tube circuit with the grid connected directly to the negative side of the filament. No voltage difference between the grid and the negative side of the filament.

(voltage) of the grid is neither negative nor positive with respect to the negative side of the filament, it will not exert a repulsion nor an attraction on the space-charge electrons. Under this condition, the three-element tube will perform in a manner similar to the two-element tube.

If the connections to the C battery are reversed, that is, the positive side of the C battery is connected to the grid and the negative side of the C battery is connected to the negative side of the A battery, the tube will act in an entirely different manner. A circuit of this kind is shown in Fig. 13. The grid of the tube

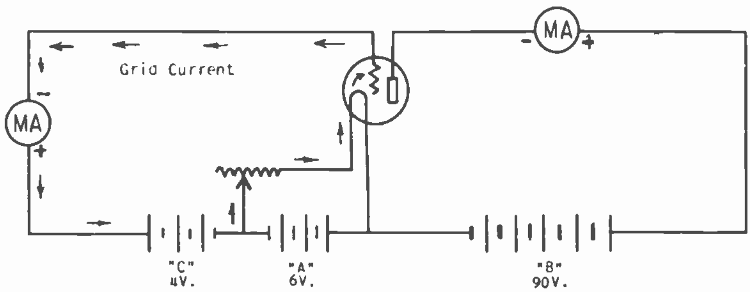


Fig.13 Three-element tube circuit with positive grid. Grid current will flow and the plate current will be high.

is now made positive with respect to the negative side of the filament. Remember that this also makes the grid positive with respect to the electrons in the space charge. Since the grid is now positive, it will attract electrons from the space charge the same as the plate. This means there will be a current flow from the negative terminal of the C battery to the filament across to the grid, through the grid milliammeter and back to the positive terminal of the C battery. This path of grid current flow is shown by the arrows in Fig. 13.

The actual surface area of the grid wires exposed to the electron stream is very small; so this grid current flow will not be of any appreciable amount unless the grid is made highly positive with respect to the filament. Since the surface area of the grid is so small, quite a number of those electrons which the grid attracts from the space charge will fly through the open spaces between the grid turns and come into the field of attraction possessed by the positive plate. This results in a much higher plate current flow than would ordinarily exist with the given filament and plate voltages. The grid, in effect, is partially neutralizing the space charge, thus allowing a greater quantity of electrons to be emitted from the filament. (Remember that the repulsion of the negative space charge against the filament tends to prevent the emission of electrons.) This larger number of electrons will be attracted to the grid and plate. The number of electrons which the grid receives will be in proportion to its voltage and its surface area; likewise, the number of electrons which the plate receives will be in proportion to its voltage and surface area. Because of the higher voltage and greater surface area of the plate, the majority of these additional electrons will pass through the open spaces between the grid wires and strike the plate, resulting in a much greater plate current flow.

Summarizing the foregoing information, we have:

(1) If the grid of the tube is connected directly to the negative side of the filament, the tube will function exactly the same as though the grid were not present.

(2) If the grid of the tube is made negative with respect to the negative side of the filament, the plate current flow will be reduced below the value that would flow if the grid were not present in the tube. It is possible to increase the negative voltage on the grid (with respect to negative filament) until the current flow to the plate is entirely stopped. As long as the grid of the tube is kept negative, there will be no flow of current through the grid circuit, because the negative grid will not attract the negative electrons.

(3) If the grid of the tube is made positive with respect to the negative side of the filament, electrons will be attracted to the grid, resulting in a slight flow of grid current. At the same time, a higher flow of plate current will result, because the presence of the positive grid in the midst of the negative space charge tends to neutralize the space charge, thus allowing a greater electron emission and, hence, a higher plate current.

Since the grid of the tube is so effective in determining the amount of current which will flow in the plate circuit of a vacuum tube (when the filament and plate voltages are constant), it is logical that we should refer to the grid as the "control element". Its action may be likened to a water valve whereby when the valve is opened (the grid is made positive or less negative), more water would flow through a hydraulic circuit (higher plate current) and if the valve were closed (grid is made more negative), less water would flow through a hydraulic circuit (lower plate current). A vacuum tube is called a "valve" in Europe for this very reason.

The ability of the grid to either increase or decrease the plate current is of exceedingly great importance in all Radio and Television work. This property enables the vacuum tube to produce comparatively large currents in its plate circuit by impressing a very small voltage on the grid circuit.

9. MEASURING VOLTAGES. In all vacuum tube circuits, it is essential that the tube be operated under the conditions specified by the manufacturer in order to secure best results from that tube. In later lessons, we will explain the function of the vacuum tube as an amplifier, detector and as a generator of radio-frequency voltages. In each case, a definite voltage must be applied to the filament, the plate and the grid in order to secure the desired results. The plate voltage, the filament voltage and the grid voltage are the three voltages which must be at the correct value when operating three-element tubes. When referring to or measuring these voltages, it is necessary to establish some reference point in the tube's circuit. When a DC voltage (a battery) is being used as the filament supply, **the negative side of the filament is used as the reference point.**

To measure the filament voltage, a voltmeter should be connected between the positive and negative sides of the filament as shown by V_1 in Fig. 14. The rheostat R may be adjusted until the

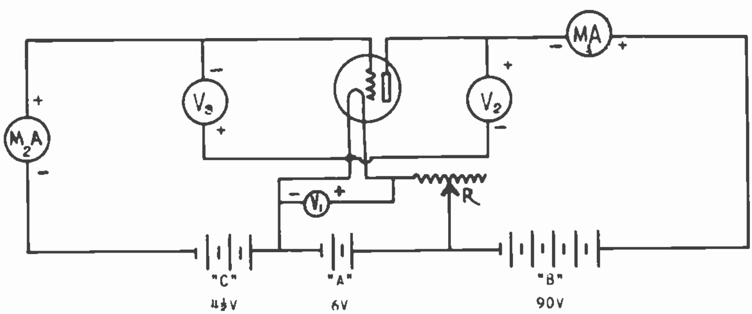


Fig.14 Diagram with meter connections indicated to measure filament voltage, plate voltage, grid voltage, plate current and grid current.

voltage across the filament as read on meter V_1 is the value specified by the manufacturer. If, for example, the voltage of the A battery is 6 volts, then the rheostat R should be adjusted until the voltmeter V_1 is reading exactly 5 volts for this particular tube. Next, to measure the plate voltage, a voltmeter must be connected between the plate and the negative side of the filament. This position for the voltmeter is shown by meter V_2. The B battery is supplying the plate voltage; however, the 6-volt A battery is in series with the 90-volt B battery; hence, voltmeter V_2 should be reading 96 volts. As stated before, it is immaterial as to which side of the A battery the negative side of the B battery is connected. If the negative side of the B battery were connected to the negative side of the A battery, then the voltmeter V_2 would be reading only 90 volts. The 6 volts supplied by the A battery is only a small percentage of the total plate voltage of 90 volts supplied by the B battery, so it is generally disregarded.

Next, to measure the grid voltage applied to the tube, we shall connect the voltmeter V_3 between the grid and the negative side of the filament, making certain that the positive terminal of the voltmeter is connected to the negative side of the filament and the negative terminal of the voltmeter is connected to the grid of the tube. As you will notice, this voltmeter is directly across the C battery with the positive of the C battery connected to the positive of the meter. The meter V_3 will be reading 4.5 volts. Whereas the negative terminal of the B battery may be connected to either the positive or negative of the A battery without seriously affecting the tube's operation, the positive terminal of the C battery must always be connected to the negative side of the filament.

10. GRID BIAS. With the positive side of the C battery connected to the negative side of the A battery in Fig. 14 and with the negative side of the C battery connected to the grid of the tube (through milliammeter MA_2), the grid of the tube will be made negative with respect to the negative side of the filament. The voltage difference between the grid and the negative side of the filament, when no voltage is being amplified is known as the "grid bias". The voltages applied to the filament and plate are always called the filament voltage and plate voltage respectively; however, the fixed voltage applied to the grid of a tube is called the grid bias voltage.

The definition for grid bias is "the fixed voltage difference between the grid and the negative side of the filament when no alternating voltage to be amplified is applied to the grid circuit." If the grid of the tube is made negative with respect to the negative side of the filament (see Fig. 11), the tube is said to have a negative bias applied. If the grid is connected directly to the negative side of the filament as shown in Fig. 12, the tube is said to have a zero bias. If the voltage applied between the grid and the negative side of the filament is in the direction as shown in Fig. 13, the tube is said to have a positive bias.

As long as the grid of a tube is kept negative with respect to the negative side of the filament, it cannot attract the electrons in the space charge, so no current will flow through the grid circuit. There will be no flow of grid current through the grid circuit in Figs. 11 and 12. In Fig. 13, however, the grid is made positive with respect to the negative side of the filament; hence, the electrons in the space charge will be attracted and grid current will flow. In Fig. 12, where the grid is at the same potential as the negative side of the filament, it may be that a few of the electrons passing through the grid to the plate will strike the grid wires and since there is no repulsion, these electrons may stick to the grid turns. They will then return back to the negative side of the filament through the external grid circuit. Thus, a very small grid current may flow, even when the tube has a zero bias.

11. **TUBE DETERIORATION.** The voltages applied to the vacuum tube circuit shown in Fig. 14 correspond to the manufacturer's specifications for a type 01-A tube. With these voltages applied, a plate current of 2.5 ma. will flow in the plate circuit (assuming that the tube is in good condition). After any vacuum tube has been in operation for a period of time (usually 1,000 hours, or more), the electron emitting material on the filament will become weak, resulting in a decreased electron emission. Then, the space charge will not consist of as large a quantity of negative electrons and with the specified voltages applied to the filament, grid and plate, the plate current will be less than normal. When the filament emission of a tube becomes so low that the operating characteristics of the tube are affected, it will no longer function properly in the circuit and it is necessary to replace it with a new tube. Tubes having a thoriated tungsten filament may be "reactivated". The reactivation process consists of applying a higher voltage than normal to the filament for a short period of time, thus causing the thorium atoms in the center of the tungsten wire to be driven towards the outside. Reactivation will alter the condition of the filament and make it possible to secure sufficient electron emission for a short period of time; however, it is not as satisfactory as replacing with a new tube. Thoriated tungsten filament type tubes are the only type which can be reactivated. Those tubes employing an oxide-coated filament will not respond to reactivation.

12. **ABBREVIATIONS.** The letters A, B and C are always used to designate the supply voltage for the filament, plate and grid respectively. The A battery generally consists of a storage battery similar to those used in automobiles. A battery of this type is necessary for filament supply, because of the high current drawn by the filament.

The B batteries used for plate supply usually consist of several, small 1.5-volt dry cells connected in series to secure a higher voltage. The average B battery is capable of delivering a current of approximately 50 ma. If a higher current than 50 ma. is drawn from an ordinary B battery, the result will be a rapid depletion (wearing out) of the chemicals and the battery will not give satisfactory service over the length of time specified by the manufacturer.

The C batteries used for grid bias are also constructed with small dry cells connected in series. The ordinary voltages produced by C batteries are 1.5, 4.5, 9, 13.5 and 22.5! The dry cells used for C batteries are always much smaller than those used for B batteries. The C battery is not designed to have any current drawn from it, since it is always used merely to make the voltage of the grid negative with respect to the negative side of the filament. In most vacuum tube applications, especially if the tube is to be operated as a voltage amplifier, the grid is always kept at a negative potential (respective to negative filament) and no grid current will flow. Fig. 15 shows typical A, B and C batteries as used for radio work.

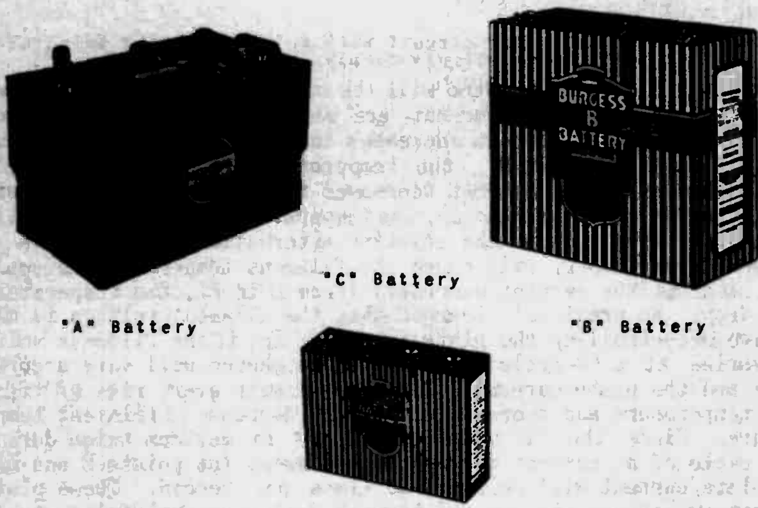


Fig. 15 Photographs of A, B, and C batteries.

13. ELECTRON EMITTERS FOR AC TUBES. In all of the circuits given so far, the voltage supply for the filament of the tube has been a battery. With a battery supplying the voltage, a pure DC current passes through the filament wire. When pure DC passes through the filament, the temperature of the filament will remain constant and the space charge will not vary. We know that if the temperature of the filament is decreased, the emission will decrease, and if the temperature of the filament is increased, the emission will increase. In other words, the filament emission and the space charge depend upon the temperature of the filament; hence, if the temperature is varied, both will change. From the I^2R Law, we learn that the temperature of the filament depends upon the current passing through it and its resistance. Assuming that the filament resistance remains constant, as the current passing through the filament wire is varied, the filament emission, the space charge and the plate current will all change.

In modern vacuum tube operation, the voltage supply for the filament is usually secured from an AC source, rather than from a battery. Suppose, for example, that a 6-volt 60-cycle AC generator[1] is connected to the filament as shown in Fig. 16. The current pass-

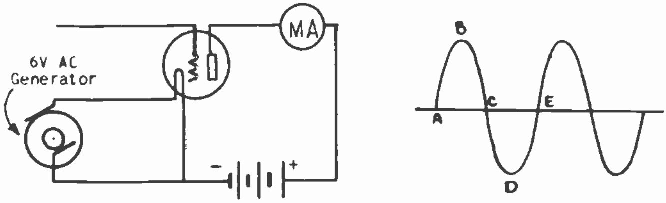


Fig. 16 Three-element tube circuit with an AC generator being used for the filament voltage supply.

ing through the filament wire will be a 60-cycle AC current. Two cycles of this 60-cycle current are shown at the right side of Fig. 16. As the AC current increases in amplitude on its positive alternation (from A to B), the temperature of the filament will rise. Then as the AC current decreases in amplitude on the positive alternation (from B to C), the temperature of the filament will decrease. Likewise, on the negative alternation, the increase of current (from C to D) will cause the filament temperature to again rise, and as the current decreases (from D to E), the temperature will drop. We previously learned that the filament voltage is effective in controlling the plate current. So, if the filament voltage varies at a 60-cycle rate, the space charge will vary accordingly and the plate current will increase with every rise of filament temperature and decrease with every decrease of filament temperature. Since the filament temperature is maximum twice during each cycle of AC current through the filament (at points B and D), the plate current will pulsate 120 times per second. These plate current pulsations will be fed through following amplifying stages (assuming that this tube is being used in a radio receiver) and a disagreeable 120-cycle hum will be produced from the speaker of the radio set. This hum is extremely objectionable and must be prevented.

There are two ways of preventing this hum when AC is used as the filament supply. The first and more popular method is shown in Fig. 17. The construction of the electron emitter is in two parts instead of one. The 60-cycle AC current is passed through the filament wire the same as in Fig. 16; however, the filament wire itself is not prepared with electron emitting material; hence, no electron emission will occur from the filament wire. In order to distinguish the filament wires which do not emit electrons from those which do emit electrons, those wires which do not emit electrons are called "heater" wires and from now on will be referred to as such. They are called heater wires because their sole purpose in the tube is to produce heat. Referring to Fig. 17, a metal sleeve called the "cathode" is placed down over the heater wire with an insulating material serving as separation. When the

[1] Notice the symbol used for an AC generator in Fig. 16. This is the symbol always used on wiring diagrams.

heater wire becomes hot, the metal sleeve (cathode) will also become heated, because of the radiation from the heater wire. Due to the mass of the large metal sleeve, its temperature will remain constant after it has once become heated, regardless of the current changes through the heater wire. The electron emitting material is coated on the outer surface of the metal sleeve. There is no direct electrical connection between the heater and the cathode.

With this type of construction it can be seen that as soon as the cathode becomes sufficiently heated to emit electrons, the emission thereafter will be at a steady rate, regardless of the AC current changes through the heater wire. The plate current, therefore, will not fluctuate at a 60-cycle rate and no hum will be produced. This heater-cathode construction of the electron emitter is known as the "indirectly heated cathode". This expression means that the emission does not come directly from the wire through which the heating current flows, but rather from another surface which is heated by radiation from the conducting wires.

Fig.17 Enlarged drawing showing the construction of a heater - cathode emitter.

The addition of the cathode to the tube does not mean that another element has been added, so this type tube is still called a three-element tube. Tubes of this type require five prongs on the base, the additional prong being necessary for the cathode. Since the electron emission is directly from the cathode, the negative terminal of the plate battery must be connected to the cathode in order to make the plate circuit complete. (See Fig. 18.) Connecting the negative terminal of the plate battery to either side of the heater wire would not make the plate circuit complete, because there is no electron flow from the heater wire to the plate.

Fig. 19 shows the symbol used in wiring diagrams for the indirectly heated three-element tube and Fig. 20 shows a bottom view of the prongs on the tube base.

The other method of constructing the electron emitter to prevent the production of hum in a receiver is to use a large, ribbon-like filament wire instead of a small, fine wire. If a large ribbon of wire is used for the filament, when its temperature reaches the electron emitting point, it will not cool and heat rapidly as the AC current passes through it. There will, however, be a very slight fluctuation of temperature, so this method of construction is really not as satisfactory as the indirect heater-cathode type of construction. By inspecting a manufacturer's tube manual, you will find that there are several power amplifier tubes employing the ribbon type of filament construction. This is known as a directly heated filament (sometimes called a directly heated cathode).

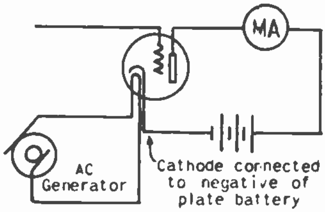


Fig. 18

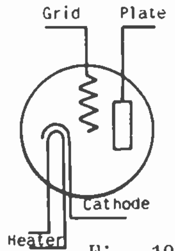


Fig. 19

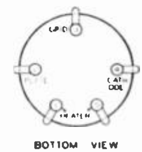


Fig. 20

Fig. 18 Diagram illustrating that the negative side of the plate battery must be connected to the cathode in order to make the plate circuit complete.

Fig. 19 Symbol for a three - element heater - cathode type tube.

Fig. 20 Bottom view of tube base indicating the respective prongs. The heater prongs are larger than the others.

This name is applied because the electron emission occurs directly from the wire through which the heating current flows. Tubes of this type are generally employed as the last amplifier tube in a radio receiver. Since there are no amplifiers following this tube to increase any hum which might be developed, the hum level in the speaker will be sufficiently low as to be negligible.

Several of the high-powered tubes used in the design of radio transmitters employ filaments of the directly heated type, but nearly all of the tubes manufactured for use in radio receivers are of the indirect heater-cathode type.

Several combinations of words that are frequently used when speaking of vacuum tubes are abbreviated with letters. The more important abbreviations are given in the following table:

P = Plate	E_p = Plate Voltage
F = Filament	E_f = Filament Voltage
G = Grid	E_f = Heater Voltage
H = Heater	E_c = Grid Bias
C = Cathode	I_p = Plate Current
	I_f = Filament Current
	I_g = Grid Current

CONVERSION TABLE

MULTIPLY	BY	TO OBTAIN
Amperes	× 1,000,000,000,000	Micromicroamperes
Amperes	× 1,000,000	Microamperes
Amperes	× 1,000	Milliamperes
Cycles	× .000,001	Megacycles
Cycles	× .001	Kilocycles
Farads	× 1,000,000,000,000	Micromicrofarads
Farads	× 1,000,000	Microfarads
Farads	× 1,000	Millifarads
Henrys	× 1,000,000	Microhenrys
Henrys	× 1,000	Millihenrys
Horsepower	× .7457	Kilowatts
Horsepower	× 745.7	Watts
Kilocycles	× 1,000	Cycles
Kilovolts	× 1,000	Volts
Kilowatts	× 1,000	Watts
Kilowatts	× 1.341	Horsepower
Megacycles	× 1,000,000	Cycles
Mhos	× 1,000,000	Micromhos
Mhos	× 1,000	Millimhos
Microamperes	× .000,001	Amperes
Microfarads	× .000,001	Farads
Microhenrys	× .000,001	Henrys
Micromhos	× .000,001	Mhos
Micro-ohms	× .000,001	Ohms
Microvolts	× .000,001	Volts
Microwatts	× .000,001	Watts
Micromicrofarads	× .000,000,000,001	Farads
Micromicro-ohms	× .000,000,000,001	Ohms
Milliamperes	× .001	Amperes
Millihenrys	× .001	Henrys
Millimhos	× .001	Mhos
Milliohms	× .001	Ohms
Millivolts	× .001	Volts
Milliwatts	× .001	Watts
Ohms	× 1,000,000,000,000	Micromicro-ohms
Ohms	× 1,000,000	Micro-ohms
Ohms	× 1,000	Milliohms
Volts	× 1,000,000	Microvolts
Volts	× 1,000	Millivolts
Watts	× 1,000,000	Microwatts
Watts	× 1,000	Milliwatts
Watts	× .001	Kilowatts

Courtesy: Hygrade Sylvania Corp.

Notes

(These extra pages are provided for your use in taking special notes)

Notes

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UNIT NO. 1

A STUDY OF GRAPHS AND SQUARE ROOT

LESSON NO. 8

JAMES WATT

..determined perseverance brought him glory and success.'

James Watt, the inventor of the steam engine, was born in the modest little town of Greenock, Scotland, in the year 1736. Like many other famous men of history, he, too, started life in an atmosphere of poverty and with the added handicap of delicate health. In his early life he showed an unusual interest in things of a mechanical nature and made an electrical machine that startled his friends with shocks. But the object of his greatest interest was the teakettle which spouted steam in the kitchen. Little did those who perhaps wondered at his interest in such a commonplace kitchen utensil realize that James and the teakettle were to startle the world with a new form of motive power.

When he was eighteen years of age, he went to Glasgow to learn the trade of making mathematical instruments, but meeting with no success, he finally went to work for a watchmaker so that he might learn his trade. He received no money for his work and was even required to pay the watchmaker one hundred dollars for a year's teaching. This he earned by doing odd jobs of a varied nature. Life became a dark, discouraging struggle and perhaps James never would have achieved success had he not met and married Margaret Miller, whom he loved dearly. Margaret cheered him in his darkest hours and fired his soul with fresh determination to conquer in spite of all.

The action of the teakettle still remained fresh in James' mind, and he experimented almost incessantly in an attempt to perfect an engine that would be driven by steam. People had little or no faith in his idea and refused to help him. Even when he went to London for his patent, the officials were indifferent. Then, just when it seemed as though James were doomed to failure, a wealthy manufacturer became interested in his engine and was finally induced to manufacture them. The first engine was built. It worked amazingly well. Orders began to come in for other engines. The Russian Government offered James the then staggering sum of $5,000 a year if he would come to Russia. Success, the reward of determined perseverance, had come to him at last! Other troubles beset him as the years passed, but they failed to diminish the brilliance of his achievements.

Today, James Watt is regarded as one of the greatest inventors of all ages.....a man possessed with an indomitable spirit to win.....the kind of spirit that can bring you success, happiness and financial security!

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Lesson Eight

A STUDY of GRAPHS and SQUARE ROOT

"It is important for every student of Radio and Television to have a thorough understanding of graphs. It is the graph that gives you a technical "picture" of the functioning of the various components which constitute Radio and Television circuits.

The second part of this lesson is devoted to a simple and straightforward method of extracting the square root of a number.

I am sure that you will find these two subjects easy to comprehend."

PART I. GRAPHS

A graph is a picture of a series of events. It is a time saver used by all engineers. There are very few people who have never seen a graph since their use is so universal that even the daily newspapers employ them to show changes in the stock market and in business trends throughout various periods of time. From a graph a person can see certain conditions at a glance which would require considerable time to comprehend if the same information was given in a table. The preparation of a graph may involve considerable time, but the information it conveys can be quickly observed. Since graphs are so extensively used, a knowledge of their construction and interpretation will enable the student to understand more clearly the various phases of Radio and Television.

It is the purpose of this lesson to present the general construction of graphs and to show the student the time and effort that can be saved by using graphs in preference to tables of lengthy explanations concerning the same information.

1. **GENERAL APPEARANCE.** A graph is constructed upon a piece of paper which is ruled into a number of horizontal and vertical lines. These lines are all equal distances apart, so that they form many small squares. Ordinarily every fifth line is heavier than the others and these heavier lines form larger squares. Paper of this kind is called coordinate or cross-section paper and can

be obtained in various size sheets with large or small squares according to the purpose for which it is to be used.

The type of graph used almost exclusively in the study of Radio and Television is called a "rectilinear" graph. It is constructed upon a pair of perpendicular lines or axes. Fig. 1 shows

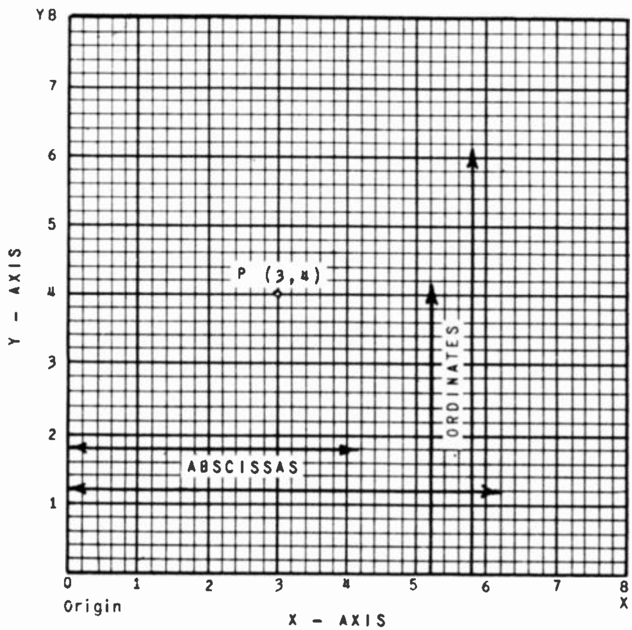


Fig.1 Illustrating the co-ordinate axes. The co-ordinates of point P are (3, 4).

the two axes. The horizontal line is labeled OX and the vertical line is labeled OY. Their point of intersection is marked O and is known as the origin. It is the zero point from which all distances are measured. The horizontal line is usually called the X axis and the vertical line is known as the Y axis. The X axis is also called the axis of abscissas and the Y axis, the axis of ordinates.

The spaces on the coordinate paper are assigned values in accordance with the data supplied with the problem. Since these values will vary greatly, they must be chosen to suit the requirements of the particular problem at hand. The figures given in the problem must be carefully studied in order that the spaces may be assigned suitable values.

Fig. 2 is a simple graph which illustrates the temperatures taken every hour on a February day. The bottom horizontal line is the X axis and the vertical line to the left of the figure is the Y axis. The X axis represents the hours and the Y axis the degrees of heat. The point of origin, in this case, is not at 0, but at 20 since there is no need for lower values of degrees than 20. Notice that each small square along the X axis represents one-half hour. Along the vertical axis each small square represents one degree.

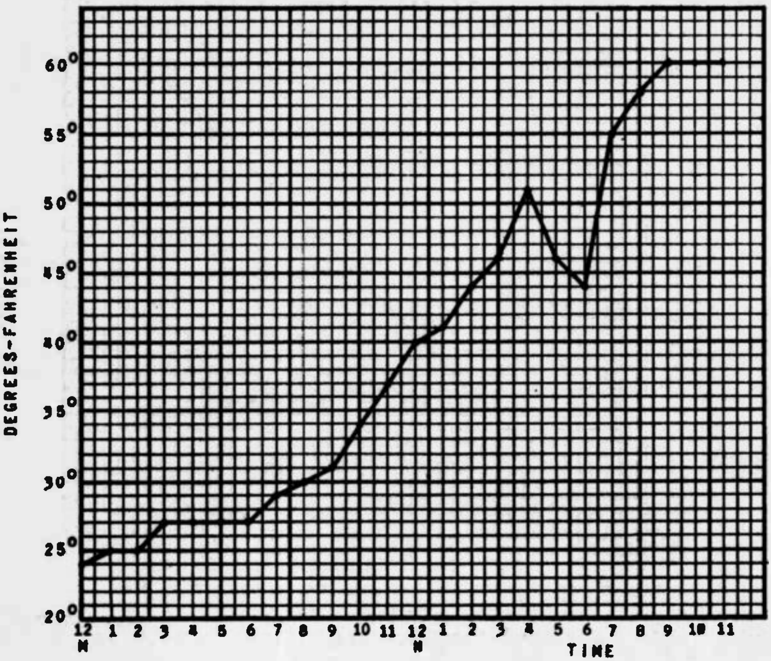


Fig.2 Chart showing the temperature in degrees over a 24-hour period.

A list of temperatures for all the twenty-four hours was needed to make this graph. To read all this data and to compare the temperatures at various hours would require several minutes. A single glance at the graph is sufficient to see the movement and temperature range for the entire time.

Suppose that a man is driving an automobile at a speed of 20 miles an hour. The distance covered in one hour is 20 miles, in two hours, 40 miles, etc. This information can be put in graphical form as illustrated in Fig. 3. The bottom horizontal line is the X axis and the vertical line at the left is the Y axis. In this case, their intersection is the origin. The X axis represents the hours and the Y axis the distance traveled. One large square on the X axis represents one hour and each small square one-fifth of an hour. On the Y axis each large square represents 20 miles and each small square 4 miles. Notice that the graph is a straight line.

2. DRAWING LINE GRAPHS. From the preceding discussion, it is apparent that each point of a graph is located by using two known quantities, one to be located on a horizontal line and one on a vertical line. By connecting the various points, a line is obtained which clearly indicates the information contained in the written data.

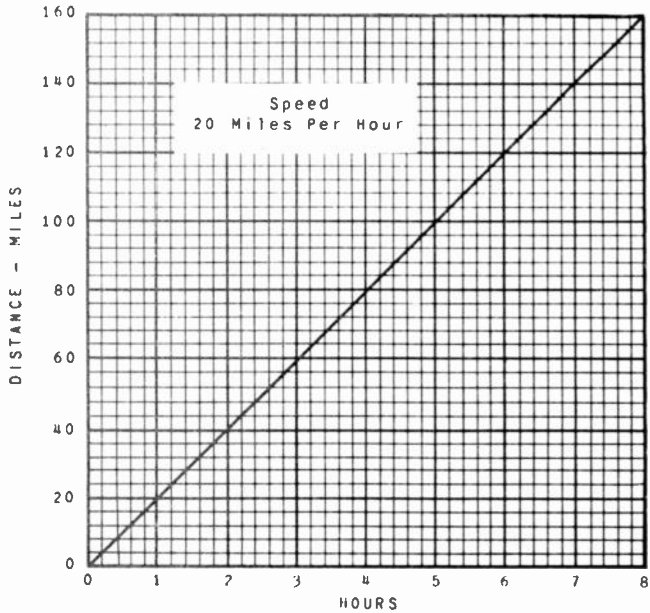


Fig.3 Graph showing that the distance covered by an automobile, traveling at a constant speed, varies directly with the elapsed time.

Distances measured along the X axis are called abscissas and distances measured along the Y axis are called ordinates. The process of placing the points on the graph is known as "plotting". To plot any point, we must know the abscissa and ordinate of that point. These two values are known as the coordinates of the point and are indicated by writing the figures within a pair of parentheses and placing a comma between them as shown in Fig. 1. Let us plot the point whose coordinates are (3,4). The X and Y axes of Fig. 1 are divided into convenient units; in this case, each large square represents one unit. The abscissa of the point is 3 and the ordinate is 4; therefore, place your pencil at the point marked 3 on the X axis. From there move the pencil up along this vertical line until it is opposite the point marked 4 on the Y axis. Mark this point with a dot; it is the one sought.

The following illustrative examples show in detail the exact method used to plot graphs.

Example 1: The hourly temperatures throughout a 24 hour period are given by the following table:

12:00	Midnight	24° F.	12:00	Noon	40° F
1:00	A.M.	25°	1:00	P.M.	41°
2:00	"	25°	2:00	"	44°
3:00	"	27°	3:00	"	46°
4:00	"	27°	4:00	"	51°
5:00	"	27°	5:00	"	46°
6:00	"	27°	6:00	"	44°
7:00	"	29°	7:00	"	55°
8:00	"	30°	8:00	"	58°
9:00	"	31°	9:00	"	60°
10:00	"	34°	10:00	"	60°
11:00	"	37°	11:00	"	60°

Put this information in the form of a graph.

Solution.

Step 1: *To assign values to the spaces on the coordinate paper which are suitable for the problem.* The two quantities are hours and degrees. Let us plot the hours along the X axis. There are 24 of them and, therefore, too many to let a large square represent 1 hour. We will represent 1 hour by 2 small squares; thus each small square is equal to ½ hour. These values are marked along the horizontal axis as shown in Fig. 2.

The number of degrees range from 24 to 60; therefore, we will let each small square along the vertical axis represent 1 degree. Starting from 20 degrees, these values are marked along the Y axis.

Step 2: *To locate the points.* By reference to the table we see that the temperature at midnight was 24. A pencil is placed at the point marked midnight, which is at the extreme left of the X axis. From there, it is moved up along this vertical line until it is exactly opposite 24 degrees on the Y axis. A dot is made at this point; it is the first point of the graph.

The next information in the table is that the temperature at 1:00 A.M. was 25 degrees. The pencil is placed at the point marked 1:00 A.M. on the X axis and is moved up along this vertical line until it is opposite the point marked 25 degrees on the Y axis. This point is marked with a dot; it is the second point of the graph.

By exactly the same method, the other points of the graph are located from the information given in the table. There are 24 points in all.

Step 3: *The points are now joined in order with a line.* The finished graph should look like Fig. 2. The graph is called a "curve" whether it actually is a curve, a series of straight lines, or one straight line.

Example 2: Suppose we had set up a circuit such as shown in Fig. 4. This circuit contains a 10 ohm resistor, an ammeter, a voltmeter, a 100-volt battery and a potentiometer. By varying the position of the potentiometer arm, any voltage between 0 and 100 volts can be applied to the resistor. It is first moved until the voltmeter reads 10 volts, at which time the reading of the ammeter

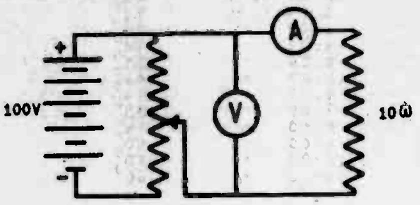


Fig.4 Electrical circuit from which data for graph shown in Fig.5 is obtained.

is recorded. By increasing the voltage in 10-volt steps and recording the amount of current flowing at each step, the following table is constructed:

VOLTAGE	CURRENT
0 Volts	0 Amperes
10 "	1 "
20 "	2 "
30 "	3 "
40 "	4 "
50 "	5 "
60 "	6 "
70 "	7 "
80 "	8 "
90 "	9 "
100 "	10 "

Put this information in graphical form.

Solution:

Step 1: *Place the scales on the graph.* (See Fig. 5.) It is possible to plot the voltage on either the X or Y axis; however, it is customary to plot on the X axis the factor which is being changed (the voltage), and on the Y axis the factor which results from these changes (the current).

The voltages range from 0 to 100; therefore, we will let each large square represent 10 volts and each small square 2 volts. These values are marked on the X axis. The currents range from 0 to 10 amperes and we can let each large square equal 1 ampere and each small square, .2 ampere. These values are marked on the Y axis.

Step 2: *Locate the points on the graph.* Notice that in this graph the intersection of the axes is the origin. By reference to the table, it is seen that when the voltage is zero, the current is zero; therefore, the origin is the first point of the graph. When the voltage was 10 volts, the current was 1 ampere. Place a pencil at the point marked 10 volts on the X axis and move it up along this vertical line until it is opposite the point marked 1 ampere on the Y axis. Make a dot at this point; it is the second point of the graph. In a similar manner, plot the remaining points.

Step 3: *Connect the points by lines.* It is seen that one straight line will join all of the points; therefore, this "curve" is a straight line.

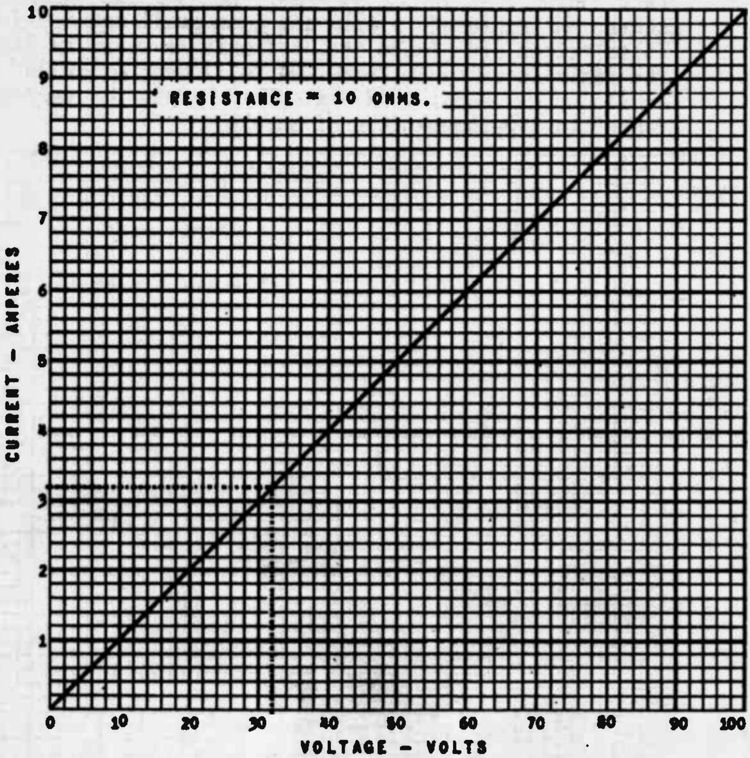


Fig.5 Graph showing the voltage plotted against the current. Data for this graph was obtained from Fig.4.

Step 4: *Write the constants on the graph.* The constants are those values which do not change during the experiment. In this case, the constant is the 10 ohm resistor. It does not change its resistance as the voltage and current change. This is necessary so that others may know under what conditions the experiment was conducted.

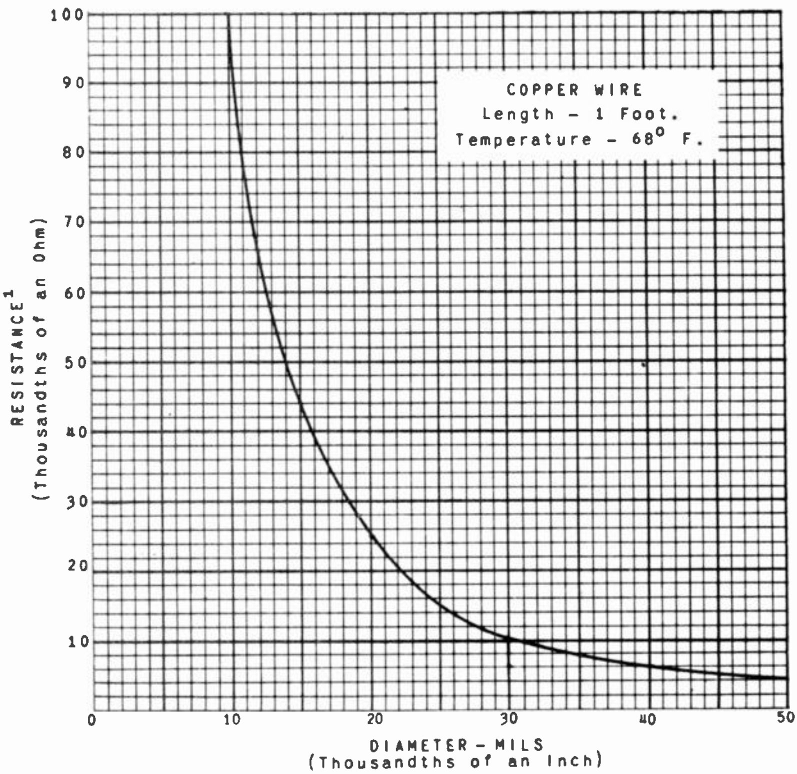
Example 3: From a copper wire table, the resistance of 1 foot of copper wire of various diameters was obtained. This information is contained in the following table:

DIAMETER	RESISTANCE
10 Mils (.01 inch)	.1 Ohm
20 "	.025 "
30 "	.01 "
40 "	.006 "
50 "	.004 "

Use this information to plot a graph.

Solution:

Step 1: *Choose suitable scales for the two quantities.* The diameters range from 10 to 50 mils. Let us use each large square to represent 5 mils and each small square, 1 mil. These values are placed on the X axis as shown in Fig. 6. The resistances range from .004 to .1 ohm; we can let each small square equal .002 ohm. The Y axis is marked off from 0 to 100-thousandths of an ohm.



[1] One-thousandth of an ohm equals .001; hence, 100-thousandths of an ohm equals .001 times 100 or .1 of an ohm; 25-thousandths of an ohm equals 25 times .001 or .025 of an ohm; etc.

Fig.6 Graph illustrating that the resistance of a conductor varies inversely with the diameter.

Step 2: *Locate the points on the graph.* From the table it is seen that a 10 mil wire has a resistance of .1 ohm. A pencil is placed at 10 on the X axis and is moved up along this vertical line until it is opposite 100 (.1 ohm) on the Y axis. A dot is placed at this point; it is the first point of the graph. The other 4 points are found in the same manner. Note that .025 and .01 are 25 and 10-thousandths of an ohm, respectively.

Step 3: *These points must now be joined by a smooth curve.* Since the curve in this case is not a straight line, we cannot use a ruler to join the points. It can be done free hand, or a "French curve" such as shown in Fig. 7 may be used. With the type of curve shown in Fig. 2, it is permissible to join the points together by short, straight lines, since the variation of temperature is somewhat irregular. However, when the plotting of the points indicates that the curve is following some general law, then a smooth curve (that is, a curve that does not have any breaks in it), must be used to join the points together. There will probably be some points which lie to one side or the other of the curve. It can be assumed that these points are a result of errors in the experimentation.

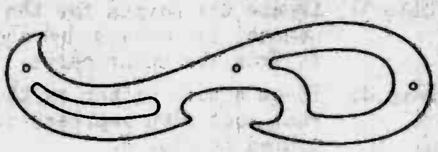


Fig.7 Outline of a "French curve". This instrument is for the purpose of drawing a smooth curve through several points.

Step 4: *Place the constants on the graph.* In this case they are the material of the wire, copper; the length of the wire used, 1 foot; the temperature at which the resistances were measured, 68° F.

Example 4: It is sometimes convenient to compare two quantities by drawing two or more curves on the same graph. This involves no new principle, but care must be taken that the values assigned to the spaces are suitable for both sets of data. The following table gives the number of telephone calls for each hour between 7 A.M. and 9 P.M. in the business district and the residential district of a city. Use this information to plot two curves which show a comparison between these calls.

HOUR	CALLS IN BUSINESS DISTRICT	CALLS IN RESIDENTIAL DISTRICT
7 A.M.	100	100
8 "	200	700
9 "	900	3,000
10 "	6,000	6,800
11 "	10,500	7,000
12 Noon	10,000	6,400
1 P.M.	8,000	6,000
2 "	7,400	4,800
3 "	9,500	4,500
4 "	8,500	4,000
5 "	6,000	3,500
6 "	3,400	3,400
7 "	1,500	3,200
8 "	400	3,000
9 "	200	2,000

Solution:

Step 1: Assign suitable values to the spaces on the axes for the two quantities, which are hours and calls. There are 15 hours ranging from 7 A.M. to 9 P.M. These are placed along the X axis as shown in Fig. 8. Each large square equals 1 hour.

The number of calls extends from 200 to 10,500; therefore, it will be best to use one thousand as the unit. We can let each large square along the Y axis represent 1,000 calls and each small square 200 calls.

Step 2: Locate the points for the calls in the business district by the method used in previous examples. Since the variation of calls is irregular, the points can be connected by short, straight lines.

Step 3: Locate the points for the calls in the residential district. Connect the points by short, **dotted** lines to distinguish it from the other curve.

Step 4: Place a note either on the graph or on the lines to show what each line represents. The finished graph is illustrated in Fig. 8.

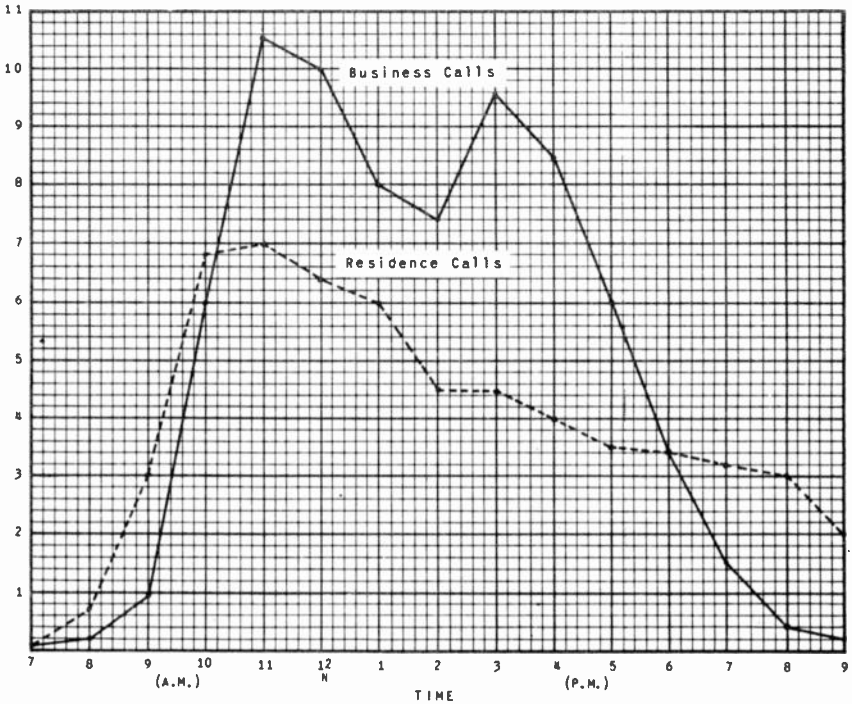


Fig. 8 Graph illustrating the number of telephone calls in the business and residential districts of a city during a 14-hour period.

3. PLOTTING NEGATIVE NUMBERS. Sometimes the data obtained in an experiment contains negative numbers. For example, if the temperature readings were taken on a very cold day, it is possible that some of them would be below zero. Temperatures below zero can be represented by negative numbers; thus 10 degrees below zero can be written -10 degrees F. When the data contains negative numbers, the method of plotting is exactly the same, but the scales along the axes must be different. Suppose the temperature range obtained is from -15 degrees F to +15 degrees F. The positive numbers, of course, indicate temperatures above zero. If these values are to be plotted along the Y axis, the point of intersection of the axes is marked -15, the next small square above is marked -14 and so on

until 0 is reached. Above 0, the values assigned to the squares increase from 1 to 15. A graph of this type is shown in Fig. 9. Many of the graphs used in Radio and Television have negative numbers and are constructed in this manner.

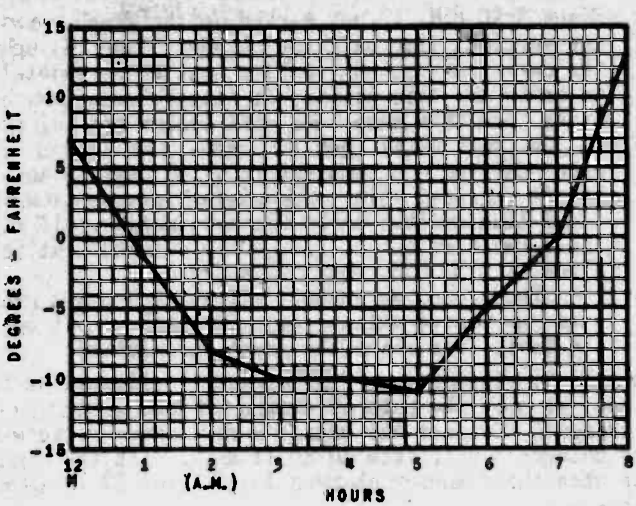


Fig.9 Graph illustrating the use of negative numbers. It shows the temperatures during an 8-hour period.

4. INTERPRETING GRAPHS. We shall now inquire into the usefulness of a graph. Graphs are especially useful for determining intermediate values not found in the experiment performed to obtain the data. They also show very clearly the rate of increase or decrease of one factor as the other factor is changed. Furthermore, a graph can, many times, save an immense amount of calculation. Several examples will be given which illustrate these properties of graphs.

Example 1: Determine from Fig. 2 the temperatures at 8 A.M.; 2:30 P.M.; 3:30 P.M.

Solution:

Step 1: The reading of values from the graph is the reverse of locating the points on the graph. We have the curve and one quantity and it is required to find the other quantity.

Place a pencil at the point marking 8 A.M. on the X axis and move it up along this vertical line until you reach the curve. Then follow the horizontal line which intersects the curve at this point to the left until you reach the Y axis and notice the value at this point. It is found to be 30 degrees. Therefore, the temperature at 8 A.M. was 30 degrees.

Step 2: Notice that there is no point on the X axis marked 2:30 P.M. We assume, however, that 2:30 is half way between 2 and 3. Therefore, follow the vertical line which is half way between 2 and 3 upward until it intersects the curve.

From this point, move along the horizontal line to the left until the Y axis is reached. Note that the value opposite this line is 45 degrees. The temperature at 2:30 P.M., therefore, was 45 degrees.

Step 3: Since 3:30 P.M. is not marked on the graph, we will follow the vertical line half way between 3 and 4, upward until the curve is reached. Notice that no horizontal line intersects at this point. It lies between two horizontal lines. In this case, we will follow both of these lines to the left until they intersect the Y axis. The lower line represents a temperature of 48 degrees and the upper one 49 degrees. Since the point of intersection of the vertical line and the curve is approximately half way between these two horizontal lines, it is assumed that the temperature at 3:30 P.M. was 48.5 degrees.

The preceding example illustrates how a graph can be used to locate values, especially those not contained in the table from which the graph was plotted.

Example 2: The graph of Fig. 6 clearly illustrates how a graph may be used to show the rate of change of one factor as the other one is changed. Compare the change in resistance of the wire as its diameter changes 1 mil, from 10 to 11 mils, with the change in resistance when the diameter changes 1 mil, from 22 to 23 mils.

Solution:

Step 1: By the same method used in the preceding example, the resistance of the wire at 10 mils is found to be 100-thousandths (.1) ohm and at 11 mils, approximately 80-thousandths (.08) ohm. Thus a change of 1 mil has produced a change of 20-thousandths (.02) ohm.

Step 2: In a like manner, it is found that the resistance of the wire at 22 mils is 20-thousandths (.02) ohm and at 23 mils, 18-thousandths (.018) ohm. In this case, it is seen that a change of one mil has produced a change of 2-thousandths (.002) ohm.

Step 3: Note that the change in resistance produced by a one mil change in diameter depends upon the diameter of the wire before this change is made. Thus a change of 1 mil, when the diameter is 10 mils, causes 10 times as much change in resistance as the same 1 mil change causes when the diameter is 22 mils. Or, a 20-thousandths ohm change is 10 times as large as 2-thousandths.

Example 3: By use of the graph in Fig. 5, determine how much current flows through the 10 ohm resistor when the applied voltage is 32 volts. Also, find the voltage needed to force a current of 5.2 amperes through this resistor.

Solution:

Step 1: Find the point marked 32 on the X axis and follow this vertical line up until it crosses the curve. From here, follow the horizontal line to the left and note that this line crosses the Y axis at 3.2 amperes. This, therefore, is the current that flows, due to this applied voltage. The dotted lines in the figure show how this value was found.

Step 2: Find the point representing 5.2 amperes on the Y axis. This is evidently one small square above the point marked 5. Move along this horizontal line to the right until the curve is reached. From this point, follow the vertical line down to where it intersects the X axis. Note that this point represents 52 volts, which is the voltage required to force this current through the resistor.

In the preceding example, the values desired could have been found by using Ohm's Law. Often, however, the relationship expressed by a graph is such that it can be given only by a very complex algebraic equation. When this is the case, a graph is decidedly advantageous as it eliminates considerable mathematical calculation.

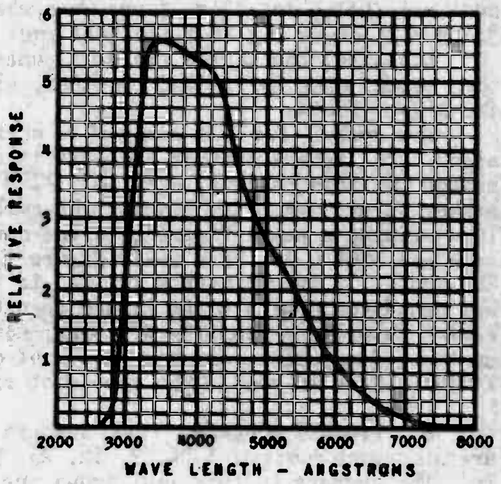


Fig.10 Graph showing the relative output of a cesium-magnesium photocell with light of various wavelengths.

A graph of this type is shown in Fig. 10. This graph is one of many used in Television work. It shows the response or output of one kind of photoelectric cell when light of various wavelengths is allowed to fall upon the cell. The equation which could be used to represent the relationship expressed by this graph would be so complicated that considerable time would be needed to calculate the response for a given wavelength. On the other hand, the graph makes this work relatively easy.

It is hoped that the foregoing discussion has made you conscious of the need for graphs in engineering work. We believe that you will find that a knowledge of this subject will be very profitable to you in your future study of Radio and Television.

PART II. SQUARE ROOT

Throughout your work in Radio and Television you will often find it necessary to take the square root of a number. This is a simple, straightforward process and will be explained in detail.

5. **DEFINITIONS.** *The square root of a number is one of the two equal factors which, when multiplied together, gives that number.* For example, $25 = 5 \times 5$. In this case, 5 is the factor which, when multiplied by itself, equals 25, the given number. Therefore, we say that the square root of 25 is 5. Other examples are: 16, whose square root is 4; 36, whose square root is 6, etc.

The cube root of a number is one of three equal factors which, when multiplied together, gives the number. For example 27 equals $3 \times 3 \times 3$, or we say that the cube root of 27 is 3.

Likewise, the fourth root of a number is one of four equal factors which, when multiplied together, gives the number, and so on for higher roots.

The symbol for the root of a number is called the "radical sign". The square root of a number is expressed by enclosing that number in this radical, such as: $\sqrt{100} = 10$. The cube root of a number is expressed by placing the number under the radical sign, then writing a small figure 3 in the opening of the radical sign, such as: $\sqrt[3]{64} = 4$. This small figure is known as the "index" of the root. It is ordinarily omitted in the case of the square root, but must be used with roots higher than the square root, as: $\sqrt[5]{243}$; $\sqrt[7]{129}$. In order to simplify printing, some modern textbooks on mathematical discussions may have the root of a number expressed thus: $\sqrt[3]{}(256)$. This is read, "The cube root of 256".

6. **PERFECT SQUARES.** The numbers 1, 2, 3, 4, 5, 6, 7, 8, 9, are the square roots of 1, 4, 9, 16, 25, 36, 49, 64, 81, respectively. The numbers in this last group are known as perfect squares, since the square root of each is a whole number and can be expressed exactly. This group includes all of the perfect squares less than 100. These perfect squares and their square roots should be learned since they will be used constantly in the process of extracting the square roots of larger numbers.

7. **METHOD FOR EXTRACTING THE SQUARE ROOT OF A PERFECT SQUARE.** This method may best be explained by working an example and explaining each step. It is strongly advised that in studying this process you actually do each step as you read it. Merely reading the steps will not be sufficient to fix them in your mind. It is only by writing each figure and step of the process that you will be able to learn the method of finding the square root. It is not essential that the principles underlying the process or the reasons for using the various steps be understood. These should be taken for granted and the process itself memorized.

Example 1: Find the square root of 70,225.

Solution:

Instruction	*Operation*

Step 1:

Separate the number into periods of two figures each, beginning at the right and place a curved line over each as indicated. The number of periods thus formed will be the same as the number of figures in the root or answer.

Step 1:

```
 ⌒ ⌒⌒ ⌒⌒
 7 02 25
```

Step 2:

Draw a line straight up and down at the left of the number and a broken line to the right as shown.

Step 2:

```
|7 02 25|______
```

Step 3:

Consider the first period at the left, 7. Determine the largest perfect square equal to or less than this period. It is seen to be 4. Place the 4 under the first period and write its square root, 2, to the right of the number. It is the first figure of the answer. Subtract the 4 from the 7, leaving a remainder of 3. Bring down the next period, 02, and place it beside the 3 as shown. This gives 302.

Step 3:

```
|7 02 25| 2
|4
|3 02
```

Step 4:

Take 2, the first figure of the root, multiply it by 2 and put the product, 4, to the left of 302, back of the up and down line. The 4 is called the trial divisor.

Step 4:

```
 |7 02 25| 2
 |4
4|3 02
```

Step 5:

Determine how many times 4 is contained in 30, the first two figures of 302. It is contained 7 times; therefore, 7 is the second figure of the root. Write this figure in the root and also to the right of the 4 (or the trial divisor), giving 47, (which is called the complete divisor) back of the up and down line. Now, multiply

Step 5:

```
  |7 02 25| 27
  |4
47|3 02
  |3 29
```

the 47 by the 7 just put in the root and write the product, 329, under the number 302. Note that the 329 is larger than the 302 and, therefore, cannot be subtracted from it. So the 7 used as the second figure of the root was too large. It is for this reason that the 4 was called the trial divisor. Since 7 was too great, we will try 6. Write 6 as the second figure of the root and to the right of the 4. Multiply 46 by 6 and write the product, 276, under the 302. Subtract 276 from 302, giving 26. Bring down the next period, 25, and place it beside the 26. This gives 2625.

```
    7 02 25 | 26
    4
46  3 02
    2 76
      26 25
```

Step 6:

Take 26, the root thus far obtained, and multiply it by 2. Write the product, 52, to the left of the 2625. The 52 is the second trial divisor.

Step 6:

```
    7 02 25 | 26
    4
46  3 02
    2 76
52    26 25
```

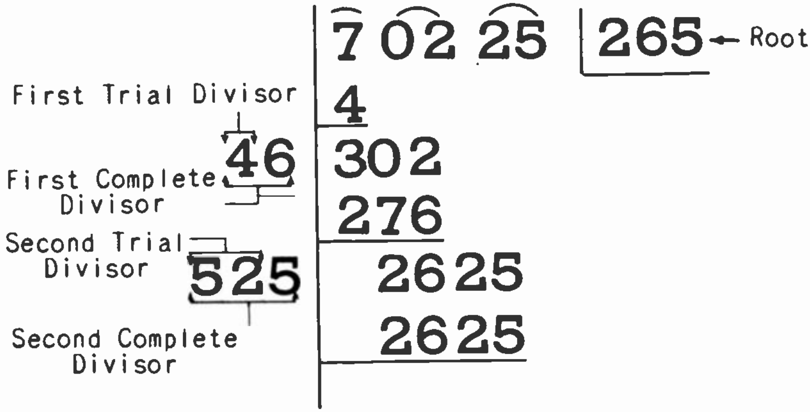
Step 7:

Determine how many times 52 is contained in 262, the first three figures of 2625. This is found to be 5. Write the 5 as the third figure of the root and also place it to the right of the 52, the trial divisor, making the complete divisor 525. Multiply the 525 by 5, the figure just placed in the root, and write the product, 2625, under the 2625. Since there is no remainder, the root is exact and the original number is a perfect square.

Step 7:

```
     7 02 25 | 265
     4
46   3 02
     2 76
525    26 25
       26 25
```

In conclusion, it is stated that the square root of 70,225 is 265, or $\sqrt{70,225} = 265$. To check your work, multiply 265 by 265; the result should be 70,225.



Example 2: Find the square root of 165,649.

Solution:

Instruction	*Operation*
Step 1: Separate the number into periods of two figures each, beginning at the right and place a curved line over each period.	**Step 1:** $\overset{\frown}{16}\ \overset{\frown}{56}\ \overset{\frown}{49}$
Step 2: Draw a vertical line at the left of the number and a broken line in which to place the root.	**Step 2:** | 16 56 49 |__
Step 3: Look at the first period of the root, 16, and determine the largest perfect square equal to, or less than, this period. This is found to be 16. Write the 16 under the first period and place its square root, 4, as the first figure of the root. When the 16 is subtracted from the first period, the remainder is 0. Bring down the next period, 56.	**Step 3:** | 16 56 49 | 4; 16; 56
Step 4: Multiply 4, the figure of the root by 2, and write the product, 8, as the trial divisor to the left of the vertical line.	**Step 4:** | 16 56 49 | 4; 16; 8 | 56

Step 5:

Find how many times 8 is contained in 5, the first figure of 56. It is contained 0 times; therefore, write 0 as the second figure of the root. Also, put 0 beside the trial divisor, giving 80. Bring down the next period, 49, and place it beside the 56, giving 5649.

Step 5:

```
    | 16 56 49 |_40
    | 16
 80 |    56 49
```

Step 6:

Determine how many times 80 is contained in 564, the first figures of 5649. This is found to be 7. Write 7 as the third figure of the root and to the right of the trial divisor, giving 807 as the complete divisor. Multiply the 807 by 7 and write the product, 5649, under the number 5649. There is no remainder; therefore, the root is exact and the number is a perfect square.

Step 6:

```
    | 16 56 49 |_407
    | 16
807 |    56 49
    |    56 49
```

The square root of 165,649 is, therefore, 407, or $\sqrt{165,649} = 407$.

Example 3: Find the square root of 332.6976.

Solution:

Instruction	*Operation*

Step 1:

When finding the square root of a number containing a decimal, the division of the number into periods is done by starting at the decimal point and marking off in both directions from the decimal point. The two figures of a period must never be separated by a decimal point.

Step 1:

```
3 32.69 76
```

Step 2:

Draw a vertical line at the left of the number and a broken line in which to place the root.

Step 2:

```
| 3 32.69 76 |___
```

Step 3:

The first period is 3. The greatest perfect square equal to, or less than 3 is 1; therefore, place 1 under the 3 and write its square root, 1, as the first figure of the answer. Subtract 1 from 3,

Step 3:

```
| 3 32.69 76 |_1
| 1
| 2 32
```

leaving 2. Bring down the next period, 32, and place it to the right of the 2, making 232.

Step 4:

Multiply the 1 in the root by 2 and place the product, 2, as the trial divisor.

Step 4:

```
  |3 32.69 76 |_1
  |1
 2|2 32
```

Step 5:

Determine how many times 2 is contained in 23, the first two figures of 232. This would appear to be 9, but by trial it is found that 8 is the largest number that can be used. Write 8 as the second figure of the root and also beside the trial divisor, giving 28 as the complete divisor. Multiply the 28 by 8 and write the product, 224, below the 232 and then subtract. The remainder is 8. Bring down the next period, 69, beside the 8, making 869.

Step 5:

```
   |3 32.69 76 |_18
   |1
 28|2 32
   |2 24
   |   8 69
```

Step 6:

Multiply the root thus far found, 18, by 2 and write the product, 36, as the trial divisor.

Step 6:

```
   |3 32.69 76 |_18
   |1
 28|2 32
   |2 24
 36|   8 69
```

Step 7:

The trial divisor, 36, is contained in 86, the first two numbers of 869, 2 times. Place 2 as the third figure of the root and beside the trial divisor making the complete divisor 362. Multiply the 362 by 2 and place the product, 724, below the 869. Subtract; the remainder is 145. Bring down the next period, 76, beside the 145, making 14576.

Step 7:

```
    |3 32.69 76 |_18.2
    |1
  28|2 32
    |2 24
 362|   8 69
    |   7 24
    |   1 45 76
```

We must now place the decimal point in the root. This is easily done by remembering that there will be as many figures in the whole part of the root as there are periods in the whole part of the number. There are two periods in the whole part of the number, 3 32; therefore, there will be two figures in the whole part of the root.

Step 8:

Multiply 182, the number thus far found in the root, by 2, giving 364. This is the trial divisor.

Step 8:

```
     3 32.69 76 | 18.2
     1
 28 | 2 32
    | 2 24
362 |   8 69
    |   7 24
364 |   1 45 76
```

Step 9:

The trial divisor, 364, is contained in 1457, the first four figures of 14576, 4 times. Write 4 as the fourth figure of the root and beside the trial divisor, making 3644 as the complete divisor. Multiply 3644 by 4, giving 14576. This is placed below the number, 14576, and since there is no remainder, the root is exact and the number is a perfect square.

Step 9:

```
      3 32.69 76 | 18.24
      1
  28 | 2 32
     | 2 24
 362 |   8 69
     |   7 24
3644 |   1 45 76
     |   1 45 76
```

Thus, the square root of 332.6976 is 18.24, or $\sqrt{332.6976} = 18.24$!

If the decimal part of a number contains an odd number of figures, a zero is added to the right to make a full period. For example, when dividing 26.234 into periods, a zero is added to the right of the 4 and the number will appear as 26.23 40.

8. **FINDING THE SQUARE ROOT OF A NUMBER WHICH IS NOT A PERFECT SQUARE.** Most of the numbers which we will encounter will not be perfect squares; that is, their square roots cannot be exactly expressed as whole numbers, nor can they be expressed exactly as decimals, no matter how many decimal places are taken. The square root of 2, when carried to three decimal places, is 1.414. This is not the exact square root; in fact, if it is carried to 15, or even 1,000 decimal places, it still will not be exact. Of course, the more decimal places to which it is carried, the closer the root approaches the exact value, but it can never be obtained.

Example 4: Find the square root of 42 to two decimal places.

Solution:

Instruction

Step 1:

Since there are to be two decimal places in the root, there must be two periods in the decimal part of the number. Therefore, add four zeros to 42, separate into periods and draw the lines as previously explained.

Operation

Step 1:

```
|42.00 00 |____
```

Step 2:

The first figure of the root is found to be 6. 36 is written below the first period and subtracted from it. The remainder is 6. Bring down the next period, 00, beside the 6.

Step 2:

```
    |42.00 00| 6
    |36
    | 6 00
```

Step 3:
Multiply the 6 of the root by 2 and place the product, 12, as the trial divisor.

Step 3:

```
    |42.00 00| 6
    |36
  12| 6 00
```

Step 4:

By trial it is found that the next figure of the root is 4. This is placed in the answer and beside the 12, making the complete divisor 124. The 124 is multiplied by 4 and the product, 496, is placed below the 600. The remainder is found to be 104. Bring down the next period, 00, beside the 104, making 10400.

Step 4:

```
    |42.00 00| 6.4
    |36
 124| 6 00
    | 4 96
    | 1 04 00
```

Step 5:

Multiply the 64 of the root by 2; place the product, 128, as the trial divisor.

Step 5:

```
    |42.00 00| 6.4
    |36
 124| 6 00
    | 4 96
 128| 1 04 00
```

Step 6:

The third figure of the root is found to be 8. This is written beside the trial divisor, making 1288. The 1288 is multiplied by 8 and the product, 10304, is written below the 10400. The remainder is 96.

Step 6:

```
     |42.00 00| 6.48
     |36
  124| 6 00
     | 4 96
 1288| 1 04 00
     | 1 03 04
     |      96
```

The remainder is disregarded since it would affect only the third and following decimal places. Result: $\sqrt{42} = 6.48$ (approx.)

9. **SQUARE ROOT OF A COMMON FRACTION.** *The square root of a common fraction is equal to the square root of the numerator divided by the square root of the denominator.* For example:

$$\sqrt{\frac{16}{25}} = \frac{\sqrt{16}}{\sqrt{25}} = \frac{4}{5}$$

If both numerator and denominator are small perfect squares, find the square root of the fraction by this method; however, if one or both are not perfect squares, then it is best to reduce the common fraction to a decimal, then extract the square root of the decimal fraction. For example, find the square root of $\frac{3}{8}$. Reducing $\frac{3}{8}$ to a decimal, we obtain .375! In order that we have three decimal places in the root, we must have three periods in the number; therefore, add three zeros to the right of the .375, making it .375000! The square root of this number is found to be .612! (Check this.) Of course, it would be possible to find the square root of 3, then find the square root of 8 and divide the former by the latter to obtain the same result. This, however, requires the extraction of two square roots, so it is a longer process and unnecessary.

Table of Useful Reference Numbers

1 cu. ft. of water weighs 62.5 lb. (approx.) = 1000 oz.
1 gal. of water weighs $8\frac{1}{3}$ lb. (approx.).
1 atmosphere pressure = 14.7 lb. per sq. in. = 2116 lb. per sq. ft.
1 atmosphere pressure = 760 mm of mercury.
A column of water 2.3 ft. high = a pressure of 1 lb. per sq. in.
1 gal. = 231 cu. in. (by law of Congress).
1 cu. ft. = $7\frac{1}{2}$ gal. (approx.) or, better, 7.48 gal.
1 cu. ft. = $\frac{4}{5}$ bu (approx.).
1 bbl. = 4.211 − cu. ft. (approx.).
1 bu. = 2150.42 cu. in. (by law of Congress) = 1.24446 − cu. ft.
1 bu. = $\frac{5}{4}$ cu. ft. (approx.).
1 perch = $24\frac{3}{4}$ cu. ft. but usually taken 25 cu. ft.
1 in. = 25.4001 mm (approx.).
1 ft. = 30.4801 cm.
1 m = 39.37 in. (by law of Congress).
1 lb. (avoirdupois) = 7000 grains (by law of Congress).
1 lb. (troy or apothecaries) = 5760 grains.
1 gram = 15.432 grains.
1 kg = 2.20462 lb. (avoirdupois).
1 liter = 1.05668 qt. (liquid) = 0.90808 qt. (dry).
1 qt. (liquid) = 946.358 cc. = 0.946358 liter, or cu. dm.
1 qt. (dry) = 1101.228 cc. = 1.101228 liters, or cu. dm.
$\pi = 3.14159265358979+ = 3.1416 = \frac{355}{113} = 3\frac{1}{7}$ (all approx.).
1 radian = 57°17′ 44.8″ = 57.2957795°+.
1° = 0.01745329 + radian.
Base of Napierian logarithms = e = 2.718281828 . . .
$\log_{10} e$ = 0.43429448 . . .
$\log_e 10$ = 2.30258509 . . .
1 horse-power second = 550 foot-pounds.
1 horse-power minute = 33,000 foot-pounds.

$\sqrt{2} = 1.4142136$.	$\sqrt{3} = 1.7320508$.
$\sqrt{5} = 2.2360680$.	$\sqrt{6} = 2.4494897$.
$\sqrt[3]{2} = 1.2599210$.	$\sqrt[3]{3} = 1.4422496$.

Notes

(These extra pages are provided for your use in taking special notes)

Notes

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MIDLAND RADIO
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SCHOOLS
INC.

POWER & LIGHT BUILDING, KANSAS CITY, MISSOURI

UNIT NO. 1

MAGNETS AND ELECTRO-MAGNETISM

LESSON NO. 9

INDEPENDENCE

The man who is financially independent is most fortunate.

The fourth of July, 1776, was a momentous day for every American citizen, for it was on that day that the Fathers of our great country attached their signature to the world-famous document that ushered in a new era of free thought and Government.....the Declaration of Independence! Then for seven, long, war-torn years, the American Colonists fought valiently against great odds for that which was rightfully theirs....."a Government by the people, for the people and of the people". Finally, after years of terrible suffering, their will to win was victorious and Great Britain acknowledged American Independence with the signing of the Treaty of Peace on September the third, 1783.

No doubt you are familiar with the history of the epochal period which we have so briefly outlined above .....but.....*do you realize that YOU, TOO, face a battle for independence.....the battle of life!* Individual independence from financial worries, poverty and the dull monotony of routine unskilled labor is entirely dependent upon several closely related factors. We will outline them for you on this page.

AMBITION

Ambition is the bitter foe of failure. Arm yourself to the teeth!

FORESIGHT

George Washington selected his battle fields with care. You want to fight your battle of life where your chances of success will be the greatest. That is why you have selected the Radio-Television industry!

DETERMINATION

When you have selected your battle field (industry), you must arm yourself with "bull-dog determination" to prepare for and win success in your chosen field!

TRAINING

Today, poorly trained troops would have little chance of victory over an opposing army that was highly trained. You *must* train yourself. You must develop *Will Power* so that you can fight off discouragement and overcome every obstacle that may confront you. Training is your heavy artillery!

You already have the ambition, foresight and determination. Midland is supervising your training. *See that you stick to that training so that you will be better equipped to win your battle of life and...... FINANCIAL INDEPENDENCE!*

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Lesson Nine

MAGNETS AND ELECTRO-MAGNETISM

"Magnetism.....an invisible but powerful force that attracts and repels, is a subject that you should understand thoroughly. To successfully explain the phenomenal action of the different kinds of coils that are used in modern Radio receivers and transmitters, it is necessary that I refer to the theory of magnetism frequently.

"The generation of electricity is dependent upon magnetism: therefore, the amazing growth of the Electrical, Radio and Television industries would have been an impossibility had it not been for the discovery of magnetism. Because of its importance, I earnestly suggest that you carefully study the fundamentals given in this lesson."

The fact that a particular rock or mineral called "lodestone" attracts to itself small particles of the same material has been known for many centuries. Lodestone, in appearance, is reddish-brown and is one form of iron-ore. It is found throughout many parts of the world, but is, by no means, as abundant as other forms of iron-ore which do not possess this peculiar property. Since it was especially plentiful in the neighborhood of Magnesia, a town in Asia Minor, it was called "magnetite" by the ancient Greeks. If a piece of lodestone is dipped into iron filings, it is found that they adhere to it more particularly at certain places. In general, there are two such places on any piece of lodestone where the filings stick in the greatest quantities. (See Fig. 1.) These two spots are known as the **poles of the magnet**. If a piece of lodestone is suspended by a silk thread, it does not come to rest in just any chance position, but only in such a position that the line joining the two points where the filings adhere in the greatest quantities points north and south. (See Fig. 2.)

Fig.1 Illustrating the attraction of Lodestone or Magnetite for Iron Filings.

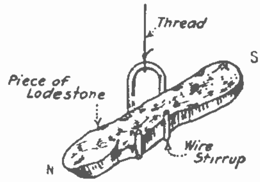


Fig.2 Using a piece of Lodestone as a Compass.

1. NATURAL AND ARTIFICIAL MAGNETS. Such a piece of lodestone is known as a natural magnet. Natural magnets are, in general, not used for commercial purposes; however, before the process of making artificial magnets was discovered, they were sometimes employed as a crude type of compass. One of the most important characteristics of these natural magnets is their ability to magnetize other magnetic bodies. For example, it is possible to magnetize a steel darning needle by stroking it in one direction with a piece of magnetite (lodestone). The piece of magnetite may then be used to magnetize a second or a third needle, since it does not lose any of its own magnetism in this process. A magnet made by this method is called an artificial magnet and its magnetic properties can be illustrated by the fact that it attracts iron filings as shown in Fig. 3. A magnetized needle produced in this manner may be used

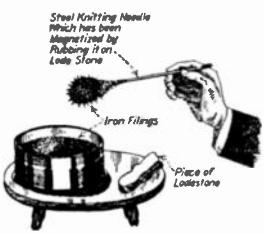


Fig.3 Using one Magnet to make another.

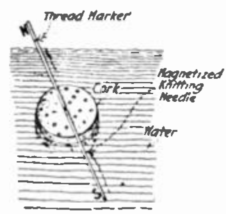


Fig.4 Darning Needle Compass.

to magnetize other needles by stroking them with the magnetized needle. A method used commercially for the manufacture of artificial magnets will be explained later in this lesson.

If a steel knitting needle is magnetized in the manner just described and is then carefully balanced upon a cork floating in a glass of water, the cork and needle will turn until the axis of the needle is in a north and south direction. This is shown in Fig. 4. If the glass of water is turned until that end of the needle which was pointing toward the north now points directly southward, the needle and cork will rotate until this end of the needle is again pointing north. In fact, no matter how many times the needle is moved from its position of rest, it always rotates until the same end is pointing north. This is the principle of the magnetic compass. It consists of a magnetized needle carefully pivoted at its exact center upon jewel bearings. It is enclosed in an airtight case to protect it from air currents and it rotates over a scale graduated in degrees. The end of the needle pointing toward the north is called the "north seeking pole", while the opposite end is called the "south seeking pole". These two terms are usually shortened to "north pole" and "south pole".

2. MAGNETIC ATTRACTION AND REPULSION. It has been shown that a magnet attracts iron filings. This power was known for many centuries before it was discovered that under certain conditions a magnet exerts a repelling force instead of an attracting force. This can be very easily demonstrated. If a bar magnet, which has its poles marked for reference, is brought into the vicinity of a pocket compass, it is noticed that the north pole of the magnet attracts the south pole of the compass and at the same time repels the north pole of the compass. This force of repulsion may be clearly seen if the north pole of the magnet is rapidly brought close to the north pole of the compass. The compass needle immediately rotates until its north pole is as far from the magnet as possible. If the compass used in this experiment is not enclosed, as shown in Fig. 5,

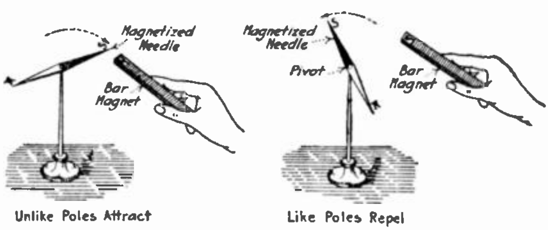


Fig. 5 Illustrating the Laws of Magnetic Attraction and Repulsion.

one can try to hold these two north poles together and in so doing, the force which is tending to push them apart may be perceived. In a like manner, it can be shown that the south pole of the bar magnet attracts the north pole and repels the south pole of the compass.

These forces of attraction and repulsion exist between any two magnets. It may be used to determine whether or not a piece of iron or steel is magnetized. The fact that a body attracts the compass needle is not sufficient proof that it is magnetized, since a magnet will attract unmagnetized pieces of iron and steel. If the body in question attracts one end of the compass needle and repels the other end, the body is magnetized, since the force of repulsion is possible only between two magnetized bodies.

From the preceding discussion, we can formulate a general law relative to the magnetic forces of attraction and repulsion. It is:

1. *Like poles repel each other.*
2. *Unlike poles attract each other.*

Thus, a north pole always repels a north pole and a south pole always repels a south pole. On the other hand, a north pole attracts a south pole. Notice that this law is very similar to the one concerning the attraction and repulsion existing between electric charges. We learned that the negative electron attracts the positive proton, but repels all other electrons.

3. **THE EARTH AS A MAGNET.** The earth has the ability to attract one end of the compass needle and repel the other end. We may then suspect the earth itself to be a magnet. This theory has been proved. The earth is a huge magnet, much thicker in proportion to its length than most magnets with which we are familiar, but otherwise just exactly like them. The earth has a north seeking pole and a south seeking pole, just like any other magnet, but from the laws of attraction and repulsion, we see, curiously enough, that the south seeking pole is in the Arctic regions, while the north seeking pole is in the Antarctic regions, not far from Little America. These magnetic poles do not coincide exactly with the north and south geographical poles, but are located as shown in Fig. 6. Furthermore, the positions of the magnetic poles are known to

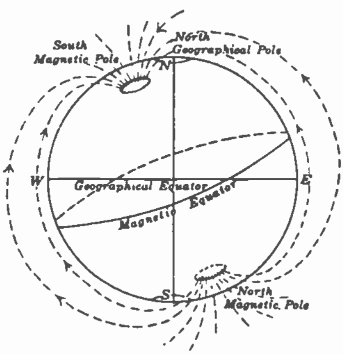


Fig.6 Showing the Location of the Magnetic Poles in Relation to the Geographical Poles.

be changing slowly from year to year. Why this is so, and, for that matter, why the earth is magnetized at all, is not yet known.

4. **THE FIELD AROUND A MAGNET.** Michael Faraday was the first to conceive that a true understanding of the actions of a magnet could be secured by studying the empty space around one as well as the magnet itself.

Artificial magnets may be divided into two classes, permanent and temporary magnets. Permanent magnets are those which retain a certain amount of their magnetism after the magnetizing force has been removed. We are all familiar with two forms of permanent magnets, one of which is the bar magnet and the other is the horseshoe magnet. If we place a sheet of stiff paper over a bar magnet and then sprinkle some iron filings on this sheet, we will discover, upon tapping this sheet that the iron filings arrange themselves in regular lines leading from one pole of the magnet through the air to the opposite pole. This is due to the fact that each filing is slightly magnetized by the influence of the original magnet and, therefore, places itself in the direction in which a compass needle would point if it were in the same spot. This can be verified by actually using a small compass instead of the filings. Fig. 7 shows the distribution of filings around a bar magnet. In Fig. 8, we see these lines about a horseshoe magnet. *These lines are known as magnetic lines of force and the vicinity about a magnet in which they lie is known as the "field" of the magnet.* A magnetic line of

Fig.7 Arrangement of Iron Filings around a Bar Magnet.

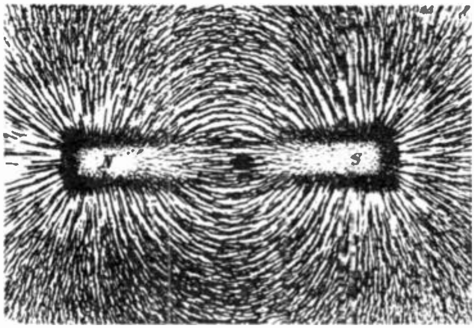
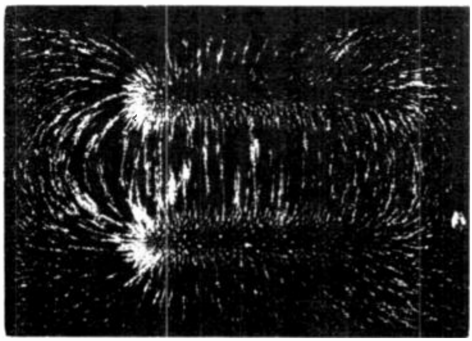


Fig.8 Arrangement of Iron Filings around a Horseshoe Magnet.



force may be defined as *a line which indicates at its every point the direction in which a north seeking pole would be moved by the attraction and repulsion of all the poles in the neighborhood.* We shall find this conception of magnetic lines of force a convenient way of remembering how a magnet will affect other magnets in its vicinity.

A magnetic line of force is visualized as emerging from the north pole of a magnet, traveling through the surrounding air, entering the south pole of the magnet and then traversing the magnet from the south pole to the north pole. It is customary to place small arrows on the lines of force showing the direction in which they travel, as shown in Fig. 9.

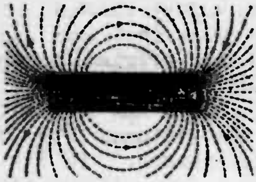


Fig.9 Illustrating the Direction of the Lines of Force Around a Bar Magnet.

It must be remembered that these lines are merely representations of the direction of attraction or repulsion at any point in the field and it should not be imagined that it would be possible to place a small piece of iron or steel in between two lines and that it would not experience any force; that is, the magnetic force is present at every point in the field. It is, however, customary to represent the strength of the field at any point by the number of lines passing through a small area around that point. Or, we may say, that if the lines are fairly close together at that point, the field is relatively strong, while if the lines are somewhat widely spaced, the field is rather weak. Fig. 10 illustrates a weak and a strong magnetic field.

Fig.10 (A) A Weak Magnetic Field. (B) A Strong Magnetic Field.

These magnetic lines of force act very much like a bundle of stretched rubber bands; that is, they are, at all times, trying to shorten their length. Also, each line exerts a sidewise crowding effect upon its neighbors. This fact helps us to understand the forces of magnetic attraction and repulsion. In Fig. 11 are shown two bar magnets placed end to end with the north pole of one near the south pole of the other. The figure also shows the magnetic field about the two magnets. It should be observed that many of the lines of force leaving the north pole of one magnet travel across the intervening space and enter the south pole of the other. Since the magnetic lines of force do tend to shorten their length, it is easy to see that an attraction exists between the north pole of one magnet and the south pole of the other, as the lines between them tend to shorten. In Fig. 12 are shown two bar magnets with the north pole of one placed directly opposite the north pole of the other. The magnetic lines of force which exist about this arrangement are also shown. Notice that in the space between the two poles, the lines are nearly parallel and, due to the sidewise crowding effect of the lines, it is apparent that there is a repelling force between

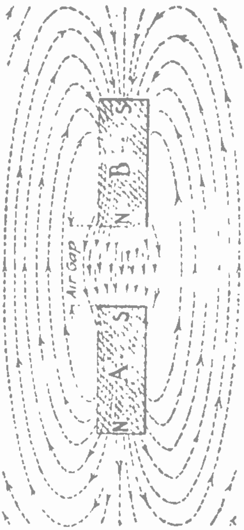


Fig.11 Magnetic Lines of Force around Two Opposite Poles.

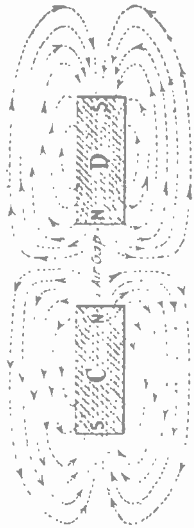


Fig.12 Magnetic Lines of Force around Two Like Poles.

the two poles. Figs. 13 and 14 show the forces of attraction and repulsion between two horseshoe magnets.

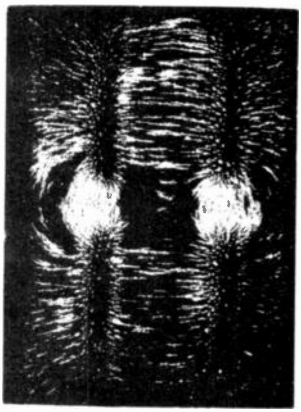


Fig.13 Arrangement of Iron Filings around Two Horseshoe Magnets with Unlike Poles Opposite.

Fig.14 Arrangement of Iron Filings around Two Horseshoe Magnets with Like Poles Opposite.

5. MAGNETIC MATERIALS. It is not possible to magnetize all materials. Those that can be magnetized are known as "magnetic materials", while all others are called "non-magnetic". Magnetic ma-

terials include iron, steel, all iron or steel alloys, also cobalt and nickel. Cobalt and nickel, however, are only slightly magnetic. You can determine for yourself just what materials are magnetic by trying to pick up various objects with a small horseshoe magnet. Just why some materials are able to be magnetized while others are not is not definitely known as yet.

6. **THEORY OF MAGNETISM.** If a bar magnet is sawed in two, it is found that each piece is, itself, a complete magnet with its own north and south poles. It is a fact that no matter how many small pieces are made of the original magnet, each piece is a perfect magnet as shown in Fig. 15. Carrying this idea a bit further, it is

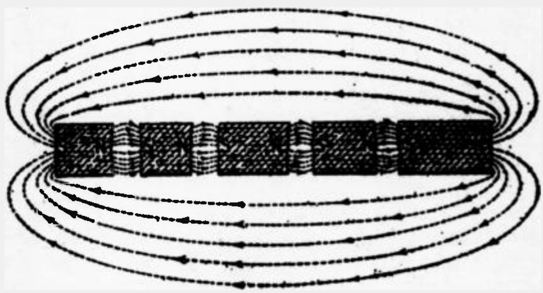


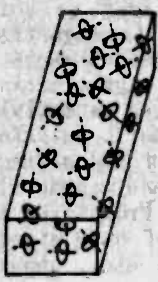
Fig.15 Effect of Breaking a Bar Magnet into Several Pieces.

assumed that each individual molecule of the substance is, itself, a perfect magnet. In an earlier lesson we learned that molecules are composed of atoms. Each atom, in turn, consists of one or more electrons revolving in circular orbits around a center nucleus. We know that electrons in motion do have considerable energy. In an unmagnetized piece of iron, the atoms are thought to be arranged in a somewhat haphazard fashion as shown in Fig. 16. It is assumed that these electrons, by their motion, create a magnetic field about each atom and in an unmagnetized piece of iron the poles of one molecule are neutralized by those of its neighbors. (See Fig. 17.)

If we slightly magnetize a piece of iron by stroking it with a permanent magnet, some of the molecules align themselves as shown in Fig. 18: that is, many of the molecules are turned so that the magnetic forces of one molecule, caused by its revolving electrons, add to those of nearby molecules and thus create an intense magnetic force which is evident at the two ends or poles of the piece of material.

If the magnetizing force is sufficiently great, it might be possible to align all the molecules of a piece of iron. The magnetic forces created by the revolving electrons are in the same direction, with the north poles of all of the molecular magnets turned one way and their south poles the opposite way. This condition is illustrated in Figs. 19 and 20. When this point has been reached, it is impossible to add any further magnetism to the piece of iron. This condition is known as "magnetic saturation".

There are several simple experiments which tend to prove the foregoing theory. If an unmagnetized bar of steel is placed with one end on the pole of a bar magnet and is then tapped with a ham-



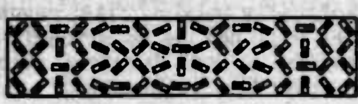


Fig.17 Arrangement of Molecules in an Unmagnetized Piece of Iron.

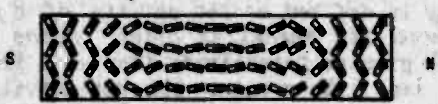
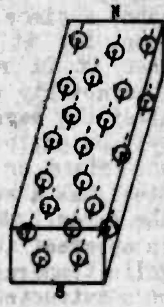


Fig.18 Arrangement of Molecules in a Partially Magnetized Piece of Iron.



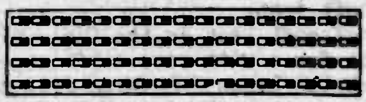


Fig.16 Arrangement of Atoms and Electron Orbits in an Unmagnetized Piece of Iron.

Fig.19 Arrangement of Molecules in a Piece of Iron Saturated with Magnetism.

Fig.20 Arrangement of Atoms and Electron Orbits in a Piece of Iron Saturated with Magnetism.

mer, it becomes a weak permanent magnet. If the bar is removed from the magnet and is again tapped, its magnetism disappears. The tapping assists the arrangement of the molecular magnets in the first part of the experiment, when the bar magnet is near, and then destroys their arrangement in the second part when the bar magnet is removed. When a permanent magnet is heated to a cherry red, it loses its magnetism completely, and if it is allowed to cool without being in a magnetic field, it remains in a demagnetized condition. This is due to the fact that heating the magnet greatly agitates its molecules, and as the bar cools, the molecules settle down in haphazard positions. It is also possible to hold a bar of soft iron in the direction of the magnetic lines of force of the earth, as shown in Fig. 21, and by striking it a sharp blow, it

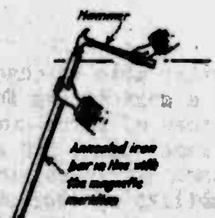


Fig.21 Using the Magnetic Field of the Earth to Magnetize an Iron Bar.

becomes slightly magnetized. From these experiments it is evident that the proper care of a permanent magnet demands that it never be heated or severely jarred.

7. RETENTIVITY AND PERMEABILITY. A piece of soft iron, when placed in a magnetic field, will very easily become a strong, temporary magnet, but, when removed from the influence of the magnetic field, it loses practically all of its magnetism. On the other hand, a piece of steel will not be so strongly magnetized as soft iron, but it will retain a much larger portion of its magnetism when it is removed from the influence of the permanent magnet. This ability of the steel to retain a portion of its magnetization after the magnetizing force has been removed is called retentivity. *Retentivity is defined as the ability of a magnetic material to retain or hold its magnetism after it has been magnetized.* Steel has a much greater retentivity than soft iron and in general, the harder the iron, the greater its retentivity. From this, it is apparent that permanent magnets should be made of hard steel, while temporary magnets, such as are used in relays, etc., should be constructed of soft iron.

Place a piece of soft iron in the field of a permanent magnet and map the lines of force with some stiff paper and iron filings. Notice that many of the lines of force from the permanent magnet take a longer path so that they may travel through the piece of soft iron. Also observe that the lines of force in the piece of soft iron are very close together, indicating that the magnetic field at that point is quite strong, as shown in Fig. 22. From

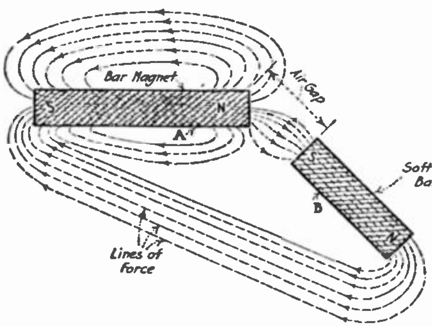


Fig.22 Showing the Reason for Attraction Between a Magnet and a Piece of Soft Iron.

this we can conclude that soft iron is better able to conduct magnetic lines of force than air. In fact, a magnetizing force will produce several thousand times as many lines of force in a piece of soft iron as it will produce in the same volume of air. *The ease or readiness with which magnetic lines of force are set up within a substance is known as the **permeability** of that substance.*

The permeability of air and all non-magnetic materials is one. The permeability of cobalt and nickel is several hundred, that of hardened steel, several thousand, while that of soft or wrought iron, in some cases, may be as high as ten or twelve thousand. The permeability of a magnetic material is not constant but varies with the previous state of magnetization of the material. As an example, let us consider a piece of cast steel. At one point where it is partly magnetized, its permeability is 1600, and as the magnetizing force is increased by adding more and more lines of force, the saturation point is approached and it becomes more and more difficult to add lines of force to the piece of cast steel, and at a point not far from saturation, the permeability has dropped to 320. When we say that the permeability of a substance is 1,000, we mean that a given magnetizing force will produce 1,000 times as many lines of force in this substance as it will produce in the same volume of air.

8. RESIDUAL MAGNETISM. *Residual magnetism is a measure of the amount of magnetism or number of lines of force that a magnet retains after the magnetizing force is removed.* It must not be confused with retentivity. An example will make this clearer. If we magnetize two different magnetic materials, so that the first contains 15,000 lines of force and the second, 5,000 lines of force,

Fig.23 William Gilbert (1540 - 1603). English physician and physicist; first Englishman to appreciate fully the value of experimental observations; first to discover through careful experimentation that the compass points to the north not because of some influence of the stars, but because the earth is itself a great magnet; first to use the word "electricity"; first to discover that electrification can be produced by rubbing a great many different kinds of substances; author of the epoch-making book entitled "De Magnete, etc.," published in London in 1600.

and further, if the retentivity of the first piece is such that it retains one-third of its magnetism while the second retains one-half of its magnetism, then the residual magnetism in the first piece is $\frac{1}{3} \times 15{,}000$ or 5,000 lines of force, and in the second piece is $\frac{1}{2} \times 5{,}000$ or 2,500 lines of force. Thus, it is seen that the retentivity of the first piece is less than that of the second (since $\frac{1}{3}$ is less than $\frac{1}{2}$), although the residual magnetism left in the first piece (5,000) is greater than that left in the second (2,500).

9. MAGNETIC CIRCUITS. It has been shown in an earlier part of this lesson that magnetic lines of force "flow" in complete circuits from the north pole of the magnet through the surrounding air to the south pole, then through the magnet from the south to the

north pole. Each magnetic line of force forms a closed loop and it is possible to calculate the various values pertaining to the magnetic circuit in much the same way as those of an electrical circuit. In the electrical circuit, there is a flow of electrons, while in a magnetic circuit there is a flow of magnetic lines of force (flux). In the electrical circuit, there is an electrical pressure or voltage, while in the magnetic circuit there is a magnetizing force, or as it is commonly called "magnetomotive force", abbreviated M.M.F.

Corresponding to the resistance of an electrical circuit, there is the "reluctance" of a magnetic circuit. *Reluctance is that property of a material which opposes the creation of magnetic lines of force in the material.* There is a formula for magnetic circuits which is quite similar to Ohm's Law as used in electrical circuits. The three ways in which the formula may be written are as follows:

$$\varphi = \frac{F}{\mathcal{R}} \qquad F = \varphi\mathcal{R} \qquad \mathcal{R} = \frac{F}{\varphi}$$

Where: φ (pronounced fi) = the flux or number of lines of force.
F = the magnetomotive force measured in gilberts. (See Fig. 23.)
$\mathcal{R}$ = the reluctance measured in oersteds[1].

In explanation of the terms used in these equations, a gilbert is defined as the amount of magnetomotive force required to create one line of force in a magnetic material whose reluctance is one oersted. An oersted is defined as the reluctance of a magnetic material in which it takes one gilbert of magnetomotive force to create one magnetic line of force. These units have been so chosen that the reluctance of a cubic centimeter of air is one oersted. (A comparison between a cubic centimeter and a cubic inch is shown in Fig. 24.) The resistance of a conductor is generally specified in

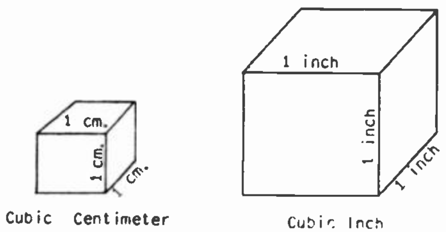


Fig.24 Comparison between a Cubic Centimeter and a Cubic Inch.

"ohms per mil-foot". This is the resistance of a wire having a diameter of 1 mil (.001 inch) and a length of one foot. Likewise, the reluctance of a material is expressed as so many oersteds per cubic centimeter. The reluctance of all magnetic materials is less than one oersted per cubic centimeter; however, their reluctance, like their permeability, is not constant, but depends upon the degree of magnetization of the material. This makes the calculation of magnetic circuits somewhat difficult, just as the calculation

[1] So named in honor of Hans Christian Oersted (1777-1851), a Danish professor who did notable work in the field of magnetism.

of electrical circuits would be if the resistance of the conductors changed with the amount of current flowing through them (disregarding the effect of heat). To use these three formulas requires a set of magnetization curves for the particular material involved Magnetization curves show the reluctance of the material for different degrees of magnetization. Fortunately, however, we will not be required to use these three formulas and they are shown merely to give a more definite understanding of the action of a magnetic circuit.

With the material just given, it is possible to give another definition of permeability. *Permeability is the ratio of the number of lines of force set up in a cubic centimeter of the magnetic material by a magnetizing force of one gilbert to the number of lines of force that would be set up by one gilbert in a cubic centimeter of air.*

10. **ELECTROMAGNETS.** When discussing the theory of magnetism, we learned that the magnetic field of a permanent magnet was caused by the motion of the revolving electrons. Thus, we should suspect that an electric current which consists of a flow of electrons along a conductor would also produce a magnetic field. This can be demonstrated by the following experiment.

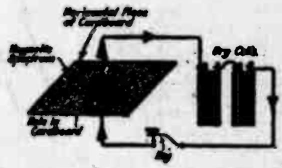


Fig.25 Mapping the Magnetic Lines of Force About a Wire Carrying Current.

Fig.26 End View of Wire carrying Current, Showing Magnetic Field.

If a piece of wire is stuck through a piece of light cardboard so that the wire is in a vertical position and the cardboard is horizontal, then by connecting a battery to the terminals of the wire, we can, by sprinkling iron filings on this piece of cardboard and tapping it slightly, map the position of the magnetic field about the wire. This is shown in Figs. 25 and 26. It is seen that the magnetic lines of force form concentric circles about the conductor and that the wire will attract iron filings as shown in Fig. 27. By placing a small compass needle near the conductor, we may determine the direction of the lines of force and it is found that if the current flows from the bottom of the conductor to the top, the

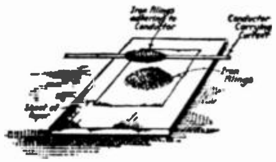


Fig. 27 Illustrating the Attraction Between Iron Filings and a Conductor Carrying Current.

magnetic lines of force flow in a clockwise direction about the conductor. There is a very convenient rule for determining the direction of the lines of force about a wire. Point your left thumb in the direction in which the current (electrons) is flowing; then the fingers of your left hand will curl about the conductor in the direction of the magnetic lines of force. Try this rule on the conductors shown in Figs. 28 and 29. This rule may also be used to determine the direction of the current flow in a DC circuit if the polarity[1] of the voltage source is unknown. A small pocket compass

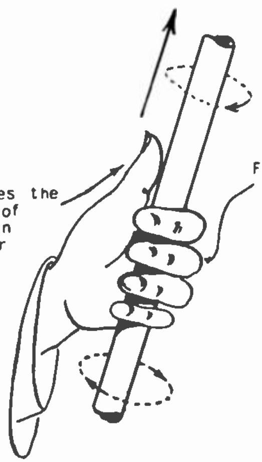


Fig. 28 Left Hand Thumb Rule for Determining the Direction of the Magnetic Lines of Force About a Wire.

may be placed close to one of the conductors of a circuit and the direction of flow of the magnetic lines of force is determined; then by use of the "left-hand rule", the direction of the current is easily ascertained. This is illustrated in Fig. 30. If the current flowing in the conductor is increased, more electrons pass a given point in the conductor per second and this increased electron

[1] Polarity is defined as the property of having opposite poles. Thus a battery has polarity since it has a positive and a negative pole. Likewise, a magnet has polarity, since it has a north and south pole. When we say that we do not know the polarity of a voltage source, we mean that we do not know which pole is positive and which is negative.

flow produces a stronger magnetic field about the conductor. The greater the current, the stronger the magnetic field becomes.

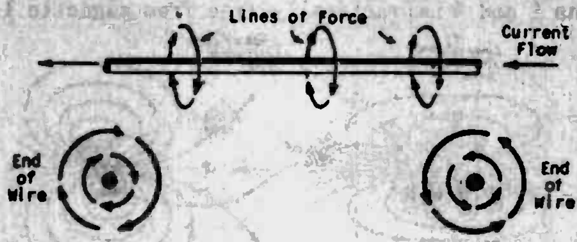


Fig.29 (Left) End View of Conductor with Current Flowing Out of the Paper. (Top) Magnetic Field Surrounding a Wire Carrying Current. (Right) End View of Conductor with Current Flowing Into the Paper.

The magnetic field surrounding a single loop of wire carrying current is illustrated in Fig. 31. Notice that all the circular

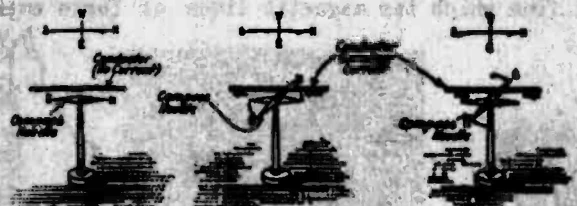
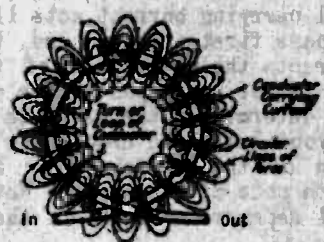


Fig.30 Using a Compass to Determine the Direction of Current Flow in a Wire.

lines of force enter one face of the loop and leave the opposite face. By placing several loops together in the form of a loose

Fig.31 Magnetic Field Around a Single Loop of Wire Carrying Current.



coil, most of the lines will thread through the whole coil as shown in Fig. 32. If the turns are close together, more of the lines will flow through the coil and fewer will encircle the separate turns. (See Fig. 33.) This, of course, increases the flux at the two ends of the coil. This may be explained by considering Fig. 34 which illustrates a longitudinal section. The field in the space between turns 2 and 4 is practically free from magnetic lines since

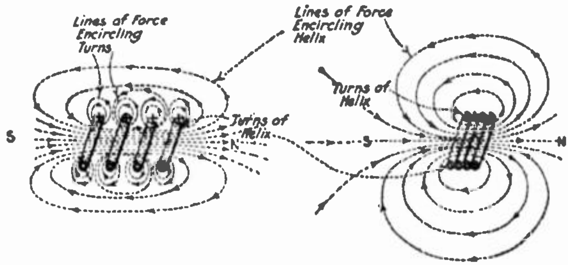


Fig. 32 Fig. 33

Magnetic Fields Around Two Coils.

the field about one turn neutralizes the field about the other. A coil of this type is often called a "helix", or a "solenoid".

Fig. 35 illustrates the magnetic field about a coil. It is seen to be very similar to the field about a bar magnet. That end of the coil from which the magnetic lines of force emerge is the

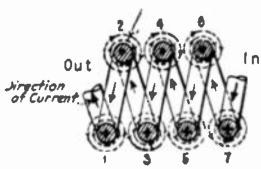


Fig.34 Field Around Turns in a Coil

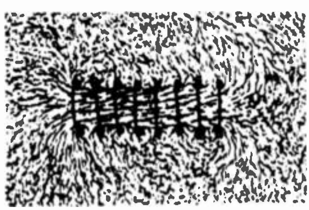


Fig.35 Mapping the Magnetic Field Around a Coil

Fig.36 Left Hand Thumb Rule for Determining the Magnetic Polarity of a Coil

north pole of the coil, while the opposite end, where the magnetic lines of force enter, is the south pole. Also, we can prove that a coil carrying current acts like a bar magnet by placing a pocket compass first near one end, then the other. One end of the coil attracts the north pole of the compass while the opposite end attracts the south pole of the compass. There is another "thumb rule" for determining the magnetic polarity of a coil. Place the fingers of your left hand around the coil so that they point in the direction of the current flow. Your thumb will then point toward the north pole of the coil.[1] Notice that the magnetic polarity of the coil depends not only on the direction of current flow, but also

[1] Both this thumb rule and the preceding one are based on the fact that current flows from negative to positive, as proved by the electron theory. In some texts which use the older idea of current flowing from positive to negative, you will find corresponding rules in which the "right-hand rule" is employed. (See Fig.36.)

upon the direction in which the coil is wound. The magnetic polarity of a coil can be changed either by reversing the current or by winding the coil in the opposite direction. If the current flowing through a coil is increased, the magnetic field about each turn is strengthened and, as a result, the total magnetic flux threading through the coil is made correspondingly greater.

By placing a soft iron bar within the center of the coil, the strength of the magnetic field can be greatly increased with the same amount of current flowing through the coil. The reluctance of an iron bar is considerably less than that of air and so by decreasing the reluctance of part of the magnetic circuit, a much stronger magnetic field is produced by the same amount of magnetizing force. Fig. 37 shows the field about a coil which has an iron core. Notice

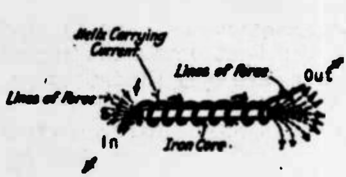


Fig.37 Magnetic Field Around a Coil which has an Iron Core.

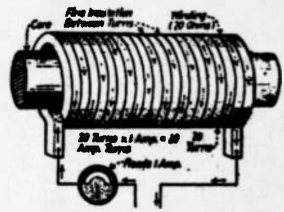


Fig.38 Illustrating the Meaning of Ampere-Turns.

that most of the lines are confined within the iron core itself; that is, its reluctance is so low compared to air that nearly all of the lines will flow through it. Since the field about each turn of the coil adds to the field about all of the other turns, it is possible, by increasing the number of turns on the coil, to increase the magnetic field for a given amount of current flowing. The magnetizing force, measured in gilberts, is equal to 1.26 times the current flowing times the number of turns. The current must be expressed in amperes. Usually, however, we are not interested in the amount of magnetizing force, but only the relative amount between different coils which have the same kind of core. We can express this relative amount by multiplying the current in amperes by the number of turns on the coil. This product is known as the "ampere-turns" of that particular coil. For example, if a coil of 20 turns has 1 ampere of current flowing through it, there are 20 ampere-turns of magnetizing force as shown in Fig. 38. The same magnetizing force could be secured with a coil of 10 turns having 2 amperes flowing through it. If 2 amperes flow through 25 turns, the magnetizing force is 50 ampere-turns.

It is not possible to increase the ampere turns of a coil by merely winding more turns on the coil. For example, suppose that a coil of 100 turns has a resistance of 100 ohms. If 100 volts are applied across this coil, then by Ohm's Law (I = E÷R), 1 ampere of current will flow through the coil. The ampere-turns are 100 turns × 1 ampere = 100. By winding 100 more turns on this same coil, the resistance of the whole coil (200 turns) increases to 200 ohms.

With the same 100 volts applied, there will be .5 ampere through the coil and the ampere-turns are .5 ampere × 200 turns = 100. Since the resistance of the coil increases directly with the number of turns, the addition of more turns serves to decrease the current and the number of ampere-turns do not change. To increase the number of ampere-turns, the applied voltage must be increased or larger wire, which has a lower resistance, must be used in the construction of the coil.

To summarize, the three things that determine the strength of the magnetic field about a coil are:

1. The amount of current flowing.
2. The number of turns on the coil.
3. The permeability of the core.

The magnetic field around an electromagnet is usually many times greater than the magnetic field of the best permanent magnet obtainable. For that reason, electromagnets are used almost exclusively in Radio and Television work.

Electromagnets can be constructed to pick up and carry several tons of iron. They are known as hoisting magnets and are used exteneively in steel mills to carry scrap iron from one end of the mill to the other. These magnets are used in connection with a traveling derrick or crane. The magnet is lowered by the derrick to the pile of scrap iron and is then energized by allowing current to flow through its coils. After it has attracted large particles of scrap iron, it is moved to the opposite end of the mill. The current through the coils of the magnet is now cut off and the magnet

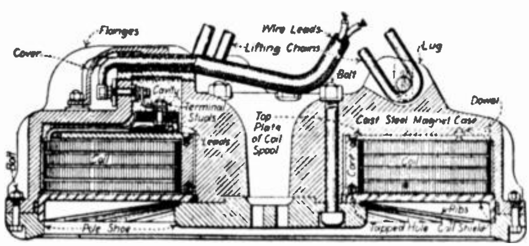


Fig.39 Cross-Sectional View of Electromagnet Used for Carrying Heavy Loads.

allows its load to fall. The cores of these magnets, as well as all other electromagnets, are made of soft iron which has a very low retentivity. Fig. 39 shows a cross-sectional view of a large hoisting magnet. A permanent magnet is made by subjecting a piece of unmagnetized steel to the influence of an intense magnetizing force. This may be accomplished by placing the piece of steel inside of a coil through which a large direct current flows. The magnetic flux produced by the coil flows through the piece of steel and in so doing aligns many of its molecules. This process usually requires only a few seconds. Sometimes the field coils of a generator can be used for this purpose. Fig. 40 illustrates several methods of producing artificial permanent magnets.

11. MAGNETIC SHIELDS. If it is desired to shield a particular object from a magnetic field, a piece of glass, brass, wood, or rubber between the object and the magnet would be very ineffective. It would be noticed that the magnetic lines of force pass through these materials the same as though they were not present. This is due to the fact that all these materials have the same reluctance as air. If a sheet of iron is placed between the magnet and object, the iron acts as a magnetic shield, preventing the majority of the lines of force from passing through the object. This

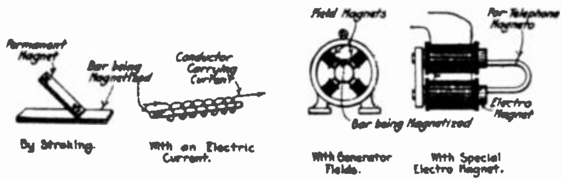


Fig. 40 Methods of Making Permanent Magnets.

shielding effect is due to the lower reluctance of the magnetic screening material, which causes the lines of force to take the easiest path through the magnetic shield. Therefore, to shield an object from a steady magnetic field, it must be enclosed in a solid iron case. It should be realized that no material will perfectly shield an object from a magnet. Just as there is no perfect insulator or conductor of electricity, likewise, there is no perfect magnetic shield. Soft iron is the best shielding material so far discovered and the results obtained by employing this sub-

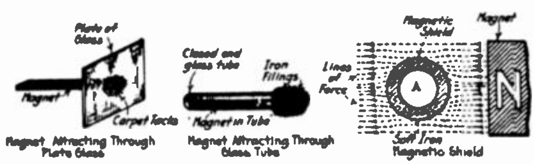


Fig. 41 Illustrating Magnetic Shielding.

stance are sufficiently satisfactory to warrant its use. Fig. 41 illustrates magnetic shielding.

12. SUMMARY OF LAWS AND TERMS USED IN THIS LESSON. In the study of any subject you will find there are certain fundamental laws which should be mastered before a complete understanding of the subject is possible. For example, in the study of medicine, you would need to learn the various terms which are part of the technical language of this profession——certain basic laws upon which all subsequent learning is founded. In previous lessons, there have been introduced a number of definitions which describe the action of an electrical circuit under various conditions. Magnetism, a subject inseparably associated with electricity, also has

its technical terms and definitions. To facilitate the learning of these fundamental laws, we have selected the most important ones contained in this lesson and are listing them in the following summarized form. We believe you will find this a convenient method for referring to the highlights of this lesson.

1. Attraction and Repulsion.

Attraction can exist between either pole of a magnet and a piece of unmagnetized magnetic material. There will also be attraction between the north pole of one magnet and the south pole of another. There will be repulsion between like poles of two magnets; that is, between two north or two south poles. In a simpler way, we can state that like poles repel, while unlike poles attract.

2. Magnetic Lines of Force.

A magnetic line of force is an imaginary line which is drawn from the north pole of a magnet through the surrounding air to the south pole of the magnet and then through the magnet from its south pole to its north pole. Any point in this line represents the direction in which a compass needle would point if situated at that spot. These lines form closed loops, never cross each other and are always trying to shorten their length. Many such lines may be drawn through the air from the north pole to the south pole of the magnet. In fact, we can select any point in the vicinity of the magnet and draw a line so that it passes through that point.

3. Magnetic Field.

The field of a magnet is the space surrounding the magnet in which the forces of attraction or repulsion make themselves evident. Or, we can define the field as the space surrounding the magnet in which the magnetic lines of force are situated. Close to the magnet, the field is strong; that is, the forces of attraction or repulsion are relatively great. As we progress outward from the magnet, the field becomes weaker and the attracting and repelling forces are less noticeable. The magnetic lines of force not only show the direction of the attracting and repelling forces, but also their strength at any point in the field. Where the lines are close together, the field is strong and where the lines are widely spaced, the field is weak. The field of a magnet at any point is often expressed as so many lines per square inch or per square centimeter.

4. Flux.

The term flux is defined as a continuous flowing. We can think of the magnetic lines of force as flowing from one pole to the other pole of the magnet. Therefore, these lines, taken as a whole, are known as the magnetic flux.

5. Retentivity.

Retentivity is the ability of a magnetic material to retain some of its magnetism after it has been removed from the influence of the original magnetizing force. Various grades of iron and steel have different retentivities. A permanent magnet should be made of a substance having a high retentivity and since very hard steel has the greatest retentivity of all magnetic materials, permanent magnets are usually made of this substance.

6. Permeability.

Permeability is a measure of the readiness or ease with which a material allows the creation of magnetic lines of force within itself. If the permeability of a substance is high, it is relatively easy to add magnetic lines of force to this substance. On the other hand, if the substance has a low permeability, it is very difficult to add magnetic lines of force to the substance. In the section on the theory of magnetism, we found that the magnetization of a magnetic material consisted of aligning the molecules of the material so that all of their north poles pointed toward one end and their south poles toward the opposite end. We also saw that it was possible to align all of the molecules of the substance, in which case the material was said to be saturated with magnetism. If a magnet has so many magnetic lines of force flowing through it that it is near the saturation point, it is very difficult to add more lines of force to the magnet. Therefore, we can say that at that point, the permeability of the substance is low. In recent years, two new magnetic alloys have been produced which have very high permeabilities. They are permalloy and alnico.

7. Residual magnetism.

Residual magnetism is the amount of magnetism or number of magnetic lines of force that are left in a material when the magnetizing force has been removed. Soft iron possesses very little residual magnetism. The amount of residual magnetism in any material depends upon the retentivity of the material and the intensity of the magnetizing force.

8. Magnetomotive Force.

Magnetomotive force is the force which produces the magnetizing action in a magnetic circuit. Magnetomotive force is to the magnetic circuit what electromotive force (voltage) is to the electrical circuit. It is the force which aligns the molecules and establishes the magnetic lines of force.

9. Reluctance.

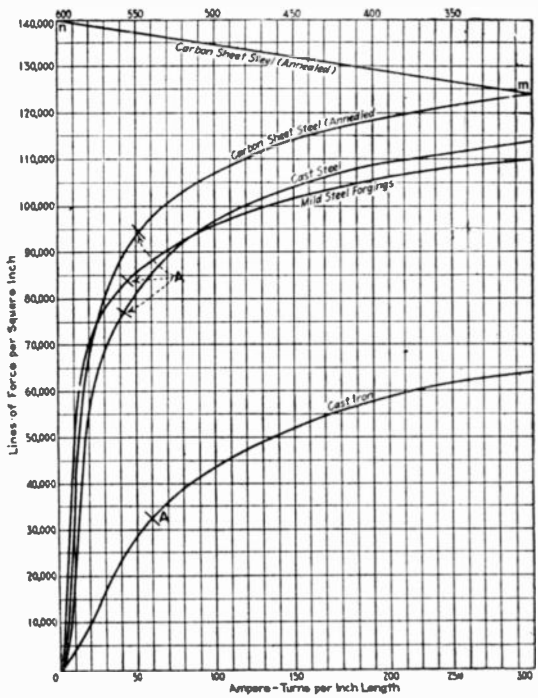
Reluctance is the opposition which a substance offers to the flow of magnetic lines of force through it. It could be called "magnetic resistance", since it opposes the flow of the magnetic lines of force in the same manner that electrical resistance opposes the flow of current. We know that the word "reluctant" means unwilling. We may, therefore, say that the reluctance of a substance is the "unwillingness" or the "hindrance" which the substance offers to the magnetic flux. The reluctance of iron and steel is low. Thus, a piece of iron in a magnetic field offers less reluctance than air to the magnetic lines. Therefore, the lines become denser in the iron, making it a magnet. With a given magnetomotive force, the amount of magnetic flux that is created depends upon the reluctance of the magnetic circuit.

10. Ampere-turns.

Ampere-turns is an expression which represents the strength of the magnetizing or magnetomotive force present in an electromagnet. It is found by multiplying the number of amperes of current flowing through the coil or electromagnet by the number of turns wound on the coil. The more ampere-turns, the greater is the magnetizing force.

11. Factors determining strength of an electromagnetic field. To create a strong field about an electromagnet requires, first, a large magnetomotive force. This is accomplished by winding many turns of wire upon a coil form and then using a voltage great enough to force sufficient current through the coil so that the number of ampere-turns produced is large. Next, a low reluctance path for the magnetic flux must be provided. This may be done by using soft iron as the core of the coil. We may say, then, that the factors which determine the strength of the field about an electromagnet are: first, the number of turns in the coil; second, the amount of current flowing through it; third, the reluctance of the magnetic circuit.

Reference Graph



Magnetization curves of various irons and steels. The approximate location of the saturation points are indicated by the letters A.

Notes

(These extra pages are provided for your use in taking special notes)

Notes

(These extra pages are provided for your use in taking special notes)

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POWER & LIGHT BUILDING, KANSAS CITY, MISSOURI

UNIT NO. 1

COILS AND INDUCTIVE REACTANCE

LESSON NO. 10

THOMAS ALVA EDISON

.....he never lost his love for work!

The snap of a tiny switch and a room or vast assembly hall is brilliantly illuminated by incandescent lamps.....just one of the many amazing contributions to civilization created by the fertile mind and dynamic energy of Thomas Alva Edison.

Born in the quiet little town of Milan, Ohio, young Edison's curiosity led him from one startling event to another. When he was six years of age, it is said that he decided to find out where the mother goose got her goslings, so he proceeded to sit on a nest of goose eggs. Needless to say, this experiment did not prove to be successful. Entering school, he again encountered disappointment, for although he possessed an active mind, he seemed destined to remain at the foot of his class. As a result, he left school and continued his education under the guidance of his sympathetic mother.

As time passed, he found it necessary to earn money, so he applied for a job as "train boy" on the Grand Trunk Railroad. He sold candies, peanuts, papers and a general assortment of things that appealed to the traveller. Then he conceived the idea of printing his own newspaper, the Weekly Herald. He bought an old press, some type and set himself up in the publishing business in one of the cars that was used very little. The modest little paper was a success and Edison made forty-five dollars each month from his venture. In addition to the printing press, he was permitted to have a laboratory in the car, where he conducted experiments. One day, the bumping of the car sent a bottle of phosphorus crashing to the floor where it set fire to the woodwork. The conductor, incensed at what he thought was pure carelessness, boxed young Edison's ears so effectively that he suffered permanent, but not complete, deafness, a tragic blow to the young man. But instead of seeking sympathy, he continued his experiments in a room provided by his father.

Now drama entered his life. He saved a baby that had wandered onto the railroad tracks and the grateful father offered to teach him telegraphy. Edison was such an apt pupil that he was soon able to secure a job as a telegraph operator. He attempted to experiment by day and operate by night, and as a result, lost his job because he fell asleep. Job followed job, and again his inquisitive mind produced trouble. While securing some sulphuric acid from the battery room, he spilled the container. The acid "ate" holes in the floor and dropped down to the manager's office where it continued to "eat" in a very thorough manner. On the following day, Edison was given his final pay check and an invitation to leave. He turned homeward and remained with his parents for many months. Trouble, trouble and more trouble.....all caused by his desire to experiment.

But now a ray of sunshine peeped through the dark clouds. The Grank Trunk Railroad had adopted one of his devices that made it possible to use a single submarine cable for two circuits. Thomas Alva Edison was on his way to world-wide fame.

(NOTE: The interesting story of the life of Thomas Alva Edison will be continued in future lessons.)

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Lesson Ten

Coils and Inductive Reactance

"Permanent magnets were discovered before electromagnets. Therefore, in the preceding lesson you studied about permanent magnets, followed by a short introduction to electromagnets.

"In this lesson, I am going to give you an insight into some of the important uses of coils in the functioning of Radio and Television apparatus. Besides learning about how coils function, you will be given some important formulas. It is not necessary for you to memorize this information, but you should become thoroughly familiar with it."

1. ELECTROMAGNETIC INDUCTION: About 1831, both Michael Faraday and Joseph Henry discovered that it was possible to change magnetic energy directly into electrical energy. The method of producing an electrical current by the use of magnets is the underlying principle of the electric generator which has made the modern age of electricity possible.

Electromagnetic induction may be demonstrated with a simple arrangement as shown in Fig. 1. A single conductor wound to form a two-turn coil is situated in the magnetic field between the poles of a horseshoe magnet. A galvanometer is connected across the two free ends of the two-turn coil. A galvanometer is an electrical instrument capable of measuring extremely small values of current. It has a scale with zero at the center and the needle can deflect in either direction from its normal midposition, depending upon the direction of current flow through the instrument. The two terminals on a galvanometer are not marked positive and negative, so the direction of connection is immaterial. It can, however, be used only for direct current measurements. The symbol for a galvanometer is shown in Fig. 2.

In Fig. 1, if the two-turn coil of wire is moved up and down over the south pole of the magnet, it is found that a current flow is produced through the coil. This current flow will be indicated by a deflection of the galvanometer needle. As the coil is moved down over the south pole, the galvanometer needle will deflect to the right; then as the coil is moved up over the same pole, the galvanometer needle deflects to the left of its zero midposition.

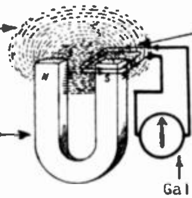


Fig.1 Illustrating electromagnetic induction. The arrows indicate the direction of current flow through the coil when it is moved up. When the coil is moved down, the current will reverse.

Fig.2 Symbol for a galvanometer.

We have previously learned that an electrical pressure, or voltage, is always necessary in order to produce a current flow; hence, in this experiment, it is quite evident that the movement of the coil up and down through the magnetic lines of force surrounding the permanent magnet has produced an electromotive force or voltage in the turns of the coil. This voltage causes a current to flow through the conducting wire and the current is indicated by the deflection of the galvanometer needle. An electrical voltage produced in this manner is called an "induced voltage".

If the coil of wire is allowed to remain stationary and the horseshoe magnet is moved up and down through the coil, a similar occurrence will be noticed; that is, the galvanometer needle will deflect. This deflection indicates that a current is passing through the coil and that a voltage is being induced into the coil. From this we may conclude that it is immaterial as to whether the coil is moved up and down over the pole leg of the horseshoe magnet, or whether the coil is allowed to remain stationary and the pole leg of the magnet is moved up and down through the coil of wire. In both cases, a voltage was induced in the coil of wire and a current flow was indicated.

When neither the coil nor magnet is moved, there is no voltage induced in the coil. This leads to the conclusion that there **must be a relative motion** between the conducting wire (coil) and the magnetic field surrounding the magnet in order to induce a voltage.

From this and many other similar experiments, a general law was formed. This law states: *Whenever there is a relative motion between a magnetic field and a conductor, a voltage is induced in the conductor.* This law is known as the "Law of Electromagnetic Induction" and was first postulated in 1831 by Michael Faraday, the famous English physicist and chemist.

2. INDUCTION IN A STRAIGHT CONDUCTOR. Let us apply the Law of Induction to a single straight conductor and point out a few of the important facts pertaining to this application.

In Fig. 3, a conductor is shown in the magnetic field between the two poles of a permanent magnet. The first position of the conductor is near the top of the south pole face as shown by the dotted conductor marked AA'. The conductor is then moved down through the magnetic field to the position BB'. During the movement of the conductor from position AA' to position BB', there has been a voltage induced in the conductor, because it has been passing or cutting through the magnetic lines of force. If the movement of the conductor is continued on down to the position CC', there will also be a voltage induced. If the conductor is stopped at any time during its downward movement through the magnetic field, there will not be a voltage induced in it, because there must be a relative motion between the conductor and the magnetic field for electromagnetic induction to occur. In this case "relative motion" means that the conductor must shear or cut through the magnetic lines of force.

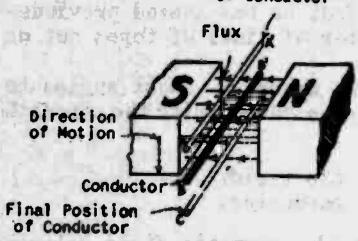
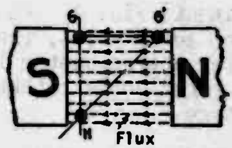


Fig.3 Diagram illustrating the induction of a voltage in a conductor when it is moved through a magnetic field.

Fig.4 End view of Fig.3. This shows how a conductor may be moved through a magnetic field in various ways.



An end view of the conductor movement in Fig. 3 is shown in Fig. 4. Moving the conductor down through the magnetic field corresponds to the movement from G to H in Fig. 4. Let us first assume that the conductor movement is from position G to position G'. Since the magnetic lines of force between the north and south poles of the magnet are straight lines, the conductor's movement between G and G' will be parallel with the lines of force. When the conductor is moving parallel to the flux, it will not be shearing or cutting through the lines of force; hence, there will be no voltage induced in it. Bear in mind that it is absolutely essential for a conductor to cut through magnetic lines of force or for the magnetic lines of force to cut through the conductor in order to induce a voltage.

Referring again to Fig. 4, if the conductor is moved at an angle through the magnetic field, such as from G' to H, it is seen that the conductor will be cutting through or shearing the lines of force; hence, there will be a voltage induced in the conductor.

The strength of the voltage induced in a conductor is a very important fact associated with the process of induction. Assuming that the speed of the conductor is the same, the movement of the conductor from G to H will result in a greater induced voltage than when it is moved from G' to H. There will be no voltage induced, regardless of speed, when the conductor is moved parallel to the lines of force between G and G'. Since the distance from G to H is shorter than the distance from G' to H, there will be a greater voltage induced when the conductor is moved from G to H, than when it is moved from G' to H, assuming that the speed is the same in each case. The reason for the greater voltage is that per unit of time, the conductor will cut or shear through more lines of force when passing from G to H.

If a conductor is moved slowly through a certain distance, for example from G to H (Fig. 4), and then is moved more rapidly through the same distance, it will be found that when the conductor is moved rapidly through this distance, the induced voltage will be greater. The same reason can be given for this fact as was stated previously; that is, per unit of time, the number of lines of force cut or sheared by a conductor will be greater.

When a given length of conductor is moved at right angles to a given magnetic field, there are two factors determining the strength of the induced voltage. These are:

1. The strength of the field.
2. The speed of the conductor.

Referring to Fig. 4, the stronger the magnetic field between the north and south poles, the greater will be the induced voltage and the faster the conductor is moved through the field (considering only at right angles; that is, G to H), the greater will be the induced voltage.

3. INDUCTION IN A COIL. Fig. 5 illustrates three different types of coils and their symbols. At A is shown a coil which is wound on an iron core. *The material inside of the coil winding is always called the core.* Immediately below the iron core coil are shown two symbols, either of which may be used to represent an iron core coil. The parallel lines drawn through the symbol or to one side of the symbol indicate the presence of iron in the core. At B and C are shown two air core coils and the representative symbol is given directly below. The actual number of turns on the coil has no bearing on the number of loops in the symbol which is used for its representation on a wiring diagram. The number of loops shown on the symbol are generally determined only by convenience.

A coil consists of a long conductor wound in turns around a circular form. The core of a coil means the material through the center of the form on which the coil is wound. The core is generally air or iron. Other materials are used in special cases.

When a coil of wire is moved through or cut by a magnetic field, there will be a voltage induced in the coil. This stands to reason because we have just explained how induction occurs in a conductor and all coils consist of conductors. The strength of the voltage induced in the coil when it is cut by or moved through a magnetic field will depend upon the same two factors which af-

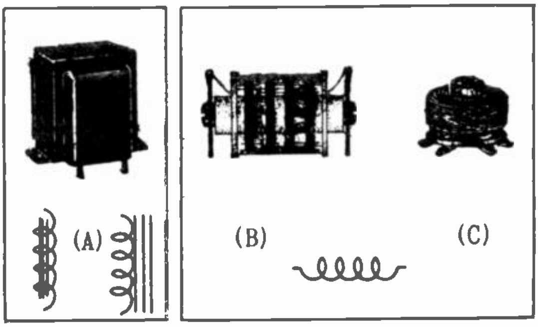


Fig.5 Photographs and symbols for iron core and air core coils.

fect the voltage induced in a straight conductor and also upon the number of turns on the coil which are cut by the magnetic field. Winding a long conductor in several adjacent turns to form a coil is merely a method of exposing a longer wire to the magnetic field, thereby securing a greater induced voltage when it is moved through the magnetic field at a certain speed.

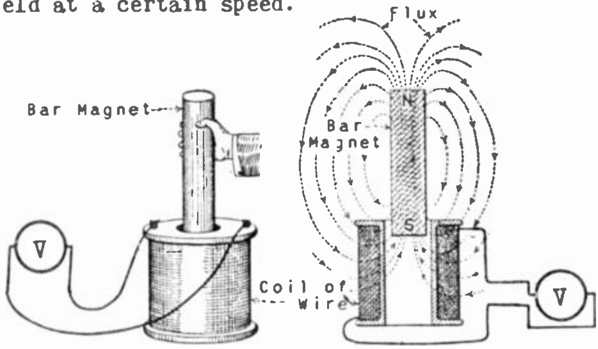


Fig.6 Diagrams illustrating how a voltage may be induced in a coil. The apparatus is shown on the left, and a cross-sectional view showing how the lines of force cut through the turns on the coil is shown on the right.

Referring to Fig. 6., when the permanent bar magnet is dropped down into or pulled out of the center of the coil, the strength of the voltage induced in the coil winding will depend upon:

1. The strength of the field around the magnet.
2. The speed at which the magnet is moved.
3. The number of turns on the coil.

The greater the field strength, the faster the speed; the more turns on the coil, the higher will be the value of the induced voltage. It will be noted that the determining factors of the voltage induced in a coil are the same as those determining the voltage induced in a straight conductor except that we must also take into consideration the number of turns on the coil which are cut by or moved through the magnetic field. Those turns on a coil winding which are not cut by a magnetic field will not be effective in determining the induced voltage. However, in the design of apparatus of this type, the coil is generally constructed and the magnetic path is properly arranged so that all of the turns on the coil winding will be cut by the magnetic field, in which case all of the turns on the coil will be effective in determining the induced voltage. As shown by the cross-sectional view in Fig. 6, when the bar magnet is moved down into or pulled out of the center of the coil, the magnetic flux surrounding the bar magnet will cut through each turn on the coil winding. With a given strength of magnetic field around the magnet and with a given speed at which the magnet is moved, the more turns wound on the coil, the greater the induced voltage in the coil windings.

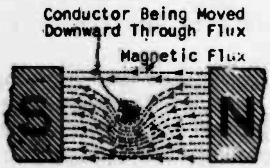


Fig. 7 Illustrating Lenz's Law. Magnetic repulsion is encountered as the current-carrying conductor is moved through the flux.

4. DIRECTION OF INDUCED VOLTAGE. The direction of an induced voltage in a straight conductor or in a coil will always be in accordance with a fundamental electrical law; namely, Lenz's Law. Lenz's Law states: *The direction of an induced voltage is such that the current impelled by it will set up a magnetic field which opposes the magnetic field that induced the voltage.*

To make this definition of Lenz's Law clear, let us refer to Fig. 7. The conductor is being moved through the magnetic field between the north and south poles of the magnet. A voltage will be induced in the conductor (Law of Induction) and if the circuit is complete, a current will flow through the conductor. Assuming that the circuit is complete, the current will flow through the conductor in such a direction as to set up a magnetic field which opposes the magnetic field between the north and south poles of the permanent magnet. The small arrows around the conductor indicate the direction of the field produced around the conductor and it will be noted that these lines of force are opposing the original lines of force that induced the voltage. Lenz's Law states that this opposition will exist. This repulsion may be clearly seen by referring to Fig. 8. In this figure, the magnetic field of the permanent magnet alone is shown at A; then at B, the magnetic field surrounding the conductor alone is shown. At C, the two magnetic fields are combined. It is seen that the magnetic field surrounding the conductor is causing considerable opposition against the magnetic field existing between the poles of the permanent magnet, resulting in a distortion of both magnetic fields.

Since this opposition or magnetic repulsion does exist, it will be necessary to apply sufficient mechanical force to overcome the magnetic repulsion in order to move the conductor on down through the magnetic field between the poles of the magnet. This statement should be studied with the fact in mind that it is impossible to create energy. The example clearly shows that the application of mechanical energy to the conductor is necessary in order to produce electrical energy (voltage) in the conductor. A conversion of energy from the mechanical form to the electrical form is taking place, but energy is not being created or lost.

By studying the foregoing illustrations and explanation, it may be seen that the magnetic field produced by a current flowing

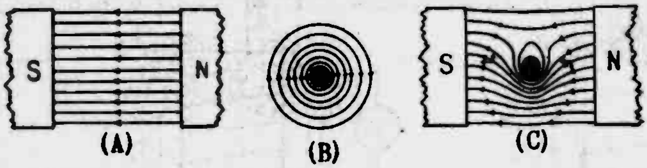


Fig.8 Illustrating Lenz's Law. Flux between poles shown at A. Field around conductor shown at B. At C, both fields are combined.

under the pressure of an induced voltage opposes the magnetic field which originally induced the voltage. This is Lenz's Law.

Lenz's Law may be applied to all electrical circuits in which there is a relative movement between a conductor and a magnetic field. Since all coils and transformers depend on the Law of Induction for their operation, Lenz's Law will apply to their every action. For this reason, it is a very important law. As we continue through our studies, Lenz's Law will be applied in several cases. At the present time, the student should be sufficiently familiar with Lenz's Law to recognize the necessity for application when the occasion arises and be capable of understanding it.

The application of Lenz's Law to a coil may be seen by referring to the simplified drawing shown in Fig. 9. At A, the permanent magnet with its north and south poles respectively is being dropped down through the center of the coil winding. The magnetic flux around the permanent magnet will be cutting through the turns of the coil and inducing a voltage therein. Since the external circuit is completed (through the voltmeter), a current will flow through the coil windings. This current flow will be in such a direction as to set up a magnetic field around the coil windings so as to oppose the magnetic field around the permanent magnet. In other words, a north pole will be produced at the top of the coil winding and a south pole at the bottom. The north pole at the top of the coil winding will repel the north pole of the permanent magnet which is being dropped down into the coil.

At B, Fig. 9, the permanent magnet is being drawn out of the coil winding. Since the magnetic lines of force around the permanent magnet are cutting through the turns on the coil in the opposite direction, a voltage of opposite polarity will be induced in the coil. This causes a current to flow in the opposite direction through the coil winding, thus setting up a magnetic field around the coil in the opposite direction. As will be noticed, a south pole is produced at the top of the coil winding and a north pole at the bottom. Due to the attraction existing between the south pole at the top of the coil winding and the north pole of the permanent magnet, the permanent magnet must be pulled out of the coil against this force of attraction.

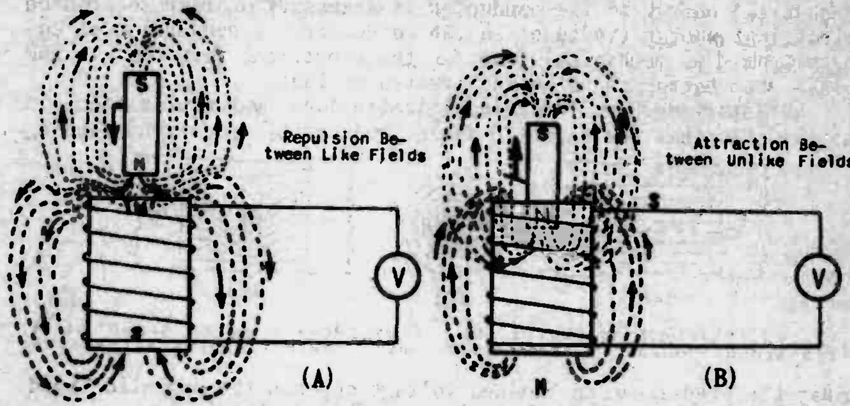


Fig. 9 Illustrating the application of Lenz's Law to a coil. Magnetic repulsion opposes the movement of the magnet into the coil and magnetic attraction opposes the movement of the magnet out of the coil.

First it was necessary to overcome the force of repulsion in order to push the permanent magnet down in the coil; then it was necessary to overcome the force of attraction in order to pull the magnet out of the coil. These examples serve to illustrate the application of Lenz's Law to a coil. The direction of the current flow through the coil at A and at B, Fig. 9, can be proved by the left-hand rule as given in a preceding lesson. The current flow through a coil will always be in such a direction as to oppose the motion of a magnetic field which induced the voltage in the coil. This is Lenz's Law.

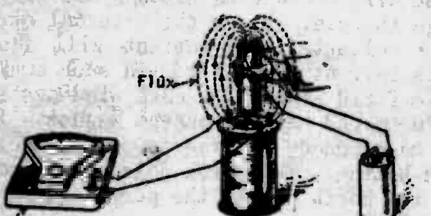


Fig. 10 Illustrating the simple process of mutual induction by moving an electromagnet in and out of a stationary coil.

5. MUTUAL INDUCTION. Instead of using a permanent magnet for the induction of a voltage in a coil as shown in Fig. 9, let us use an electromagnet as shown in Fig. 10. The battery in Fig. 10 is forcing a current through the movable coil which is being held above

the stationary coil. As a general rule, the strength of the magnetic field surrounding an electromagnet is much stronger than a magnetic field surrounding a permanent magnet. The magnetic field surrounding an electromagnet has the same properties as the magnetic field surrounding a permanent magnet. Hence, as the electromagnet in Fig. 10 is dropped down through the center of the stationary coil, a voltage will be induced in the stationary coil. The strength of this voltage will depend upon the same factors which govern the voltage induced in a coil by a permanent magnet. They are:

1. The strength of the field surrounding the electromagnet.
2. The speed at which the electromagnet is moved through the stationary coil.
3. The number of turns on the stationary coil.

Lenz's Law applies to this electromagnetic circuit the same as it applied to the permanent magnetic circuit. There is no difference between the induction of a voltage in a coil with the field surrounding an electromagnet and the induction of a voltage in a coil with the field surrounding a permanent magnet. The only exception is that, as stated before, the field around an electromagnet is usually stronger than the field around a permanent magnet; hence, the use of an electromagnet generally results in the induction of a greater voltage.

As long as there is a relative movement between the electromagnet and the turns on the coil shown in Fig. 10, there will be a voltage induced in the coil. At this point, let us pause briefly and review exactly what is taking place in the circuit. First, we have an electrical voltage producing a current flow through the movable coil, thus causing the movable coil to become an electromagnet. Then, by a relative motion, between this electromagnet and a stationary coil, a voltage is being produced in the stationary coil. Notice that there is no direct connection between the electromagnet and the stationary coil. The only relationship between the electromagnet and the stationary coil is that the process of induction is occurring between them. Whenever induction occurs between two coils, the process is known as mutual induction. A more complete definition is: *Mutual induction is the transfer of an electrical voltage from one coil or circuit into another coil or circuit by means of the relative motion between a magnetic field and a conductor.*

When speaking of the mutual induction between two coils, the coil to which the voltage is applied is always called the primary coil and the coil into which the voltage is induced is always called the secondary coil. The process of transferring an electrical voltage from a primary coil to a secondary coil depends entirely upon the fact that the coils are so mutually related to each other that the process of induction can take place.

6. **EFFECT OF DC THROUGH THE PRIMARY.** The magnetic field surrounding the current-carrying coil in Fig. 10 is a steady field, because the current passing through the coil does not change. If the electromagnet were allowed to rest at the bottom of the stationary coil, there would be no relative movement between the mag-

netic flux and the turns on the coil; hence, there would be no voltage induced. Let us assume that the electromagnet (primary coil) is allowed to rest at the bottom of the stationary coil, then break one of the connecting leads as shown in Fig. 11. When this wire is broken, there will be no current passing through the primary coil; hence, the field which formerly existed around it will collapse. This field, in collapsing, will fall back through the turns on the coil, resulting in an instantaneous voltage being induced in the coil. Now suppose that we touch the two broken ends together, thus

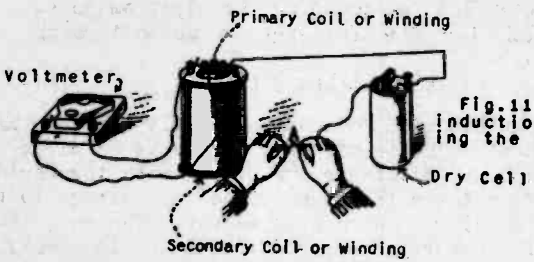


Fig.11 Illustrating mutual induction by making and breaking the primary circuit.

allowing a current to again pass through the primary coil. As the current flows through the primary coil again, the magnetic field builds up around it. The turns on the coil are again cut by the expanding field and another voltage is induced in the secondary. This induced voltage, however, is an instantaneous voltage, because mutual induction occurs only while the field is expanding outward from the primary coil. As soon as the expanding field attains its maximum strength, the lines of force around the primary will remain stationary and there will be no mutual induction into the secondary coil. Breaking the circuit again would allow the magnetic field to collapse, resulting in another instantaneous induced voltage.

From this we may conclude that when a pure DC voltage is applied to the primary, a voltage will be induced in the secondary only while the field around the primary is building up to its maximum value. Then, if the primary circuit is opened, the collapsing magnetic field will again induce an instantaneous voltage in the secondary. As long as the current through the stationary primary coil remains at a steady value, there will be no induction into the secondary because there is no relative movement between the magnetic field around the primary and the turns on the secondary.

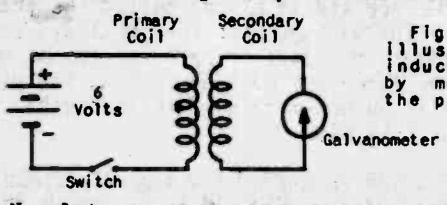
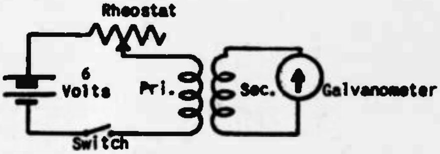


Fig.12 Wiring diagram illustrating how mutual induction can be secured by making and breaking the primary circuit.

Now let us refer to the wiring diagram shown in Fig. 12. In this circuit, the six-volt battery is connected through a switch to the primary coil and a galvanometer is connected across the secondary coil. As long as the switch in the primary circuit remains open, there will be no current passing through the primary; hence, no voltage will be induced in the secondary. When the switch in the primary circuit is closed, the current will build up to a certain value through the primary coil and, as this current builds up, the magnetic field will be expanding around the primary coil, cutting through the turns of the secondary coil and inducing a voltage therein. This voltage will be indicated by a momentary deflection of the galvanometer needle in one direction; for example, to the right. Thereafter, as long as the switch remains closed, the magnetic field around the primary will remain stationary and since there is no relative movement between the field and the secondary turns, the galvanometer will be reading zero at its center position. Now, suppose that the switch in the primary circuit is opened. As the switch is opened, the current through the primary will drop to zero; hence, the magnetic field which formerly existed around the primary coil will collapse. In collapsing, this magnetic field will cut through the turns on the secondary coil, resulting in another instantaneous voltage being induced in the secondary. This voltage will be indicated by a momentary deflection of the galvanometer. Since the galvanometer needle indicated to the right when the switch was closed, it will deflect to the left when the switch is opened.

Fig.13 A rheostat has been inserted for the purpose of changing the primary current.



Let us next investigate the effect of a pulsating DC current through the primary. Referring to Fig. 13, the same circuit is shown as in Fig. 12, except that a rheostat has been connected in series with the primary. Now, when the switch is closed in the primary circuit, a momentary deflection of the galvanometer will indicate a voltage being induced in the secondary, after which the needle will return to zero. The current passing through the primary winding can be varied by changing the movable arm on the rheostat which is connected in series with the primary circuit. Moving the rheostat arm in either direction will change the current. If it is moved toward the left, the resistance in the primary circuit will be decreased and the current will increase. As the current increases, the magnetic field around the primary expands, cutting through the secondary turns and resulting in an induced voltage as indicated by a galvanometer deflection. Moving the arm on the rheostat to the right will introduce more resistance into the primary circuit, resulting in less current flowing through the primary; hence, the magnetic field around the primary will collapse and another voltage will be induced in the secondary coil as will be indicated by a deflection of the galvanometer needle in the opposite direction. Any change in the position of the movable arm on the rheostat will change the current through the primary, thus changing the magnetic field around the primary, resulting in a voltage being induced in the secondary.

From this discussion, it should be evident that a DC current passing through a primary coil will not induce a voltage into the secondary; however, when a pulsating DC flows through the primary, a voltage will be induced on the secondary side.

7. **THE EFFECT OF AN ALTERNATING CURRENT THROUGH A COIL.** In a previous lesson we learned that an alternating current may be represented by a diagram known as a "sine wave". When an alternating current is flowing in sine wave form, the current starts from zero, rises to its maximum amplitude on the positive alternation, then decreases to zero, rises again to its maximum amplitude on the negative alternation and decreases back to zero, thus completing one cycle. The succeeding cycles are exactly the same. When such a current is passed through a coil, the magnetic field

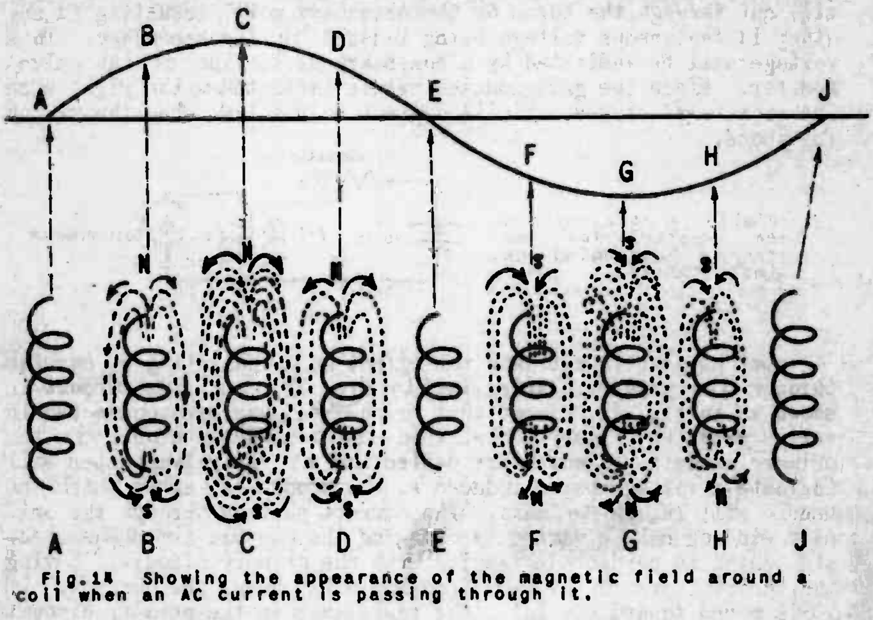


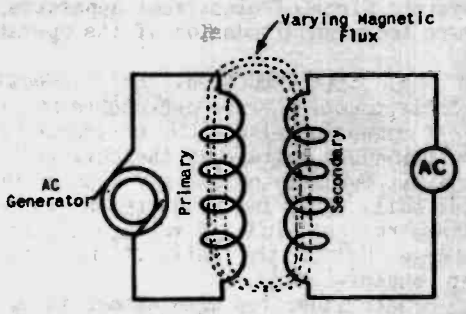
Fig.14 Showing the appearance of the magnetic field around a coil when an AC current is passing through it.

produced around the coil will be as represented in Fig. 14. For simplicity, the connecting wires to the coil and the AC generator have been omitted. At A, the coil is shown with no current passing through it and, naturally, there will be no magnetic field around the coil. As the alternating current rises to its maximum amplitude on the positive alternation, the magnetic field about the coil gradually becomes stronger. When the current has increased to half its maximum amplitude on the positive alternation, the field around the coil will be shown at B. At C, the field strength around the coil is shown corresponding to the maximum current which will be flowing on the positive alternation. As the current decreases in amplitude on the positive alternation, the field strength around the coil will decrease as shown at D. When the current reaches zero to complete the positive alternation, there will be no field around the coil as shown at E. Notice that on the positive alternation, the direction of the magnetic field around the coil has been such as to create a north pole at the top of the coil and a south pole at the bottom of the coil.

As the alternating current reverses its direction of flow, the current passing through the coil will reverse direction; hence, the magnetic field set up around the coil will be of opposite polarity; that is, the bottom of the coil will now be north and the top south. As the current rises to its maximum amplitude on the negative alternation, the magnetic field about the coil will build up as shown at F, reaching a maximum at G. Then, as the current recedes to zero on the negative alternation, the magnetic field will gradually decrease, becoming zero at J.

As the alternating current continues to flow through the coil, the magnetic field will be built up from zero to maximum; then as the current recedes to zero, the magnetic field will collapse accordingly. The changes in the magnetic field around the coil are always in direct relation to the current which is passing through the coil. At every increase or decrease of current through the coil windings, the magnetic field surrounding the coil will change accordingly.

Fig.15 When an AC current is passing through the primary, an AC voltage will be induced in the secondary.



8. **ALTERNATING CURRENT THROUGH THE PRIMARY COIL.** Referring to Fig. 15, a primary coil is shown connected across the alternating voltage output of an AC generator. The AC generator will force an AC current through the primary coil and, as just explained, the magnetic field around the primary coil is constantly varying. Since a second coil (the secondary) is located within this varying field, it is to be expected that mutual induction will occur between the two coils. As the current through the primary increases, the magnetic field expands and the lines of force cut through the secondary turns, thus inducing a voltage. Likewise as the current decreases, the lines of force around the primary collapse, again cutting the turns of the secondary coil and inducing a voltage. This will occur on the negative alternation as well as on the positive alternation, the only difference being that the field is in the op-

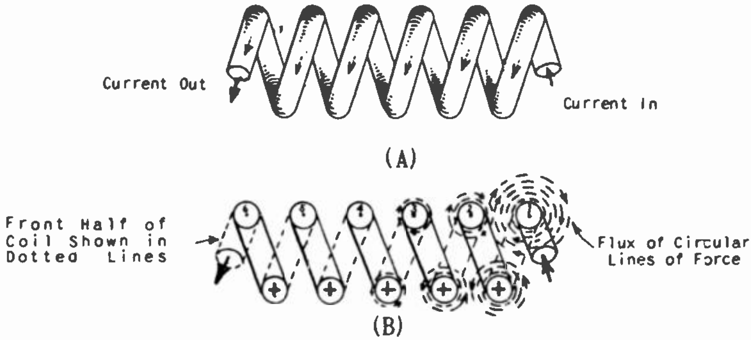
posite direction; hence, a voltage of opposite polarity will be induced in the secondary. Since the primary current is alternating, that is, first passing in one direction, then in the opposite direction through the primary coil, the voltage induced in the secondary will also be alternating in character. The AC voltmeter connected across the secondary will indicate the value of the AC voltage induced in the secondary coil. Bear in mind that a DC voltmeter cannot be used to measure this secondary voltage.

Notice in Fig. 15 that we are actually transferring a voltage from the primary circuit into the secondary circuit without any direct physical connection between the two circuits. The only common connection is the varying magnetic field around the primary. This process of transferring an electrical voltage from the primary circuit to the secondary circuit has previously been defined. It is called "mutual induction". A transformation is actually taking place; that is, electrical power is being transferred from one circuit into another circuit and, for this reason, a device of this kind is commonly called a transformer. A transformer may be defined as *a piece of electrical apparatus consisting of two or more coils placed in inductive relationship with each other.* By the expression "inductive relationship" is meant that the two or more coils are so situated and arranged that the varying magnetic field around one cuts through the turns of the other, thus allowing the process of mutual induction to occur. A transformer is a very important piece of electrical apparatus, and later in this lesson, a more thorough discussion of its operation will be given.

9. SELF INDUCTION. *Self induction is that action occurring within a coil whereby any change in the current passing through the coil causes a voltage to be induced within the coil itself.* This self-induced voltage in the coil will always be in such a direction that it tends to oppose any change in the current passing through the coil. This latter statement is in agreement with Lenz's Law. Since the self-induced voltage always tends to oppose any current change through the coil, it is often called the counter-voltage or counter-E.M.F.

Self induction also occurs in a straight conductor; however, this action is of little consequence at the present time in our studies. A complete discussion will be given later when it has a direct application.

At A, Fig. 16, a coil of wire is shown with a current passing through it. The direction of the current is shown by the arrows, so the direction of the magnetic field which will be built up around the individual turns can be determined by using the left-hand rule. The magnetic field is not shown surrounding the coil at A; however, it should be remembered that whenever a current passes through any coil, a magnetic field will be set up around the coil, thus forming an electromagnet. The object of these two drawings is to illustrate the magnetic field around the individual turns, rather than the entire field around the complete coil. A cross-sectional view of the coil is shown at B, Fig. 16. A view such as this is obtained when the coil at A is sliced in half from end to end. Removing the front half of the coil and allowing the rear half to remain in place provides the view as shown at B. Assuming that the current is entering the coil from the right-hand side, the magnetic field will be built up around the first turn marked 1 before it is built up around the next turn, and a magnetic field will be built up around the second turn marked 2 before it is built up around the third turn marked 3, etc. The expanding magnetic field around the first turn 1 is shown and it can be seen that, as this magnetic field expands, it will cut through the second turn. Likewise, as the current continues to increase through all of the remaining turns on the coil, the magnetic field will expand from each individual turn, and in so doing, wiol cut through the adjacent or neighboring turns on the coil. Of course, as soon as the current reaches its maximum value (if it is a DC current), the magnetic field will no longer expand around the individual turns and the adjacent turns will not be cut.



A Dot (·) in the Sectional End of a Conductor Indicates that the Direction of Current is Out of the Paper Toward the Reader. A Cross (+) indicates that the Current is Flowing Away from the Reader.

Fig.16 Drawings to illustrate how an expanding or collapsing field around one turn on a coil will cut through the neighboring turns.

From the fundamental Law of Induction, we know that whenever a conductor is cut by magnetic lines of force, a voltage is induced. There are no exceptions to this law, so it follows that *as the current begins to flow through the coil, the expanding magnetic field produced around each individual turn will cut through the neighboring turns on the coil and induce a voltage therein.* Here we actually have a voltage being induced within the coil itself, due to the current change occurring through the coil windings. If the current passing through the coil is a steady DC current, after it has once reached its maximum value, it will not change in amplitude and there will be no changing field around the individual turns; hence, there will not be a self-induced voltage. When the switch in a DC circuit is opened, the expanded magnetic field around each turn collapses. In collapsing, the field again cuts through the adjacent turns on the coil and produces a self-induced voltage therein.

Self induction will occur in a DC circuit whenever the switch in the DC circuit is closed or opened, because either operation will cause a change in the current passing through the coil.

When a pulsating DC current is passing through a coil, the current will be continuously varying in amplitude, so the magnetic field around the individual turns will be constantly in motion. When the field is expanding, there will be a self-induced voltage in the coil, and when the field is collapsing, there will be a self-induced voltage. The same is true when an alternating current is passing through the coil, because, from previous explanations, we know that an alternating current constantly varies in both amplitude and direction of flow.

It should be thoroughly understood that a self-induced voltage will be generated or produced within a coil *only when the current passing through the coil changes in value.* The change can either be an increase in current or a decrease in current. Also, the direction of the current flow is immaterial.

From Lenz's Law, we find that *the self-induced voltage in a coil will be in the opposite direction to the applied voltage.* This means that the self-induced voltage, at every instant, will be in opposition to the applied voltage. If the applied voltage is attempting to cause a current increase through the coil, the counter-voltage will be in opposition to the increase; in other words, the self-induced counter-voltage will be attempting to hold the current down or tending to keep it from increasing to its maximum value. Likewise, if the applied voltage is attempting to cause a current decrease through the coil, the self-induced counter-voltage will be opposing this decrease; that is, the counter-voltage will tend to maintain a current flow through the coil.

10. INDUCTIVE REACTANCE. In a DC circuit containing only a pure resistance, the total opposition to the passage of the DC current through the circuit will be the measured resistance in ohms. Also, in an AC circuit containing only a pure resistance, the opposition offered to the passage of current through the circuit will be the measured resistance in ohms. Hence, in any electrical circuit in which only pure resistance is present, the only opposition offered to the current flow through the circuit will be the pure resistance. Ohm's Law may be applied directly to the circuit in this case; that is, $I = E \div R$; $E = I \times R$; $R = E \div I$.

When a coil is contained in a DC circuit, there is opposition to the current increase when the switch is closed and opposition to the current decrease when the switch is opened. During the lapse of time between the closing of the switch and the opening of the switch, the DC current flowing through the coil remains at a steady value and there is no self-induction within the coil; hence, the only opposition offered to the DC current through it will be pure resistance of the coil winding. Ohm's Law may be applied directly to this DC circuit after the switch has been closed, but as soon as the switch is opened, Ohm's Law will not apply. This is because there is self-induction occurring within the coil as the magnetic field collapses and the total opposition offered to the current will be greater than just the pure resistance alone.

In a pulsating DC circuit, where the current through the coil is changing in amplitude, the current changes will be opposed by the counter voltages of self-induction as well as the resistance of the coil. The same is true in an AC circuit. Since an AC current continuously changes in both amplitude and direction, every change of current through the coil will be opposed by the counter-voltage of self induction as well as by the resistance of the coil winding.

From this, it is apparent that whenever a changing current (pulsating DC or AC) passes through a coil, the opposition offered to the passage of current through the coil consists of not only the pure DC resistance of the coil, but also is opposed by the counter-voltage of self induction which is generated by every current change. These two forms of opposition are entirely different in nature. The first (pure resistance) is due to the opposition offered to the passage of electrons from atom to atom within the conductor. For this reason, it is often called the *frictional or ohmic resistance*. The second form of opposition is due entirely to the self-induction occurring within the coil. It would not be proper to call this second form of opposition, "resistance", because its nature does not coincide in any way with our previous definition of pure resistance. Remember that pure resistance is determined by the physical properties of a conductor; that is, the length, diameter, kind and temperature of the conductor. The counter-E.M.F. of self induction generated within a coil whenever the current changes is not determined by the kind, length, temperature or the diameter of the conductor, so we cannot measure the opposing effect of the counter-E.M.F. of self induction in a coil in terms of "resistance". A special term is used to designate this form of opposition; the term is inductive reactance.

Inductive reactance is defined as the opposition offered to the passage of a changing current through a coil. The word "reactance" is used instead of the word "resistance" so as to prevent the possibility of confusion between these two forms of opposition to the current flow. In the future, whenever the word "resistance" is used, bear in mind that this means only the frictional opposition offered by a conductor and is determined by the physical properties of it. Also, when the word "reactance" is used, it means the opposition resulting from the counter-voltage produced within the coil itself, due to self induction.

Even though these two forms of opposition are different in nature, both of them are effective in opposing a current flow through a coil; hence, they are both measured in ohms.

Before explaining how the inductive reactance of a coil may be calculated, let us follow through an example, explaining the information just given in a more practical way.

Referring to Fig. 17, the iron core coil L is placed in series with an ordinary light bulb. A double pole, double throw (DPDT) switch is connected in such a manner that either the 110 volts DC from the battery or the 110 volts AC from the generator may be applied across the series combination of the iron core coil and light bulb. When the DPDT is thrown in the downward direction, 110 volts DC from the battery will be applied across the lamp and coil, resulting in the lamp becoming lighted to nearly full brilliance.

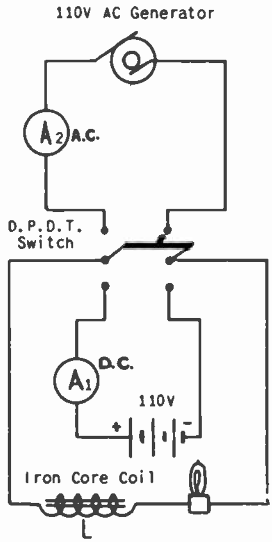


Fig.17 Circuit arrangement whereby 110 volts AC or DC may be applied across the coil and lamp. This demonstrates the inductive reactance of a coil when AC flows through it.

The DC meter A_1 will indicate the amount of current passing through the series circuit. Now when the DPDT switch is thrown in the upward position, the 110 volts from the AC generator will be applied across the iron core coil and electric lamp. With the AC voltage applied, the lamp will glow very dimly, if at all. The AC ammeter A_2 will indicate the amount of AC current passing through the series circuit. By comparing the reading of the DC meter A_1 and the AC meter A_2, we will find that the DC meter indicates a much higher current, even though the applied voltage in each case is the same.

The reason for this extreme difference in the meter readings can be explained as follows. When the DC voltage is applied across the iron core coil and lamp, the only opposition in series with the lamp is the pure DC resistance of the iron core coil winding. This will be very low, because iron core coils are usually wound with large copper wire. The total resistance is possibly around 10 or 15 ohms. This low resistance allows a high DC current to flow through the circuit and the lamp is illuminated to nearly full brilliancy. When the AC voltage is applied across the coil and lamp, due to the counter-voltage produced by self-induction occurring within the coil, the opposition offered by the coil to the passage of the AC current is tremendously high in comparison with its resistance. The inductive reactance of the coil will be many times the DC resistance. Since the opposition offered to the passage of AC current through the series circuit is greater than the opposition offered to the passage of DC current, an extremely low AC current will flow and the electric lamp will become barely illuminated, if at all.

This example illustrates the effect of inductive reactance in a circuit containing a coil through which a changing current is flowing. The inductive reactance constitutes nearly all of the opposition that is offered to the passage of current through the AC circuit. However, the DC or ohmic resistance of the coil will also oppose the flow of the AC current.

11. EFFECT OF FREQUENCY ON INDUCTIVE REACTANCE. In order to determine the inductive reactance (measured in ohms) offered by a coil to the passage of a changing current through it, it is necessary to take into consideration two factors; namely, the frequency of the current passing through the coil and the inductance of the coil. First, let us see how the reactance of a coil is affected when a current changing at a definite speed is passing through it.

When discussing the process of induction, we found that one of the three factors which determined the voltage induced in a coil was "the speed of the magnetic field changes". It was stated: If the magnetic field is changing rapidly, there will be a greater number of lines of force cutting through the turns on the coil in a given length of time; hence, the induced voltage will be greater. Since the frequency of a current means the number of cycles per second, we know that if a low-frequency current is passing through a coil, the magnetic field surrounding the individual turns will rise and fall rather slowly, whereas when a high-frequency current flows through a coil, the magnetic field will expand and collapse very rapidly. If the changing magnetic field is cutting through the conductors on the coil more times per second, it is to be expected that a greater counter-voltage will be self-induced in the coil and a greater opposition to the current, or "inductive reactance", will result.

For example, assume that a low-frequency current such as shown in Fig. 18 is passing through a coil. The frequency of this cur-

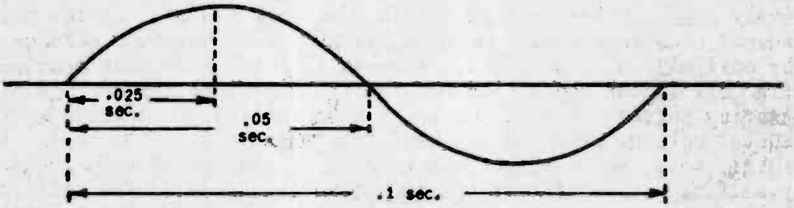


Fig. 18 One cycle of a 10 c.p.s. alternating current, showing the time in seconds for portions of the cycle to elapse.

rent is 10 cycles per second; hence, .1 second will be required to complete one cycle. If .1 second is required to complete one cycle, then only half this time or .05 second will be required to complete one alternation. Likewise, the time required for the current to increase from zero to maximum amplitude on the positive alternation will be one-half the time required to complete the positive alternation. This is one-half of .05 or .025 second. When the current through the coil is changing very slowly, as it is in this case, the self-induced voltage within the coil will be comparatively low. This is due to the fact that the number of magnetic lines of force cutting through the adjacent conductors on the coil (per second) are relatively few. Since the self-induced counter-voltage is low, the inductive reactance of the coil will also be low.

Now, suppose that the frequency of the current passing through the coil is increased to 1,000 cycles per second. One cycle of this 1,000 cycles per second current is shown in Fig. 19. Since there

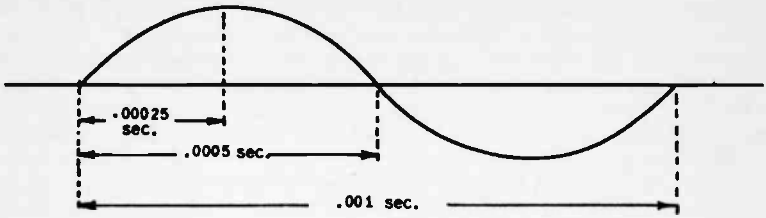


Fig.19 One cycle of a 1,000 c.p.s. alternating current, showing the time in seconds for portions of the cycle to elapse.

are 100 times as many cycles occurring in the same length of time as in Fig. 18, the time required to complete each cycle will be less than with the 10-cycle current. As shown on the drawing, the time required to complete one cycle is .001 second. It follows that the time required to complete one alternation is .0005 second and the time required for the current to change from zero to its maximum amplitude on the positive alternation is only .00025 second. If the current change is sufficiently rapid to rise from zero to its maximum value in .00025 second, the magnetic field produced by the current change will be moving very fast; hence, the speed at which the magnetic lines of force cut through the adjacent turns on the coil will be much faster than when the ten-cycle current was passing through the coil. This causes the self induction of a relatively high counter-voltage within the coil itself. If the self-induced counter-voltage is high, then the inductive reactance of the coil will also be high. Remember that the inductive reactance of a coil is the opposition offered by a coil to the passage of a changing current through it and the opposition is caused by the counter-voltage produced by self-induction within the coil. Any change, then, which affects the counter-voltage produced in the coil by self induction affects the inductive reactance of the coil in a similar manner. If the counter-voltage is increased, the inductive reactance will be increased and if the counter-voltage is decreased, the inductive reactance decreases.

From this discussion it should be concluded that the higher the frequency of the current changes passing through a coil, the greater will be the self-induced voltage within the coil and the greater will be the inductive reactance. *THE HIGHER THE FREQUENCY, THE HIGHER THE INDUCTIVE REACTANCE.*

When a pulsating direct current is passing through a coil, inductive reactance will oppose the current changes the same as when an alternating current is flowing through a coil. Even though a pulsating current does not change its direction of flow, the amplitude will be constantly varying, so the magnetic field surrounding the turns on the coil will be constantly expanding or collapsing, thus generating a counter-voltage within the coil and causing the current changes to be opposed by inductive reactance.

As will be more completely explained in a following lesson, a pulsating direct current may be likened to an alternating current even though the pulsating direct current does not change its direction of flow. A pulsating direct current is increasing above and decreasing below a normal or average value. This average value may be compared to the zero line generally shown through the center of an AC sine wave. Each pulsation of a pulsating direct current has the same effect as one cycle of an alternating current; hence, pulsating direct current with 120 pulsations per second is similar to an alternating current of 120 cycles per second. If a pulsating direct current is passing through a coil, the pulsations per second are always considered instead of the cycles per second, when calculating the inductive reactance.

12. **THE INDUCTANCE OF A COIL.** Inductance is defined as the ability of any electrical circuit to produce a counter-voltage by self-induction when the current passing through the circuit changes or varies. This definition is quite broad and can be applied to a single conductor, a single coil or a transformer. This means that a single wire will have "inductance", all coils will have "inductance" and all transformers will have "inductance". In the case of transformers, the inductance is generally called the "mutual inductance", which refers to the ability of the primary coil to induce a voltage into the secondary coil. *When the term "inductance" is applied to a single coil, it means the ability of a coil to induce a counter-voltage within itself whenever the current passing through it changes or varies.* The inductance possessed by a straight conductor will be found to be of importance in later discussions; however, at the present time, we shall not concern ourselves with it.

Whenever the word "inductance" is used, it should also be associated directly with the word "ability". It will be noticed that in the definition of inductance, it was said that inductance refers to the ability of a coil or circuit to generate a counter-voltage by self-induction, when the current passing through the circuit changes or varies. Emphasis should be placed on the word "ability" in this definition, because inductance is not a process nor an act of generating. It will be recalled from previous definition that the actual *process of generating* a counter-voltage by self-induction is known as induction, not inductance.

Since the word "inductance" refers to the ability of a coil to perform a certain purpose, apparently it is a property of the coil and will be determined by the physical construction of the coil. The inductance of a coil is determined by four factors:

1. The diameter of the coil.
2. The length of the coil.
3. The number of turns on the coil.
4. The permeability of the core.

Of the four factors just given, the length of the coil winding and the number of turns on the coil take into consideration the size of the wire used for the winding and the spacing between the turns.

The four factors which determine the inductance of a coil are all physical properties of the coil itself and when united will determine the final appearance of the coil. If the diameter of a coil is made larger, the inductance of the coil will be greater; a long coil will have a greater inductance than a short coil; if more turns of wire are placed on a coil, the inductance will be greater and an iron core coil will always have a much higher inductance than an air core coil.

It has been learned that the amount of current passing through a resistance will change the temperature of the resistance in accordance with the I^2R Law. Since the temperature of a resistance is one of the factors determining the number of ohms which it possesses, it might be stated that the current passing through a resistor will, in this way, affect its resistance.

A similar fact is true of a coil. We know that when current passes through a coil, a magnetic field is set up around the coil and there will be magnetic lines of force passing through the center of the coil. If the center of the coil consists of air, there is no possibility of the air becoming magnetically saturated; hence, its permeability will not change and the current passing through the air core coil will have no effect upon its inductance. However, if the core of a coil is made of iron, then the magnetic flux passing through the iron core will affect its permeability. The principle of magnetic saturation of an iron core has previously been discussed and it was stated therein that the permeability of iron will vary somewhat with different degrees of magnetization. After iron has been magnetized to a certain degree, it is impossible to increase the degree of magnetization further. The point of change is called "magnetic saturation". As the extent of magnetization is increased, the permeability of the iron will decrease rather than increase. From this it can be reasoned that if the current passing through an iron core coil is sufficiently high to set up a magnetic flux through the iron core strong enough to saturate the iron, the permeability of the core will decrease and the inductance of the coil will be decreased to a noticeable extent. It is only in this way that the current passing through a coil can affect its inductance. Otherwise, the inductance of a coil is determined entirely by the four physical properties previously stated.

The physical properties possessed by a resistor determine the number of ohms resistance which it possesses and the ohm is the unit used for measuring the resistance of a conductor. It is likewise necessary to select a unit for measuring the amount of inductance possessed by a coil or inductor. "Inductor" is a word sometimes used instead of "coil". The unit chosen for measuring inductance is the "henry"[1]. A coil or circuit has an inductance of one henry when a current changing at the rate of 1 ampere per second

[1] The unit of inductance, the henry, is so called in honor of the American scientist, Joseph Henry, because of his important magnetic discoveries.

induces a counter-voltage of one volt in the coil or circuit. This physical definition for the henry need not be memorized. It is more important to clearly understand that the number of "henries" of inductance possessed by a coil is a measurement of the ability of that coil to induce a counter-voltage within itself when the current passing through it changes. This may be compared to the unit "ohm". We are quite familiar with the fact that the number of ohms possessed by a conductor refers to the ability of a conductor to oppose or resist the passage of current through it. The "henry" and the "ohm" are both units of measurement; the "henry" for a coil or inductor and the "ohm" for a resistor.

The prefixes, "milli" and "micro", are attached to the henry in order to designate .001 henry and .000001 henry, respectively. It is necessary to learn the following equivalents:

1 henry = 1,000 millihenries
1 microhenry = .000001 henry

To become familiar with the use of these units for measuring the inductance of a coil, let us refer to the photographs shown in Fig. 20. The air core coil shown at A has an inductance of approx-

(A) (B) (C)

Fig. 20 Illustration of 3 coils. The air core coil at (A) has 2½ millihenries inductance, the iron core coil at (B) has 30 henries inductance and the air core coil at (C) has about 100 millihenries inductance.

imately 2.5 millihenries. The inductance of the iron core coil at B is 30 henries and the inductance of the air core coil at C is about 100 millihenries.

Later in our study, formulas will be given for the calculation of the inductance of a coil when the physical properties of it are known. When we discuss the design of Radio and Television circuits, we shall find that it is necessary to use coils possessing a definite number of henries of inductance in order to make the circuit function properly. After determining how much inductance is necessary in the circuit, the next problem is to calculate the size and length of wire, the diameter of the core and the kind of core which will be necessary to give that amount of inductance. This work will be very interesting, but before attempting such design procedure, it is necessary to understand the fundamental operation of a coil in a circuit.

13. HOW INDUCTANCE AFFECTS INDUCTIVE REACTANCE. From previous discussion we found that the inductive reactance of a coil means the opposition which is offered to the passage of a changing current through a coil. We also learned that the total opposition consists of not only the ohmic resistance possessed by the wire,

but also of the opposition offered by the counter-voltage induced within the coil itself when the current changes; that is, inductive reactance. (Remember that a coil does not have inductive reactance when a DC current is passing through it.) The inductive reactance of a coil depends partially upon the frequency of the current passing through it.

Another factor which will affect the inductive reactance of a coil is its inductance. A coil possessing a low inductance will not have as much ability to generate a counter-voltage within itself as a coil possessing a high inductance. Since the self-induced counter-voltage is higher when the inductance of the coil is higher, it is logical to conclude that the opposition offered to the passage of current through the coil will be greater. Remembering that the inductive reactance of a coil is the opposition offered by the coil to the passage of current through it, it follows that *THE HIGHER THE INDUCTANCE OF A COIL, THE GREATER THE REACTANCE.*

The total inductive reactance of a coil will not depend upon either the frequency or inductance alone, but rather upon the combination of the two. When both the inductance and frequency are low, the reactance will be low, but if both the inductance and frequency are high, the reactance will likewise be high. A fairly high inductive reactance will also be secured if the frequency is low and the inductance is high, or if the inductance is low and the frequency is high. Possibly this combination of factors for determining the inductive reactance of a coil can be seen more clearly from the formula used for the calculation of inductive reactance. This formula is:

$$X_L = 6.28 \times F \times L$$

Where:
- X_L is the inductive reactance in ohms.
- 6.28 is a constant.
- F is the frequency of the current passing through the coil in cycles per second.
- L is the inductance of the coil in henries.

The constant, 6.28, enters into the calculation of the inductive reactance because we are considering that a pure sine wave of alternating current is passing through the coil. From mathematics we learn that one cycle consists of 360 degrees and that 360 degrees consist of 2π radians. The symbol $\pi = 3.14$ (approx.); hence, 2π is 2×3.14 or 6.28. It is not necessary to understand the mathematics involved in the derivation of this constant; however, it must be remembered that this constant (6.28) is always taken into consideration when calculating the inductive reactance of a coil.

Several problems illustrating the use of the inductive reactance formula follows:

Problem 1: Calculate the inductive reactance of a 10 henry coil when a current of 100 cycles is passing through it.

Solution: The formula necessary for the solution is $X_L = 6.28 \times F \times L$. Remember that F must be in cycles and L must be in henries. Since the problem stated that the frequency was in cycles and the inductance was in henries, it is only necessary to substitute these known values in the formula in order to calculate the inductive reactance. Substituting the known values, we have:

$$X_L = 6.28 \times 10 \times 100$$

Now multiply the three figures on the right side of the equation in order to obtain the answer. Multiplying, we have 6.28 × 10 = 62.8, then 62.8 × 100 = 6280. This product of 62,800 is the inductive reactance of the coil in ohms.

Problem 2: Calculate the inductive reactance of a 150 henry coil to a current with a frequency of 25 cycles per second.

Solution: In this problem, the frequency is given in cycles and the inductance in henries so it is only necessary to substitute directly in the formula.

$$X_L = 6.28 \times 150 \times 25$$

Multiplying, we have:

$$X_L = 6.28 \times 150 \times 25$$
$$= 6.28 \times 3{,}750$$
$$= 23{,}550 \text{ ohms.}$$

The answer to the problem is: the inductive reactance is 23,550 ohms.

Problem 3: Calculate the inductive reactance of a 100 millihenry coil to a frequency of 5,000 cycles.

Solution: In this problem, the frequency is given in cycles, but the inductance is in millihenries. Millihenries must be changed to henries before substituting in the inductive reactance formula. Since 1 millihenry equals .001 henry, then 100 millihenries equals 100 × .001 or .1 henry. Now, substituting in the formula, we have:

$$X_L = 6.28 \times 5{,}000 \times .1$$
$$= 31{,}400 \times .1$$
$$= 3{,}140 \text{ ohms.}$$

The answer is 3,140 ohms of inductive reactance.

Problem 4: Calculate the inductive reactance when the frequency is 1,000 kilocycles and the inductance is 200 microhenries.

Solution: In this problem it is necessary to convert the 1,000 kilocycles into cycles and the 200 microhenries into henries. Since 1 kilocycle = 1,000 cycles, then 1,000 kilocycles = 1,000 × 1,000 or 1,000,000 cycles. Since 1 microhenry equals .000001 henry, 200 microhenries = .000001 × 200 or .0002 henry. Now substituting in the formula, we have:

$$X_L = 6.28 \times 1{,}000{,}000 \times .0002$$

(over)

$$= 6,280,000 \times .0002$$

$$= 1,256 \text{ ohms.}$$

The answer to the problem is: The inductive reactance is 1,256 ohms.

This problem can be worked more conveniently by use of the formula:

$$X_L = \frac{6.28 \times \text{kilocycles} \times \text{microhenries}}{1,000}$$

The answer secured will be the same because this formula is derived directly from the original formula. The right side of the original formula is multiplied by 1,000 to change the cycles to kilocycles, then divided by 1,000,000 to change the henries to microhenries. When changing the units in this manner, it is not necessary to change the left side of the equation and the inductive reactance is still in ohms.

Solving the problem by the use of this new formula, we have:

$$X_L = \frac{6.28 \times 1,000 \times 200}{1,000}$$

$$= 6.28 \times 200$$

$$= 1,256 \text{ ohms.}$$

The cancellation shortens the mathematical work considerably.

Problem 5: Calculate the reactance of a 40 henry coil t a frequency of 120 cycles.

Solution: Since the frequency is already in cycles and the inductance in henries, no conversion will be necessary. By direct substitution in the fundamental formula, we have:

$$X_L = 6.28 \times 120 \times 40$$

$$= 753.6 \times 40$$

$$= 30,144 \text{ ohms.}$$

The inductive reactance will be 30,144 ohms.

Problem 6: Calculate the inductive reactance of a 450 microhenry coil when a current of 800 kilocycles is passing through it.

Solution: To use the fundamental formula, it would be necessary to convert kilocycles to cycles and microhenries to henries. The formula given in Problem 4 can be used without these conversions; hence:

$$X_L = \frac{6.28 \times 800 \times 450}{1,000}$$

(Over)

$= 6.28 \times 8 \times 45$

$= 2,260.8$ ohms.

Problem 7: Find the inductive reactance of a 200 millihenry coil to a frequency of 500 kilocycles.

Solution: Converting 200 millihenries to henries, we have $.001 \times 200 = .2$ henry. Converting 500 kilocycles to cycles, we have $500 \times 1,000 = 500,000$ cycles. Substituting these values in the fundamental formula:

$$X_L = 6.28 \times 500,000 \times .2$$

$$= 628,000 \text{ ohms.}$$

This problem can be more easily solved without the necessity of conversions by using the formula:

$$X_L = 6.28 \times \text{kilocycles} \times \text{millihenries}$$

You will notice that in converting from kilocycles to cycles and from millihenries to henries, you multiply by 1,000, then divide by 1,000. If any number is multiplied and divided by the same number, its value will not be changed. For this reason, it is permissible to substitute kilocycles and millihenries directly without converting to cycles and henries. The same answer will be obtained:

$$X_L = 6.28 \times 500 \times 200$$

$$= 628,000 \text{ ohms.}$$

These typical problems should be studied very carefully, then make up several problems of your own. Use these formulas until there is no doubt as to your ability to calculate the inductive reactance of a coil when the frequency of the current and the inductance of the coil are known. A table of inductive reactances for various size coils at different frequencies is given in Fig. 21. These values may be used for practice. This table will be found useful for quick reference in future work.

TABLE OF INDUCTIVE REACTANCES

Coil Inductance in Henries	Reactance in Ohms at Various Frequencies (Cycles)						
	60	100	250	500	1000	10,000	100,000
0.01	3.77	6.28	15.7	31.4	62.8	628	6,280
0.05	18.8	31.4	78.5	157	314	3,140	31,400
0.1	37.7	62.8	157	314	628	6,280	62,800
0.5	188.5	314	785	1,570	3,140	31,400	314,000
1.0	377	628	1,570	3,140	6,280	62,800	628,000
2.0	754	1,256	3,140	6,280	12,560	125,600	1,256,000
5.0	1,885	3,140	7,850	15,700	31,400	314,000	3,140,000
10.0	3,700	6,280	15,700	31,400	62,800	628,000	6,280,000
20.0	7,540	12,560	31,400	62,800	123,600	1,236,000	12,560,000
30.0	11,310	18,840	47,200	94,200	188,400	1,884,000	18,840,000
40.0	15,080	24,720	61,800	123,600	247,200	2,472,000	24,720,000
50.0	18,850	31,400	78,500	157,000	314,000	3,140,000	31,400,000
100.0	37,700	62,800	157,000	314,000	628,000	6,280,000	62,800,000

Fig.21 Reference table giving the inductive reactance for several different size coils at different frequencies.

14. INDUCTORS IN SERIES AND PARALLEL. The words, "coil" and "inductor" are often used interchangeably, the same as the words, "resistance" and "resistor" are used in place of each other.

When coils or inductors are placed in series such as shown in Fig. 22, the inductance of each coil adds to the inductance of the

Fig.22 Coils or inductors in series.

others in the series circuit; hence, the total inductance in the circuit will be equal to the sum of the individual inductances. This method of calculating the total inductance when inductors are connected in series is similar to the method used to calculate the total resistance when resistors are connected in series. When in series, each coil tends to oppose any change in current through the entire circuit, provided the coils are sufficiently far apart or are placed at such angles that there is no magnetic coupling between them. For example, suppose we have three coils connected in series with values of 80 millihenries, 100 millihenries and 70 millihenries respectively. The total inductance in the series circuit would then be: 80 + 100 + 70 or 250 millihenries.

As a general rule: *The total inductance of coils connected in series, when there is no magnetic coupling between them, is the sum of the separate inductances.* This is expressed by the following formula:

$$L_t = L_1 + L_2 + L_3 \ldots\ldots, \text{ etc.}^1$$

Where: L_t is the total inductance of the circuit.
L_1, L_2 and L_3 are the values of the individual inductances.

When coils are connected in parallel as shown in Fig. 23, the

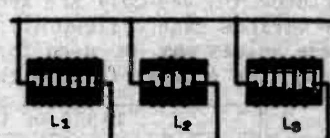


Fig.23 Coils or inductors in parallel.

total inductance of the circuit will be less than the smallest inductance connected in the circuit. The methods employed to calculate the total inductance (effective inductance) when coils are connected in parallel are similar to the methods used for calculating the corresponding conditions existing in a circuit of parallel resistors. The various methods given in Lesson 5 for the calculation of resistors in parallel are also true for coils connected in parallel. The three methods by which it is possible to calculate the ef-

[1] L is the letter always used to abbreviate inductance.

fective inductance of parallel inductors are:

(1) $$L_t = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}} \text{.....etc.}$$

(2) $$L_t = \frac{L_1 \times L_2}{L_1 + L_2}$$

(3) $$L_t = \frac{L_1}{\text{Number of Coils}}$$

These three formulas are used in different types of problems. Formula (1) is used when three or more unequal inductors are in parallel; formula (2) is used when two unequal inductors are in parallel; formula (3) is used when any number of equal inductors are connected in parallel. In order to become proficient in the use of these three formulas, a few examples will be solved.

Example 1: Calculate the effective inductance when three coils of 80 millihenries, 100 millihenries and 70 millihenries respectively are connected in parallel.

Solution: Since the three inductances are of unequal value, it is necessary to use formula (1). Substituting in this formula we have:

$$L_t = \frac{1}{\frac{1}{80} + \frac{1}{100} + \frac{1}{70}}$$

$$= \frac{1}{\frac{35}{2,800} + \frac{28}{2,800} + \frac{40}{2,800}}$$

$$= \frac{1}{\frac{103}{2,800}}$$

$$= \frac{2,800}{103}$$

$$= 27.18 \text{ millihenries}$$

Example 2: Calculate the effective inductance when a 12 henry coil is connected in parallel with a 6-henry coil.

Solution: Formula (2) should be used. Substituting in formula (2), we have:

$$L_t = \frac{12 \times 6}{12 + 6}$$

$$= \frac{72}{18}$$

$$= 4 \text{ henries.}$$

Example 3: What is the effective inductance when 3 coils, 30 henries each, are connected in parallel?

Solution: Substituting in formula (3), we have:

$$L_t = \frac{30}{3}$$

$$= 10 \text{ henries.}$$

15. VARIABLE INDUCTORS. In some types of electrical circuits it is convenient to use variable inductors, the same as variable resistors are often found convenient. Variable inductors are constructed in several different forms. In Fig. 24, two types of variable inductors are shown. The symbol at A is the one most com-

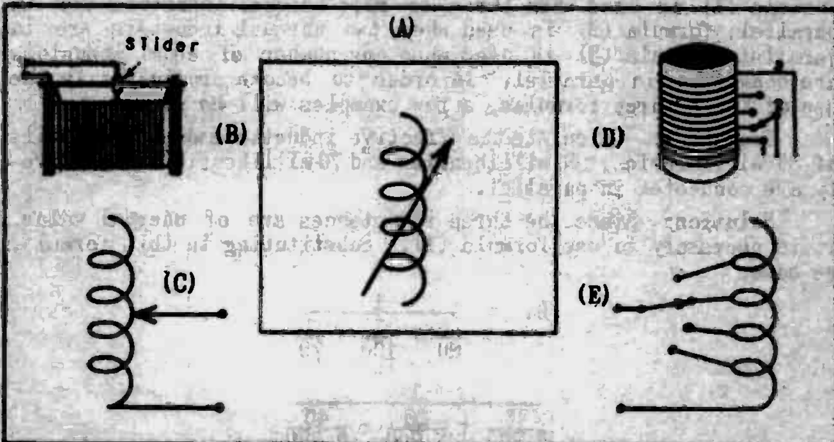


Fig.24 Drawings and symbols for variable inductors.

monly used for representation. It may represent either of the types shown. At B, a variation of the inductance of the coil is secured by means of a slider. When the slider is at the right of the coil, the inductance being used will be maximum. When the slider is moved to the left, the inductance will be less; then when the slider is completely to the left, the inductance in use will be zero. The symbol shown at C is used to represent this type of variable inductor.

The variable inductor, shown at D, has taps brought out at various turns throughout its length. These taps are terminated at a switch which has several contacts. By connecting the top to one side of a circuit and the switch arm to the other, the amount of inductance to be used in the circuit can be controlled by moving the switch arm from one contact point to another. The symbol sometimes used to represent this type of variable inductance is shown at E.

16. **NON-INDUCTIVE COILS.** In some types of electrical circuits it is necessary to employ a coil which is non-inductive. We have learned that the inductance (ability to generate a counter-voltage) of a coil is due to the varying magnetic field set up around the coil when the current flowing through it changes. Therefore, to make a coil non-inductive, the magnetic field about the coil must be cancelled in some way. In Fig. 25, several methods of cancel-

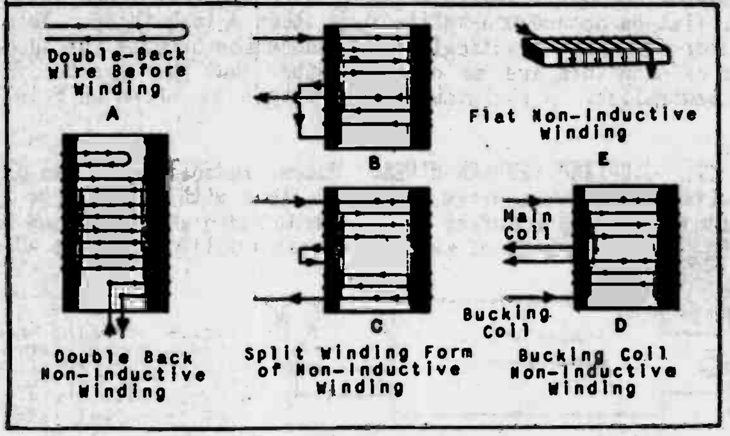


Fig.25 Various types of non-inductive coils.

ling the magnetic field around a coil are shown. At A, the magnetic field around one-half of the winding is neutralized by the field around the other half of the winding. This is accomplished by folding the length of wire to be used at its middle point, then starting from this point, wind both halves at the same time as though they were a single wire, until the ends are reached. The magnetic field produced by the current flowing in one direction through one-half of the winding is equal and opposite the magnetic field produced by the same current flowing in the opposite direction through the other half of the winding. The magnetic fields neutralize each other; hence, the winding has no inductance. At B and C, two other types of non-inductive coils are shown. In both cases, the coil is wound in two parts. One-half of the winding is wound in one direction and the other half is wound in the opposite direction. Thus, the current flowing through the top half of the coil tends to make the top end of the coil a south pole while the current flowing through the bottom half of the coil tends to make the top end a north pole. Since the two magnetic fields are equal to each other and opposite in direction, they will cancel. To make this cancellation complete, there must be the same number of turns on each half of the winding.

The inductance of a given coil can be neutralized by passing current through a separate "bucking winding" with the proper number of turns as shown at D. The bucking coil is properly wound and has the right amount of current passing through it so that its magnetic field is equal and opposite to the field around the coil whose inductance is to be cancelled. By using the left-hand rule, the proper direction for winding the bucking coil can be determined.

Wire-wound resistors are quite common in radio work. They should, however, be absolutely non-inductive since their opposition to the flow of current should be the same regardless of frequency. One way of accomplishing this is to wind the resistance wire on a thin, flat cardboard or bakelite form about ⅛-inch thick. Then the resistor will have practically no inductance because the opposite sides of each turn are so close together that the magnetic fields will neutralize. A resistance of this type is shown at E in Fig. 25.

17. COUPLING BETWEEN WIRES. Mutual induction between parallel wires, or between wires forming a loop with other wires lying outside of the loop are often bothersome in radio and telephone work. In Fig. 26, the heater of a vacuum tube is supplied with the AC cur-

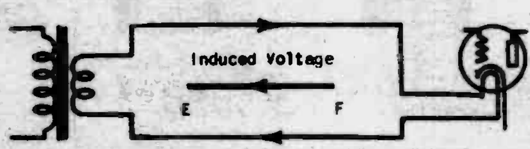


Fig.26 Drawing to illustrate how spaced wires carrying an AC current form a one-turn coil. A voltage will be induced in EF by mutual induction.

rent from the secondary of a step-down transformer. When the two wires leading from the secondary of the transformer to the filament are spaced rather widely, they form a one-turn coil. Since there is an alternating current of 60 cycles per second flowing through the circuit, there will be a magnetic field set up around this coil which varies at the rate of 60 cycles per second. If a conductor such as EF is in the vicinity of this one-turn coil, it will have induced into it a 60-cycle alternating voltage by mutual induction. This mutual induction is very objectionable in closely crowded electrical circuits such as radio sets or telephone cables. In radio sets, the result is a loud hum in the speaker, and in telephone work "cross-talk" is heard.

By running the two wires very closely together, the field around one wire will partially neutralize the field around the other wire, thus making the net magnetic field rather weak. This is shown in Fig. 27. By twisting the wires together as shown in Fig.

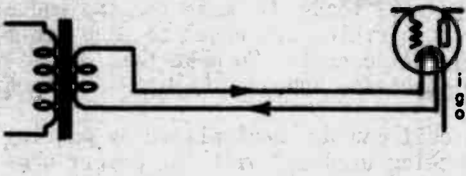


Fig.27 When the wires carrying an AC current are close together, a partial cancellation of the external field results.

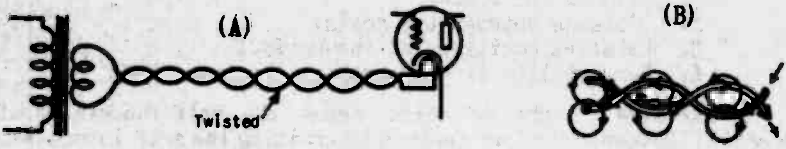


Fig.28 By twisting the wires carrying an AC current, the external magnetic field is reduced to a negligible value. The enlarged section shown at (B) illustrates the cancellation.

28, the external magnetic field produced by one conductor between each twist is opposite in direction to the field produced by the other conductor, thus practically reducing the external field to zero. An enlarged section of the twisted pair of wires is shown at B, Fig. 28. In this drawing, the field cancellation between the wires can easily be seen. All wires which carry 60-cycle AC current in a radio receiver should be twisted in this manner.

18. **MUTUAL INDUCTANCE.** The definition of inductance states: "Inductance is the ability of a coil or circuit to generate a counter-voltage within itself whenever the current through the coil or circuit changes." A complete discussion on the inductance of a single coil, the factors which determine the inductance and the effect of the inductance upon the inductive reactance has been given in foregoing paragraphs. When the inductance of a single coil is being considered, the expression "self inductance" is often used.

Mutual inductance is the ability of one coil or circuit to produce a counter-voltage in a nearby coil or circuit through the process of mutual induction when the current passing through the first circuit changes or varies. The word "mutual" is used in the descriptive phrase because it refers to the relationship existing between two separate circuits.

The expression "mutual inductance" does not refer to the actual process of transferring the electrical energy from a primary circuit into a secondary circuit, but rather refers to the ability of the primary to induce a voltage in the secondary coil or circuit. Again we must emphasize the use of the word "ability" when defining inductance, because for mutual inductance to exist between primary and secondary, it is not necessary to have current passing through the primary coil. A transformer (consisting of a primary and secondary coil) may have several henries of mutual inductance, but there will be no mutual induction taking place from primary to secondary until a changing current passes through the primary coil. Mutual inductance is measured in "henries", the same as self inductance.

We found that the self-inductance of a single coil depends upon the physical properties of that coil; hence, it is logical to conclude that the mutual inductance between two coils will depend upon the physical properties of the coils. The factors determining the mutual inductance between two coils are:

1. Size of the coils.
2. Distance between the coils.
3. Relative positions of the coils.
4. Permeability of core between the two coils.

(1) The size of the two coils, means the self inductance of each coil. (Remember the four factors determining the self inductance of a single coil.) (2) If the secondary coil is moved further away from the primary coil, the number of lines of force around the primary which cut through the turns of the secondary will be less, resulting in a lower secondary voltage. From this, it follows that the mutual inductance will not be as great when the two coils are far apart as it will be when the two coils are close together. (3) If the secondary coil is turned at right angles to the primary coil, there will not be as many lines of force cutting through the secondary turns when current passes through the primary. Hence, the voltage induced in the secondary will be less and the mutual inductance will be correspondingly decreased when the relative positions of the two coils is changed. (4) It has been previously stated that iron has a much higher permeability than air; hence, if iron is used as the material to conduct the lines of force from the primary coil through the turns of the secondary coil, there will be a much greater transfer of energy from primary to secondary, due to this increased magnetic coupling. With the increased number of lines of force cutting through the secondary turns (considering a given current through the primary), there will be a greater secondary voltage produced and the mutual inductance will be greater.

Mutual inductance is the expression commonly used when speaking of the relationship existing between the secondary and primary coils of a transformer. If the transformer is so constructed that the primary and secondary coils are in such a relationship to each other that the mutual inductance is high, this means that extremely "close coupling" exists between the primary and secondary. In other words, the transfer of electrical energy from the primary to the secondary will occur with practically no loss in electrical power. On the other hand, if the primary and secondary coils are so constructed or situated that only a very small voltage is produced in the secondary coil when the current through the primary coil changes, then the mutual inductance between the two coils is extremely low. When this condition exists, the common expression is that the two coils are "loosely coupled". The "inductive coupling between two coils" is an expression commonly used in the same terminology as mutual inductance. The expression "close inductive coupling" means a high mutual inductance and the expression "loose inductive coupling" means a low mutual inductance.

19. TRANSFORMERS. A transformer has previously been explained to consist of one primary coil and one or more secondary coils. The primary coil is that coil to which the voltage is applied, and the secondary coil (or coils) is the winding into which the voltage is

induced. Pictures of typical iron core transformers are shown at A, Fig. 29. The symbol used to represent an iron core transformer

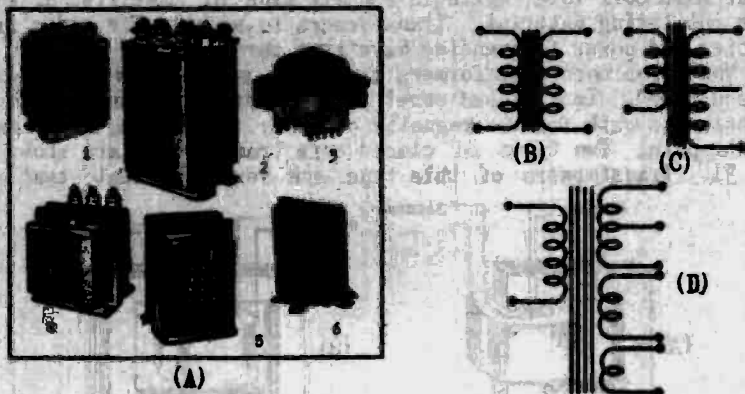


Fig. 29 Various types of iron core transformers. Symbols are shown at (B), (C) and (D).

with a single secondary winding is shown at B. If the secondary winding is tapped at the center, the symbol used will be that shown at C. When a transformer possesses several secondary windings (power transformer) each secondary will be indicated on the symbol as shown at D.

Several air core transformers are shown at A, Fig. 30. The symbols used to represent the various air core transformers are

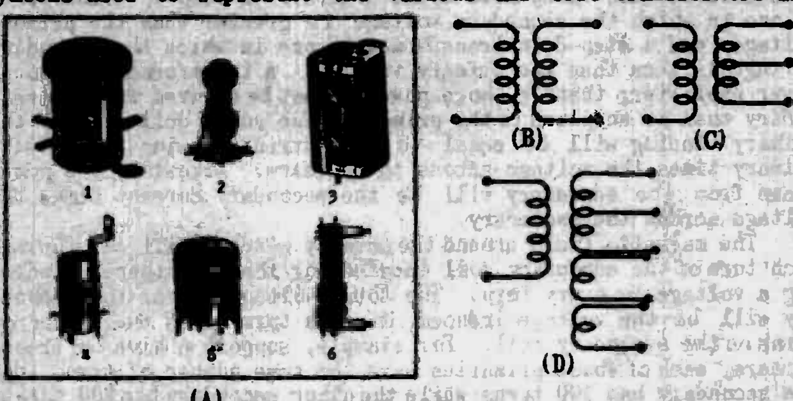


Fig. 30 Various types of air core transformers. Symbols are shown at (B), (C) and (D).

shown at B, C and D. Notice that the only difference between the symbol for an iron core transformer and that for an air core transformer is the presence of the parallel lines drawn between the primary and secondary windings. These lines are often called the "core lines"; that is, they indicate the presence of an iron core between the two windings.

Transformers that are to be used for radio frequencies ordinarily have air cores. The primary and secondary windings are wound on the same coil form, which is usually made of bakelite, or some other insulating material. Transformers to be used for audio frequencies and power frequencies have iron cores.

Most iron core transformers are wound on what is known as a "closed core". In a "closed core" transformer, the iron core forms a continuous path for the magnetic circuit; there being no air gaps in the path. Two types of closed core transformers are shown in Fig. 31. Transformers of this type are very efficient; that is,

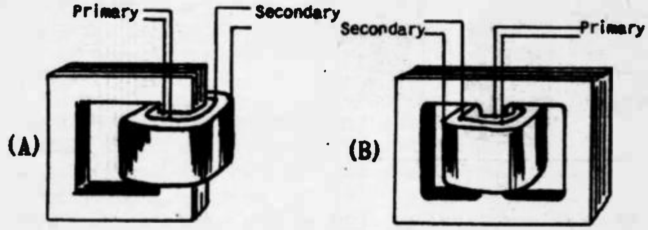


Fig.31 Schematic drawings of closed core transformers. At (A), the windings are on the right leg, and at (B), the windings are on a center leg. Both types are very efficient.

the power which may be taken from the secondary winding is only slightly less than the power delivered to the primary winding, there being very little power lost within the transformer itself. Efficiencies as high as 95% or better are common.

Transformers may be divided into two general classes, "step-up transformers" and "step-down transformers". A step-up transformer is one in which the secondary voltage is greater than the primary voltage, and a step-down transformer is one in which the secondary voltage is less than the primary voltage. A transformer is not a power amplifier; that is, more power cannot be secured from the secondary than is supplied to the primary. The power delivered to the primary winding will be equal to the current flowing through the primary times the voltage across the primary. Likewise, the power drawn from the secondary will be the secondary current times the voltage across the secondary.

The magnetic field around the primary winding will cut through each turn of the secondary coil (neglecting losses), thereby inducing a voltage in every turn. The total voltage across the secondary will be the voltage induced in each turn times the number of turns on the secondary coil. For example, suppose we have two transformers, each of whose primaries have the same number of turns, but one secondary has 100 turns while the other secondary has 300 turns. If the same voltage is applied to both primaries, the same voltage will be induced in each turn of both secondaries, but since one secondary has three times as many turns as the other secondary, the total voltage across that secondary will be three times as high as the voltage across the other secondary. *In a step-up transformer, the secondary has more turns than the primary and in a step-down transformer, the secondary has fewer turns than the primary.*

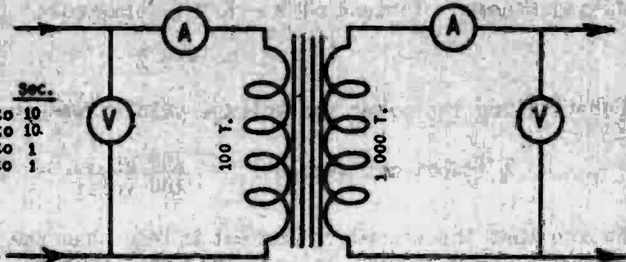


Fig. 32 A 1 to 10 step-up transformer. The chart on the right gives the turns, voltage, current and power ratios from primary to secondary.

In Fig. 32, an iron core transformer is shown with a voltmeter and an ammeter connected in both the primary and secondary circuits. Let us assume that the primary winding has 100 turns and the secondary winding has 1,000 turns. It is properly called a step-up transformer. When 10 volts is applied to the primary, it is found that the secondary voltmeter reads 100 volts. This relationship is expressed by the following equation:

$$(4) \qquad \frac{\text{Secondary Volts}}{\text{Primary Volts}} = \frac{\text{Secondary Turns}}{\text{Primary Turns}}$$

The secondary turns divided by the primary turns of a transformer is known as the "turns ratio" of that transformer. Substituting the voltmeter readings in this equation, we have:

$$\text{Voltage Ratio} \longrightarrow \frac{100 \text{ volts}}{10 \text{ volts}} = \frac{1{,}000 \text{ turns}}{100 \text{ turns}} \longleftarrow \text{Turns Ratio}$$

$$\text{Or:} \quad 10 = 10$$

Neglecting any losses which may occur, the step-up ratio, in voltage, of a transformer is equal to the turns ratio.

Next, let us assume that the primary current is 10 amperes. Calculating the power in the primary, we have:

$$W = E \times I$$

$$= 10 \text{ volts} \times 10 \text{ amperes}$$

$$= 100 \text{ watts.}$$

If there is no power loss in the transformer, it will be possible to secure 100 watts of power from the secondary. To find the secondary current, transpose the original formula for power in the following manner. Instead of $W = E \times I$, transpose[1] it so that:

$$I = W \div E$$

Substituting the power and voltage values, we have:

$$I \text{ (secondary current)} = \frac{100 \text{ watts}}{100 \text{ volts}} = 1 \text{ ampere}$$

Notice that the secondary current is less than the primary current, although the secondary voltage is higher than the primary voltage. *If a transformer steps up the voltage, it will step down the current in the same proportion.* This relationship is expressed by the equation:

$$(5) \qquad \frac{\text{Primary Amperes}}{\text{Secondary Amperes}} = \frac{\text{Secondary Turns}}{\text{Primary Turns}}$$

From equations (4) and (5), a third convenient equation may be formed. Notice that the members on the right side of both of these two equations are exactly the same. Therefore, the two left members will be equal to each other. Such as:

$$(6) \qquad \frac{\text{Secondary Volts}}{\text{Primary Volts}} = \frac{\text{Primary Amperes}}{\text{Secondary Amperes}}$$

An example will serve to illustrate the use of this formula. For explanation, we shall assume that a perfect transformer is being used.

The secondary of the transformer is to be used to supply the filament power to a vacuum tube. Let us say that the tube's filament requires three amperes at five volts and that the primary of the transformer is to be connected to a 110-volt, 60-cycle AC source. How much current will flow through the primary?

Substituting in formula (6), we have:

$$\frac{5 \text{ volts}}{110 \text{ volts}} = \frac{\text{Primary amperes}}{3 \text{ amperes}}$$

Multiplying both sides of this equation by 3, we obtain:

$$\frac{3 \times 5}{110} = \text{Primary amperes}$$

$$\text{Or:} \qquad \text{Primary amperes} = \frac{15}{110}$$

$$= .136 \text{ ampere.}$$

[1] Transposing an equation in this manner does not alter the value of original equation; it is merely changed to a different form which is more convenient for solving.

20. SUMMARY OF DEFINITIONS. Because of the several different terms used in this lesson that are entirely new, it is advisable to summarize the more important definitions. This provides a compact form from which they may be more easily studied. These definitions should be learned (not memorized) to the point where the use of any one of them will immediately suggest the relationship it bears to the function of an electrical circuit.

INDUCTION. Induction is the process or the act of generating an electrical voltage in a conductor whenever that conductor is cut by or moved through a magnetic field.

LENZ'S LAW. Lenz's Law states that a current flowing under the pressure of an induced voltage sets up a magnetic field which is opposite to the magnetic field that induced the voltage.

INDUCTANCE. Inductance is the ability of a coil or circuit to produce a counter-voltage within itself by self induction whenever the current passing through that coil or circuit changes. The word "inductance" is often used to have the same meaning as "self-inductance". Inductance is measured in henries.

MUTUAL INDUCTANCE. Mutual inductance is the ability of one coil or circuit to generate a voltage in a neighboring coil or circuit when the current passing through the first coil or circuit varies. The voltage produced in the secondary circuit will be in accordance with Lenz's Law; that is, the current impelled by the secondary voltage will set up a magnetic field which opposes the magnetic field around the primary.

SELF INDUCTION. Self induction is the generation of a counter-voltage within a coil itself when the current passing through that coil changes or varies.

MUTUAL INDUCTION. Mutual induction is the transfer of electrical energy (voltage or power) from one coil or circuit into a neighboring coil or circuit, through the magnetic coupling existing between these two circuits. The direction of the secondary voltage will be governed by Lenz's Law and the strength of the secondary voltage depends upon the mutual inductance between the two coils or circuits.

INDUCTIVE REACTANCE. Inductive reactance is the opposition offered to the passage of a changing current through a coil. It is found by use of the formula:

$$X_L = 6.28 \times F \times L$$

Where:
X_L is the inductive reactance in ohms.
F is the frequency in cycles per second.
L is the inductance in henries.

Note - Important: In some textbooks and literature, authors use the symbol ω to represent the product of 6.28 × F or 2πF. The inductive reactance formula may be seen:

X_L = ωL; which means the same as:

$$X_L = 6.28 \times F \times L.$$

Do not confuse the symbol ω used in this manner with the use of it to represent ohms. In this course, ω is the symbol for ohms.

Notes

(These extra pages are provided for your use in taking special notes)

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UNIT NO. 1

CONDENSERS AND CAPACITIVE REACTANCE

LESSON NO. 11

FORESIGHT

....many of the greatest fortunes ever amassed were founded on foresight!

So that you will fully understand the true meaning of the word "foresight", we are going to tell you about two insects that are comparable to human beings. First, we will tell you about the grasshopper, that chirpy little fellow that seems to enjoy himself immensely during the summer months, when the air is warm and his food supply is plentiful. He awakes with the rising sun, spends the day hopping or flitting about and eating tremendously; then settles down to sleep, when the sun sets, giving no thought to the future, when cold winds will blow and food will be covered by deep snow. The grasshopper has a grand time while it lasts, but gives no thought to the future.....In other words, he lacks foresight. Unfortunately, many human beings are like the grasshopper. Perhaps you know some yourself.

The other insect that we will tell you about is an interesting little hustler, which sometimes stirs up our "fighting spirit" by giving us a nip on the ankle or getting into the jam. You're right; we are talking about the ant. From earliest spring until the cold winds begin to howl, he hustles, and hustles, and digs, apparently giving no thought to pleasure. The underground home of the ant colony is cleaned and enlarged; food is stored for future use.....always in a hurry, the ant works from sun up to sun down, looking ahead to the time when winter will arrive and he must rely on his summer's work to live. This little insect has foresight. He knows that he must prepare for the future if he is to live in comfort.....and prepare for the future he does.

Many people are like the ant......the successful people that enjoy life and are financially independent. You probably know many such people yourself. They may not be wealthy, but they have a substantial income, money in the bank, a car, a nice home, they take vacations and combine work with pleasure.

That's the way you want to live, isn't it? So our advice to you is this: "Take a tip from the little ant." Prepare NOW for immediate and future opportunities so that when the cold winds blow, and the snow swirls or the rain beats against the windows, you won't be "out with the poor grasshopper". Let your motto be, "STICK, STUDY AND SUCCEED"!

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Lesson Eleven

Condensers & Capacitive Reactance

"The performance of modern Radio Receivers and Transmitters depends mainly upon the proper association of tubes, coils, and condensers within the circuits. Now that you are thoroughly familiar with the theory of tubes and coils, you are ready to take up the study of condensers.

"Before the electron theory was generally accepted, it was difficult to understand the operation of the condenser. Now, however, I am certain you will find the explanation comparatively simple.

"There are two principal types of condensers used in practically all radio apparatus today; you will find each type thoroughly explained in the following interesting and important pages."

Glance at any diagram of a Radio receiver or Radio transmitter and you will see that no matter how complicated the hookup may appear, it is composed of just five things: Vacuum Tubes, Resistors, Coils, Condensers, and Batteries. Previously, a complete discussion of resistors and coils was made. The fundamental operation of a vacuum tube was given, and a later lesson will deal with batteries. At that time you will have studied the five parts necessary to any Radio receiver or transmitter. Future lessons, therefore, will consist of the methods used to connect those five components together so that they may perform the jobs desired of them. Since condensers are one of the five fundamental components, a detailed description of their construction and operation will now be considered.

1. THE ELECTROSTATIC FIELD. In a previous lesson, it was learned that the addition of electrons to a body causes it to become negatively charged. On the other hand, when electrons are removed from a body, it exhibits a positive charge.

In Fig. 1 are shown two metallic spheres resting upon insulated stands. Some electrons are added to sphere A, and it, therefore, acquires a negative electric charge. That is, A is negative with respect to B; or, conversely, B is positive with respect to A. It is assumed that enough electrons are added to A to make it one volt negative with respect to B. If, in addition, the same number of electrons that were added to A are removed from B, this sphere acquires a positive charge of one volt. The following conditions prevail. A is 1 volt negative with respect to ground, and B is 1 volt positive with respect to ground. Therefore, the difference in potential between spheres A and B is 2 volts. In a previous lesson the statement was made that like charges repel and unlike charges attract. Since the two spheres are charged oppositely, there exists an attracting force between them.

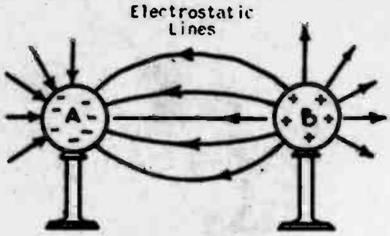


Fig.1 Electrostatic Field Between Two Charged Metal Spheres.

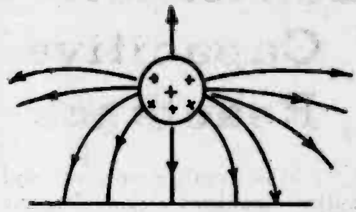
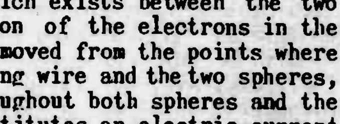


Fig.2 Electrostatic Field Between a Charged Body and the Earth.

In Lesson 9, it was seen that there is an attraction between the north and south poles of a magnet and that the direction of this force is represented by magnetic lines of force drawn from the north pole, through the surrounding air to the south pole. The magnetic lines of force constitute an electromagnetic or magnetic field. In the same manner there exists between two oppositely charged bodies an electrostatic or electric field. This field may also be represented by lines drawn from the positively charged body through the air to the negatively charged body, and they indicate, by their direction, the manner in which a free, positive charge would be moved if it were shielded from all external forces. These electrostatic lines are shown in Fig. 1.

If a connecting path, such as wire, is provided between the two spheres, the electromotive force which exists between the two ends of the wire causes a redistribution of the electrons in the entire system; that is, electrons are moved from the points where they are densest throughout the connecting wire and the two spheres, until they are evenly distributed throughout both spheres and the wire. This movement of electrons constitutes an electric current and it continues until there is no difference of potential existing between any two parts of the system. Fig. 2 illustrates the electrical field existing between a charged body and the earth. In Fig. 3 is shown the electrical field between two oppositely charged flat metal plates. We are now ready to begin the discussion of condensers.

Fig.3 Electrostatic Field Between Two Charged Flat Parallel Metal Plates.



2. **DEFINITION OF A CONDENSER.** *A condenser may be defined as any two conductors separated by an insulator.* This definition is general and may apply to parts of a circuit, which at first sight, in no way resemble condensers, with which we shall become familiar. Even the ordinary condensers used in Radio and Television present such a variety of appearances that we think it advisable at this time to show you a picture illustrating some of the more common types. In Fig. 4 are shown several condensers known as fixed con-

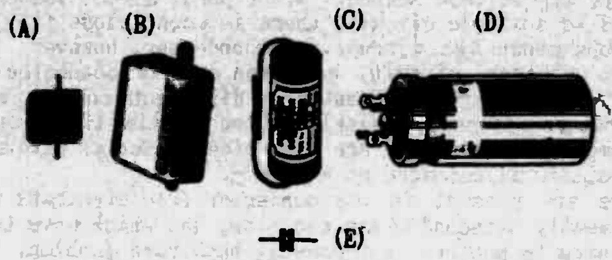


Fig.4 Illustrating Various Types of Fixed Condensers and Symbol.

densers; in other words, their capacitance cannot be changed. The symbol used to represent any of these condensers is shown at E.

It is unfortunate that the term condenser has become so common, for this term in no way describes the true function of this device; that is, the condenser does not condense anything. It does, however, have the ability or capacity to store electrons on its plates. A much better word would be capacitor, and this term is gaining rapidly in popularity. The ability for storing electrical charge or electrons is called the capacitance of the condenser. However, the term capacity is commonly used in practice instead of capacitance. Since the terms capacitor and capacitance, and also condenser and capacity, are found in radio literature, it is advisable that you become familiar with all four of these terms.

It is frequently desirable to use a condenser whose capacity may be varied at will. Several types of variable condensers and the symbol are shown in Fig. 5. The two condensers at B and C are

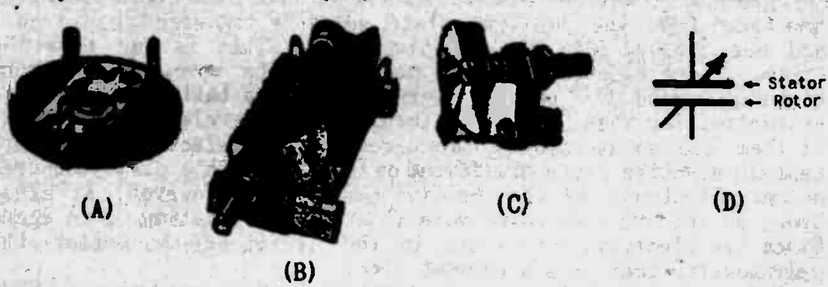


Fig.5 Illustrating Several Types of Variable Condensers and Symbol.

variable by means of a knob or dial, which is placed on the front of the receiver or transmitter, while the one shown at A is variable by means of a screwdriver; that is, after its capacity has once been set at a definite value, it is not ordinarily changed.

3. ACTION OF DC ON A CONDENSER. An electric current consists of a flow or drift of electrons from the negative terminal of the voltage source, through the external circuit, toward the positive terminal of the voltage source. If a pure, direct voltage source is applied to a closed circuit, there is a continuous flow or drift of electrons about the circuit. A condenser, however, does not constitute a closed circuit, and when one is connected across a pure DC voltage source, an entirely different condition exists. Suppose that a condenser, consisting of two parallel flat metal plates, a galvanometer, and a switch are connected in series with a battery. This circuit is illustrated at A in Fig. 6.

There are present in any conductor free electrons which are not permanently attached to any one atom, but which move to and fro from one atom to another in a somewhat haphazard fashion. When the switch in the circuit is open, there are approximately the same number of electrons on each plate of the condenser. *The material between the plates of the condenser is called the dielectric.* In this case, it is air, though it might be paper, mica, or some other insulating material. The dielectric, since it is an insulator, does not have any free electrons. The electrons in the dielectric revolve about their respective atoms in nearly circular orbits; each electron being more or less firmly fixed to its respective nucleus. At the instant of closing the switch, the needle of the galvanometer deflects and then immediately returns to zero, indicating that there is a momentary flow of current which lasts a very short time. Simultaneous with the closing of the switch, many free electrons are removed from the upper plate, causing a deficiency of electrons and hence a positive charge at this point. These electrons begin to drift toward the positive pole, and at the same time an equal number of electrons are crowded into the lower plate, producing an excess of electrons, or a negative charge on this plate.

Do not construe this to mean that the same electrons which are taken from the positive plate actually traverse the circuit and are crowded into the negative plate. This is far from the truth. Those electrons in the positive plate move a very short distance toward the positive terminal of the battery due to its attraction for them. They, in turn, push other electrons in front of them and so on around the circuit. Some electrons which are near the negative plate are forced on to it; and this plate acquires as many electrons as the positive plate lost. However, no electron, on the average, moves more than a small fraction of an inch. Since the electrons everywhere in the circuit are in motion, the galvanometer indicates a current flow.

The excess of electrons on the bottom plate produces a charged condition in the dielectric between the plates; that is, they exert a repelling force on the electrons of the atoms in the dielectric. These electrons, however, since they are not free elec-

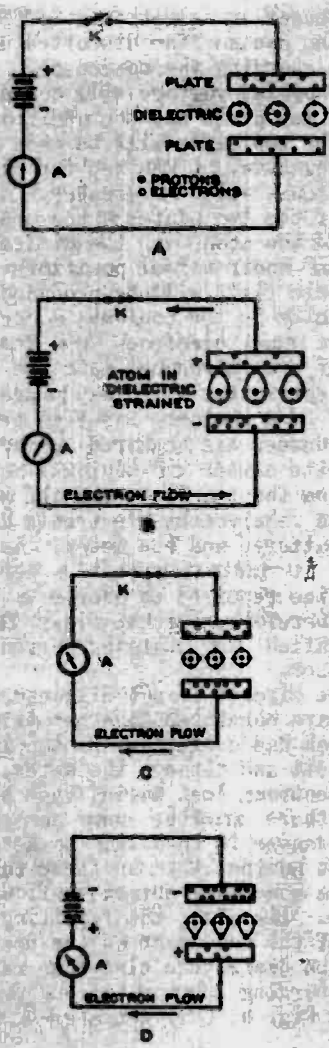


Fig. 6

(A) Uncharged Condenser.

(B) Condenser Charged with Top Plate Positive.

(C) Condenser Discharging.

(D) Condenser Charged with Top Plate Negative.

trons, are not able to move through any great distance. Furthermore, the positive charge on the upper plate exerts an attractive force on the electrons of the dielectric. This results in a distortion of the orbits of the dielectric electrons, causing them to assume the shapes shown in exaggerated form at B in Fig. 6. These electrons cannot leave the dielectric or flow directly through it, if it is a good insulating material, but are simply strained out of their normal positions and paths as shown. Also there exists between the plates of the condenser an electrostatic field, and this field may be considered as the cause of the distorted electron orbits. This process is called charging the condenser.

It is apparent that a larger applied voltage will cause the removal of more electrons from the top plate and the addition of more to the bottom plate; that is, the top plate will be made more positive and the bottom plate more negative. Likewise, the number of electrons drifting around the circuit will be greater. Also, the repelling and attracting force of the two plates on the dielectric electrons will be increased and the atoms of the dielectric will be strained more and more out of their normal positions. Or it can be said that a stronger electric field will be produced.

The unit of quantity of electricity is the coulomb; a certain definite number of electrons. When some electrons are removed from the top plate and an equal number are introduced into the bottom plate, a definite quantity of electricity, which may be measured in coulombs, or a fractional part of a coulomb, has been transferred around the circuit. The condenser has acquired a certain amount of electric charge or a definite number of coulombs on its plates. The removal of electrons from the top plate and the addition of electrons to the bottom plate requires an electronic drift through the connecting wires, the battery, and the meter. As the electrons pass through the meter, it indicates that a certain amount of current is flowing. The time required to charge a condenser is of very short duration; therefore, current flows for a very short time. This current is called the charging current or the dielectric current of the condenser.

Suppose that the battery of this circuit is now disconnected, and the terminals of the condenser are connected together through the galvanometer. The electrons which had collected on the lower plate begin to flow through the circuit and through the meter, and the top plate regains the number of electrons lost during the charging process. This continues until there are the same number of electrons on each plate, and the condenser is then said to be discharged. Again, as the electrons are moving back to their former positions, the meter indicates that a momentary current is flowing; this time in the opposite direction. Likewise, the repelling and attracting force of the two plates of the condenser on the dielectric electrons is now removed, and the dielectric electrons return to their normal orbits. This discharging current is equal, in amount, to the charging current. In Fig. 6, C illustrates a condenser discharging.

If the polarity of the battery is reversed and it is again connected in the circuit, the condenser charges, but in the opposite direction, as shown at D in Fig. 6. The top plate acquires an excess of electrons, while on the bottom plate there is produced a deficiency of electrons. The dielectric electrons are again strained out of their normal positions, but in the opposite direction and, in addition, the electric field is reversed. The same number of electrons are transferred as in the previous case, if the voltage of the battery is not changed.

It can readily be seen that the charging of the condenser is the process of raising the potential of one plate to a higher point with respect to the other. Sufficient electrons are removed from the positive plate and added to the negative plate until the potential difference existing between the two plates is equal to that of the applied voltage, at which time the charging current stops. If a higher voltage is used, more electrons are transferred through the circuit until the voltage between the two plates is again equal to the applied voltage. Therefore, increasing the applied voltage increases the amount of charging and likewise discharging current.

If a condenser whose plates have a larger surface area than the one just considered, is charged to the same applied voltage, a greater number of electrons must be removed from the positive plate and more added to the negative plate; likewise, the number of electrons transferred through the circuit is greater and the current flow correspondingly larger. This may be explained by the fact that a certain number of electrons must be removed from each square inch of the surface of the positive plate to raise its potential the required amount. Therefore, when the surface area of the plates is made larger, the total number of electrons which must be removed is greater, since each square inch of the plate must have its potential raised the same amount.

If the same two plates are placed closer together so that the thickness of the dielectric is considerably less, it requires the transfer of a greater number of electrons to charge this condenser to the same applied voltage. The dielectric electrons are strained farther from their normal positions and the charging current is larger.

When the plates are closer together, more electrons can be piled upon the negative plate with the same amount of voltage, due to the greater attractive force of the positive plate for the electrons on the negative plate. In this case, the electric field is more concentrated. The amount of charging current can be increased by raising the applied voltage, by making the surface area of the two plates larger, or by placing the two plates closer together.

4. CAPACITY OF A CONDENSER. The number of coulombs of charge required to establish a difference of potential of 1 volt between the plates of a condenser is called its capacity; or the more electrons displaced in the dielectric, the greater the capacity of a condenser.

The unit of capacity is called the farad.[1] A condenser whose capacity is one farad requires one coulomb of electricity to bring its plates up to a potential of 1 volt; that is, we would need to transfer 6.28×10^{18} electrons from the positive plate of this condenser around to the negative plate. The physical dimensions of such a condenser would be tremendous. The farad (fd.) is much too large a unit for practical purposes, so sub-divisions of the fundamental unit are used, such as the microfarad and the micromicro-

[1] Named in honor of Michael Faraday, 1791-1867, a famous English physicist and chemist who did distinguished work in electricity.

farad. A microfarad is one-millionth of a farad. A micromicrofarad is one-trillionth of a farad, or one-millionth of a microfarad. These two units are sometimes abbreviated mfd. and mmfd. A condenser of 1 mfd. capacity would require one-millionth of a coulomb or one microcoulomb of electrical charge to raise the potential difference of its plates to one volt. That is, we would have to remove one microcoulomb, or more than 6 trillion electrons from the positive plate and add this many to the negative plate. *The capacity of a condenser may then be defined as the quantity of electricity measured in coulombs with which it must be charged to raise its potential one volt.*

There is a formula which expresses the relationship between the capacity, the quantity of electricity and the potential difference between the plates of a condenser. This formula is:

$$C = Q \div E$$

or it may be written:

$$Q = C \times E$$

Where: C is expressed in farads
Q is expressed in coulombs
E is expressed in volts

Example: Let us use this formula to calculate the quantity of electricity required to charge a 10 mfd. condenser to 100 volts.

$$Q = C \times E$$

$$= .00001 \times 100 \text{ (10 mfd. = .00001 fd.)}$$

$$= .001 \text{ coulomb.}$$

Example: If it requires .001 coulomb to charge a condenser to 50 volts, let us use the formula $C = Q \div E$ to calculate the capacity of this condenser.

$$C = Q \div E$$

$$= \frac{.001 \text{ coulomb}}{50 \text{ volts}}$$

$$= .00002 \text{ fd.}$$

$$= 20 \text{mfd.}$$

Notice that the voltage of the battery does not determine the capacity of the condenser. While it will take 1 microcoulomb of electricity to charge a condenser whose capacity is one mfd. to one volt, and it will also take ten microcoulombs of electricity to charge the same condenser to a potential of 10 volts, still the capacity of the condenser is the same in either case. *The capacity of a condenser is determined by three things: (1) The area of the plates of the condenser. (2) The distance between the plates.*

(3) The nature of the dielectric. We can increase the capacity of a condenser by increasing the area of the metal plates, by decreasing the distance between the plates, or by using as the dielectric, a material which allows the accumulation of more electrons on the negative plate of the condenser for a given applied voltage.

5. **DIELECTRIC CONSTANT.** Let us assume that we have a condenser, such as shown in Fig. 7, whose plates are so arranged

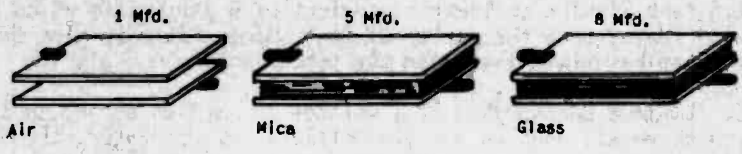


Fig.7 Illustrating the Meaning of Dielectric Constant.

that various insulating materials can be inserted between them to be used as the dielectric. Let us say that the capacity of this condenser, when air is the dielectric, is 1 mfd. If a sheet of mica is inserted between the plates and the capacity of the condenser is measured, it is found to have increased, perhaps, five times. Or it will take about five times as much electricity to charge the condenser to the same potential as before. Again, if a piece of glass is used as the dielectric, the capacity of the condenser increases 8 times. This increase in capacity is probably due to the internal atomic structure of the material used as the dielectric. Some materials are so constructed that an electric field can distort more of their electrons than it can in others. Since every insulating material has a slightly different atomic structure, it follows that each material will have different effects upon the capacity of a condenser when that material is used as the dielectric.

Every insulating material has a dielectric constant. *The dielectric constant of an insulating material is the ratio of the capacity of a condenser using this material to the capacity that the same condenser would have when using air as the dielectric.* In the preceding experiment, the dielectric constant of the mica is 5 and that of the glass 8. Nearly all variable condensers use air as the dielectric, while small fixed condensers ordinarily use either paper or mica. For your convenience, we have listed below the dielectric constants of some of the more common materials.

Air	1.
Paraffin Wax	1.99 to 2.29
Rubber	2.0 to 3.5
Fibre	2.5 to 5.0

(Continued Next Page)

Mica	2.5 to 6.7
Quartz	4.49 to 4.55
Bakelite	4.5 to 5.5
Glass (various grades)	5.0 to 10.0
Porcelain	5.7 to 6.8

Notice that mica, for example, can have a dielectric constant from 2.5 to 6.7! The dielectric constant of a particular piece of mica will depend upon the purity of that piece. This is also true of the other materials listed in the table.

6. VOLTAGE BREAKDOWN. If a voltage is applied across an insulating material, such as the dielectric in a condenser, the dielectric electrons are strained from their normal positions. As the voltage is increased, the amount of strain becomes greater, the electrons moving farther and farther from their respective atoms. With a continued increase in voltage, the point is finally reached where some of the electrons are torn from their atoms and rush over to the positive plate of the condenser. Under the influence of this high voltage, these electrons acquire considerable velocity. They collide with other atoms, dislodging electrons from them. These electrons which have been knocked off join the main electron stream traveling over to the positive plate. This flow of electrons chars a path through the dielectric, actually puncturing the dielectric material. This charred path is composed of carbonized particles of the dielectric material and since carbon is a fair conductor, current will now flow fairly easily directly through the condenser from one plate to the other. The condenser is no longer useful and must be discarded; it is said to have broken down. If a high voltage is applied to a condenser whose dielectric is air, no permanent injury is done to the dielectric. As soon as the high potential is removed, the condenser is again serviceable. All fixed condensers have stamped or printed on their outer surface the capacity of the condenser as well as the voltage breakdown. This voltage breakdown must not be exceeded.

The amount of voltage which may be safely applied to a condenser depends upon, first, the thickness of the dielectric, and second, the material of the dielectric. For a given thickness, mica will stand a much higher voltage than will paper.

The following table shows the voltage breakdown per thousandth of an inch for various materials:

Air (Dry)	50
Dry Manila Paper	110 to 320
Glass	150 to 300

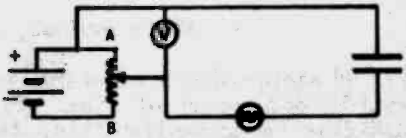
(Continued on Next Page)

Untreated Pure Para Rubber	300 to 500
Paraffin Paper	800 to 1,000
Dry Processed Porcelain	1,000
Mica	2,000 to 8,000

It is difficult to measure the breakdown voltages exactly for they vary greatly with the particular sample tested.

7. **ACTION OF PULSATING DC ON A CONDENSER.** The circuit shown in Fig. 8 consists of a condenser, a milliammeter which has its

Fig.8 Circuit Used to Apply a Pulsating DC to a Condenser.



zero position at mid-scale, a voltmeter, a potentiometer, and a 90-volt battery. The potentiometer is connected across the battery and its sliding arm is connected to one plate of the condenser. The other condenser plate is connected to the top end of the potentiometer. When the slider is at A, no voltage is applied to the condenser, since both plates are connected to the positive end of the battery. When the slider is at B, the full 90 volts are applied to the condenser, since one plate is connected to the positive terminal of the battery and the other plate to the negative terminal. When the slider is at a point between A and B, a voltage somewhat less than 90 volts is applied to the condenser. Thus by varying the position of the slider, any voltage between 0 and 90 volts can be applied to the condenser.

Starting with the slider at point A, it is moved downward until the voltmeter reads 45 volts. During the time the slider arm is in motion, the milliammeter indicates that the condenser is drawing current, or is charging to the applied voltage of 45 volts. If the slider arm is now moved back to point A, the condenser discharges, since there is no voltage applied to it. This causes the milliammeter to indicate that a current is flowing in the opposite direction. Suppose that the slider is rapidly moved from top to bottom. When it is moving down from A to B, the voltage across the condenser is increasing and the condenser is charging to this applied voltage. When it is moving up from B to A, the voltage across the condenser is becoming smaller and the condenser correspondingly discharges until the potential across it equals the applied voltage. This movement of the sliding arm on the potentiometer corresponds to applying a pulsating DC voltage to the condenser and it should be noticed that whenever the voltage applied to the condenser is changing, the milliameter indicates that a current is flowing in the condenser circuit. *From this experiment it can be concluded that current flows in a condenser circuit whenever the voltage applied to the condenser is changed, and that the great-*

er the rate at which this voltage is changed, the greater is the amount of current flowing in the condenser circuit. This can be proved by moving the slider at first slowly and then more rapidly, and noting that the deflections of the milliammeter are greater with the more rapid motion.

Let us say that the slider is moved from A to B in one second. This means that the voltage across the condenser is changed from 0 to 90 volts in a second. Assuming that the capacity of this condenser is 1 microfarad, it is possible to calculate the quantity of electricity required to charge it to 90 volts by means of the formula $Q = C \times E$. (1 mfd. = .000001 fd.)

$$Q = .000001 \times 90$$

$$= .00009 \text{ coulomb, or } 90 \text{ microcoulombs}$$

This 90 microcoulombs of charge must be transferred around the circuit in one second of time. To find the amount of current which must flow to accomplish this, the formula: *amperes = coulombs ÷ seconds*, which was learned in Lesson 3, can be used.

$$I = \frac{.00009}{1}$$

$$= .00009 \text{ ampere, or } 90 \text{ microamperes}$$

If the slider is moved from A to B in .001 second, 90 microcoulombs must be transferred around the circuit in this time. Therefore, the current flowing would be:

$$I = \frac{.00009}{.001}$$

$$= .09 \text{ ampere, or } 90 \text{ milliamperes}$$

It is evident that the greater the rate at which the voltage is changed, the shorter is the time available for charging and discharging the condenser. This means that the quantity of electricity needed to charge the condenser must be transferred in a shorter interval, which necessitates the flow of a larger current.

8. **ACTION OF AC ON A CONDENSER.** The circuit shown at B in Fig. 9 will be used to explain the action of AC on a condenser. It consists of an AC generator, an AC milliammeter, and a condenser connected in series. At A in the figure is shown one cycle of an alternating voltage. As the voltage across the alternator increases during the first half of the first alternation; that is, from A to B in the figure, the voltage across the condenser is increasing and it is taking a charge. From B to C the voltage across the alternator is decreasing to zero. Since the voltage across the condenser is decreasing, the condenser discharges until at the

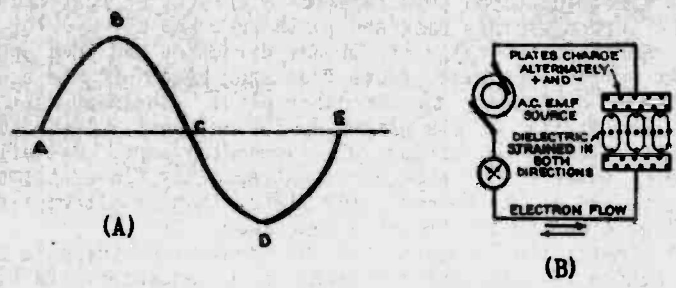


Fig.9 Illustrating the Action of AC on a Condenser.

time point C is reached, the voltage across it is zero. During the second alternation, the voltage across the alternator rises to a maximum in the opposite direction as shown from C to D. The condenser charges to the peak voltage, but in the opposite direction; that is, that plate which was positive before is now negative, and vice versa. Finally, from D to E, the voltage across the alternator is again returning to zero; therefore, the condenser discharges until the potential across its plates is again zero as shown at E. Notice that the condenser goes through four complete changes as this one cycle of alternating voltage is applied to it; that is, it charges in one direction, discharges to zero, charges in the opposite direction and finally discharges again to zero.

If the polarity of the charge is rapidly reversed, as is the case when an alternating voltage is applied across a condenser, there is a straining of the electron orbits in the dielectric, first in one direction and then in the opposite direction. This continued movement of the dielectric electrons, shown at B in Fig. 9, produces friction which results in the generation of considerable heat.

An alternating voltage of sine wave form produces in the circuit of a condenser, a flow of current which is, itself, a sine wave. An AC milliammeter connected in the circuit has a steady deflection since it is unable to follow the rapid fluctuations of the current. Since current flows in a circuit in which a condenser is connected whenever the voltage applied to the condenser changes, it follows that current will continue to flow in this circuit when an alternating voltage is applied, since this voltage is constantly changing.

If the voltage of the AC generator is increased, a larger current flows in the circuit, since the condenser must charge to a higher voltage in the same length of time, and this requires an increased current. Likewise, if the capacity of the condenser is increased, a greater quantity of electricity is needed to charge the condenser to the applied voltage, which also necessitates the flow of a larger current. Finally, if the frequency of the AC generator is raised, the output voltage rises to its maximum value in a shorter interval of time. The condenser must charge in this shorter time, and to do this requires a greater current flow.

The current surges back and forth into and out of the plates of the condenser, charging it in one direction and then oppositely. No current, however, flows from one plate of the condenser through the dielectric to the other plate. The condenser merely stores electricity in its plates during one part of the alternation and releases it during the succeeding part. The effect is the same, however, as though current actually flowed through the condenser, and it may be correctly stated that an alternating current flows effectively through a condenser.

To clarify the foregoing, let us consider a hydraulic analogy of the action of alternating current on a condenser. In Fig. 10,

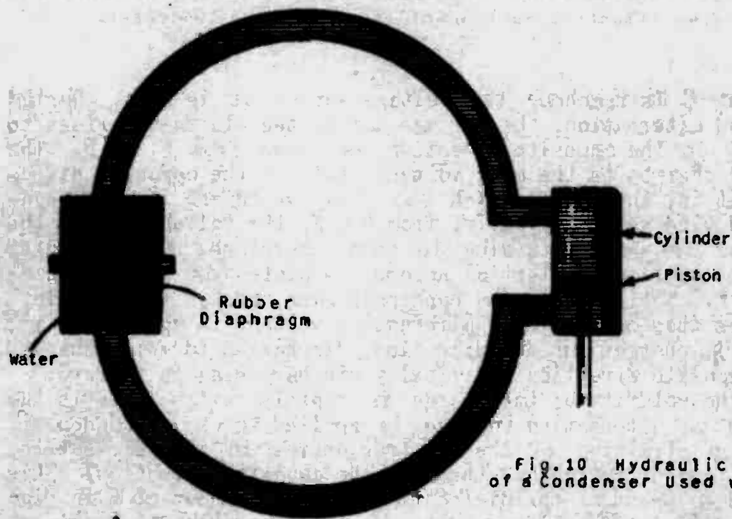


Fig. 10 Hydraulic Analogy of a Condenser Used with AC.

there is illustrated a water tank which is separated into two parts by a rubber diaphragm which does not allow the water to flow from one part of the tank through the diaphragm to the opposite part. Two pipes extend from the two parts of the tank to a cylinder in which a piston is allowed to move freely. As the piston moves up, water is forced out of the top of the cylinder, around through the pipe into the top chamber of the tank. At the same time, water is drawn out of the lower chamber of the tank into the bottom of the cylinder. The top chamber now contains more water than the bottom and the rubber diaphragm is forced downward as shown by the dotted line. As the piston moves from the top of the cylinder to the bottom, water is drawn out of the top chamber of the tank into the top of the cylinder; likewise, water is forced out of the bottom of the cylinder into the bottom chamber of the tank. When the piston is at the bottom of its downward stroke, the rubber diaphragm in the tank is forced upward. In this analogy, the double-action pump is equivalent to an alternating current generator; the two parts of the tank correspond to the two plates of a condenser; and the rubber diaphragm performs the same function as the dielectric of a condenser. When water is added to one chamber of the tank and taken from the other, the action is similar to adding electrons to one plate of a condenser and removing them from the opposite plate. The stretching of the rubber diaphragm corresponds to the strain which exists in the dielectric, when its electrons are distorted from their normal positions. When the two parts of the tank contain the same amount of water, there is no pressure on the rubber diaphragm. Likewise, when there are the same number of electrons on both plates of a condenser, no strain exists in the dielectric. Water flows back and forth through the pipes connecting the tank to the cylinder, but no particle of water makes a complete circuit of the system. In the same manner electrons alternate back and forth through the connecting wires in a condenser circuit, but none of them drifts completely around the circuit.

9. **CAPACITIVE REACTANCE.** In the preceding discussion, it was learned that the amount of alternating current that flows in a condenser circuit depends upon the capacity of the condenser, the amount of alternating voltage applied and the frequency of this voltage. If any one of these three factors is increased, a larger current flows. It is apparent that not as much current flows as would if the condenser were shorted out, for in that case, the only opposition to the flow of current would be the resistance of the connecting wires. *The condenser, itself, offers some opposition to the flow of current. This opposition is called the capacitive reactance of the condenser.* It is abbreviated Xc, and since it is an opposition to the flow of current, it is measured in ohms, just like resistance and inductive reactance. The greater the capacity of a condenser, or the higher the frequency of the applied voltage, the smaller is the capacitive reactance of the condenser, since in either case more current flows with the same applied voltage. Or it can be stated that the capacitive reactance of a condenser is inversely proportional to its capacity and to the frequency of the applied voltage. The formula for calculating the capacitive reactance is:

$$X_c = \frac{1}{6.28 \times F \times C} \qquad (1)$$

Where:
Xc is the capacitive reactance in ohms.
F is the frequency in cycles per second.
C is the capacity in farads.

Since nearly all of the condensers commonly used in Radio and Television have capacities in the order of microfarads or less, another formula has been derived in which the capacity may be substituted directly in microfarads. This formula is:

$$X_c = \frac{1{,}000}{6.28 \times F \times C} \qquad (2)$$

Where:
Xc is the capacitive reactance in ohms.
F is the frequency in kilocycles.
C is the capacity in microfarads.

Formula (2) is derived from formula (1) by the following method: We will work on only the right-hand side of this equation; thus the left-hand side will still be in ohms.

$$\text{Cycles} = \text{Kilocycles} \times 1{,}000$$

$$\text{Farads} = \frac{\text{Microfarads}}{1{,}000{,}000}$$

If we write formula (1) like this:

$$Xc = \frac{1}{6.28 \times \text{Cycles} \times \text{Farads}}$$

we can use the two preceding equations and substitute in formula (1). For cycles, we will substitute: kilocycles × 1,000; and for farads, we will substitute: $\frac{\text{microfarads}}{1{,}000{,}000}$. Formula (1) then looks like this:

$$Xc = \frac{1}{6.28 \times \text{Kilocycles} \times 1{,}000 \times \frac{\text{microfarads}}{1{,}000{,}000}}$$

The 1,000 will cancel into the 1,000,000 and the formula then becomes:

$$Xc = \frac{1}{6.28 \times \text{Kilocycles} \times \frac{\text{microfarads}}{1{,}000}}$$

Now if we multiply the numerator and the denominator of this fraction by 1000 (this does not change its value), we obtain:

$$Xc = \frac{1}{6.28 \times kc \times \frac{mfd}{1{,}000}} \times \frac{1{,}000}{1{,}000} = \frac{1{,}000}{6.28 \times kc \times \frac{mfd \times 1{,}000}{1{,}000}}$$

$$= \frac{1{,}000}{6.28 \times kc \times mfd}$$ which is formula (2).

Let us work a few examples illustrating the use of these formulas.

Example 1: What is the capacitive reactance of an 8 mfd. condenser at a frequency of 120 cycles? (Before substituting in formula (1), the 8 mfd. must be converted to .000008 fd.)

$$Xc = \frac{1}{6.28 \times 120 \times .000008} = 166 \text{ ohms.}$$

Example 2: Find the capacitive reactance of a .05 mfd. condenser at a frequency of 10,000 cycles. Formula (2) may be used if the 10,000 cycles is changed to 10 kilocycles.

$$Xc = \frac{1{,}000}{6.28 \times 10 \times .05} = 318 \text{ ohms.}$$

This condenser would allow as much current to flow, when it is connected to an alternating voltage whose frequency is 10,000 cycles, as would a resistor of 318 ohms.

The amount of current flowing in a circuit is found by dividing the applied voltage by the resistance or opposition to the flow of current, or I = E ÷ R.

If, in a condenser circuit, the resistance of the connecting wires is disregarded, the only opposition to the flow of current is the capacitive reactance of the condenser. Therefore, Ohm's Law as applied to a condenser circuit is I = E ÷ Xc. For example: If 100 volts at a frequency of 10,000 cycles is applied to the condenser of Example (2), the amount of current that flows is found by:

$$I = \frac{E}{Xc}$$

$$= \frac{100}{318}$$

$$= .314 \text{ ampere or } 314 \text{ ma.}$$

It is possible to determine the value of a condenser of unknown capacity by connecting it to a source of alternating voltage and measuring the voltage applied across the condenser with an AC voltmeter and the current drawn by the condenser with an AC milliammeter. When these values have been found, the capacitive reactance of the condenser may be calculated by using Ohm's Law as applied to capacitive circuits or Xc = E ÷ I. Knowing the capacitive reactance, the capacity of the condenser can be found if the frequency of the applied voltage is known, by this formula:

$$(3) \qquad C = \frac{1,000}{6.28 \times F \times Xc}$$

Where: C is in microfarads
F is in kilocycles
Xc is in ohms

Example 3: If a condenser draws 20 ma. from a 100-volt, 60-cycle AC source, what is its capacity?

$$Xc = \frac{100 \text{ volts}}{.02 \text{ ampere}} = 5,000 \text{ Ohms}$$

$$C = \frac{1,000}{6.28 \times .06 \times 5,000} = .53 \text{ mfd.}$$

Notice that the 60 cycles was changed to .06 kilocycles before substitution was made in the formula.

The following examples are included to give you practice in using the formulas for calculating capacitive reactances. It is to your own advantage to solve these examples, and the answers are given so that you may know whether your method of solution is correct.

Example 4: Calculate the capacitive reactance of a .001 mfd. condenser at a frequency of 1500 kilocycles. *Answer:* 106.2 ohms.

Example 5: Calculate the capacitive reactance of a .25 mfd. condenser at a frequency of 50 cycles. *Answer:* 12,739 ohms.

Example 6: What is the capacitive reactance of a .02 mfd. condenser at a frequency of 50 cycles? *Answer:* 159,235 ohms.

It can be seen that changing the frequency of an alternating current has just the opposite effect upon inductive reactance that it has upon capacitive reactance. If a pure DC voltage is applied to a condenser (DC voltage can be considered as an alternating current whose frequency is zero), it is found that the capacitive reactance of the condenser is infinite; that is, it allows no continuous current to flow. As the frequency of the applied voltage is increased, the capacitive reactance of the condenser becomes smaller. On the other hand, if a pure DC voltage is applied to a coil, it is found that its inductive reactance is zero. As the frequency of the applied voltage is increased, the inductive reactance becomes larger.

Fig. 11 is a table which gives the capacitive reactance of standard condensers at commonly used frequencies.

REACTANCES OF CONDENSERS OF STANDARD CAPACITANCES AT COMMONLY USED FREQUENCIES

CAP. IN MFDS	FREQUENCY IN CYCLES PER SECOND						
	Broadcast Radio Frequencies		Audio Frequencies		Power Supply Frequencies		
	500,000	1,500,000	50	10,000	25*	60	120
	CAPACITIVE REACTANCE IN OHMS						
.00005	6,369.4	2,123.1	63,694,267	318,471	127,388,534	53,078,503	26,539,252
.0001	3,184.7	1,061.6	31,847,133	159,235	63,694,267	26,539,252	13,269,626
.00025	1,273.8	424.6	12,738,853	63,694	25,477,706	10,615,600	5,307,850
.0005	636.9	212.3	6,369,426	31,847	12,738,853	5,307,850	2,653,925
.001	318.5	106.2	3,184,713	15,924	6,369,427	2,653,925	1,326,963
.005	63.7	21.2	636,943	3,185	1,273,885	530,785	265,393
.01	31.8	10.6	318,471	1,592	636,943	265,393	132,696
.015	21.2	7.1	212,314	1,061	424,629	176,929	88,464
.02	15.9	5.3	159,235	796	318,471	132,697	66,348
.05	6.4	2.1	63,694	318	127,389	53,078	26,539
.1	3.2	1.1	31,847	159	63,694	26,539	13,270
.25	1.28	.42	12,739	64	25,478	10,616	5,308
.5	.64	.21	6,369	32	12,739	5,308	2,654
1.0	.32	.11	3,184	15.9	6,369	2,654	1,327
2.0	.16	.05	1,592	7.9	3,184	1,327	663
4.0	.08	.03	769	3.9	1,592	664	332
6.0	.05	.02	531	2.6	1,062	442	221
8.0	.04	.01	398	2.0	796	332	166
10.0	.03	.01	318	1.6	637	265	133
15.0	.02	.01	212	1.1	425	177	88

* Full wave rectification of 25-cycle current is equivalent to 50-cycle column under "Audio Frequencies." Half wave rectification of 25-cycle should never be used because of hum.

10. **CONDENSER LOSSES.** It has been assumed that all of the condensers previously discussed were perfect; that is, all of the energy taken by the condenser when it was charged was returned when the condenser discharged. Actually, no condenser is perfect in this respect. Each has some power loss which prevents the return of all of the energy.

The first of these losses is the resistance loss. The electrons which charge the condenser must pass through the connecting wires and in and out of the plates of the condenser. These materials are conductors and all conductors have some resistance. Therefore, these electrons produce heat in the connecting wires and in the plates of the condenser. This heat represents a power loss which is equal to the current squared times the resistance through which it must flow. With well-designed condensers, this resistance loss is kept at a minimum by constructing the condenser plates and the connecting wires with a material which has a very low resistance.

The second loss is known as leakage. It has been stated that the dielectric of a condenser is an insulator. There is, however, no perfect insulator, since any material will allow a very small current to flow when a voltage is applied across it. There will, therefore, be a small, continuous current flowing from one plate of the condenser through the dielectric to the opposite plate. This leakage current, as it is called, produces a power loss since it tends to discharge the condenser. A well-designed paper condenser may have a dielectric whose resistance is 200 or 300 megohms, while a poorer type of paper condenser may have a dielectric whose resistance is only 10 megohms. Obviously the second condenser would have the greater leakage. It is also possible for leakage to occur from one terminal of the condenser to the other across the surface of the case. This is especially true if the air is rather humid, as this allows a film of moisture to collect upon the case of the condenser. If a condenser did not have this loss, it would be possible to charge it, disconnect it from the charging source, and keep it in a charged condition for an indefinite period. Actually, however, few condensers will retain a charge for more than a few minutes. Condensers of air or mica dielectrics have a very low leakage loss, while paper and electrolytic condensers have a higher leakage loss.

When a condenser is charged by a steady voltage, the electrons in its dielectric are distorted from their normal orbits. When the terminals of this condenser are touched together, these electrons, since they are not perfectly elastic, do not return to their normal positions immediately. They, therefore, prevent the condenser from instantaneously discharging to zero voltage. Some of the charge residing on the plates of the condenser is removed at the instant when the terminals touch. Successive weaker discharges can, however, be obtained from the condenser by repeatedly touching the terminals together. The charge which is lost at the first contact is called the **free charge**, and a definite interval of time is required for the remaining charge, which is called the **absorbed charge,** to be removed from the plates of the condenser. If the condenser is successively charged and discharged by a high-frequency alternating voltage, it is possible that the time available for discharging the condenser is not sufficient to allow the dielectric to come out of its strained condition; or the condenser does not have time to return all of the energy which it has received. This absorbed charge is never recovered and it, therefore, constitutes a power loss.

The higher the frequency of the applied voltage, the more reversals of the electron orbits there will be per second, and, consequently, less time available for the dielectric to come out of its strained condition. Thus the movement of the dielectric electrons lags behind the changes in the applied voltage. When the applied voltage falls to zero, the dielectric electrons are still slightly strained and it requires part of the succeeding alternation to bring them back to normal before the condenser can be charged in the opposite direction. *This lagging of the dielectric electrons is often called "dielectric hysteresis".* The term "hysteresis" means lag.

11. ELECTROLYTIC CONDENSERS. There is another type of condenser which is used extensively in all modern radio receiving sets. It is called the "electrolytic condenser".

When a metal rod, such as aluminum or tantalum, is placed in a suitable electrolyte[1], it is possible for current to flow from the metal to the electrolyte, but not in the reverse direction, when a voltage is impressed across them. This combination offers a low resistance to current flow in one direction and an exceedingly high resistance in the opposite direction. If the positive terminal of a direct voltage source is connected to the aluminum, and the negative terminal to the metal container holding the electrolyte, as shown in Fig. 12, at first a current flows from the container through the electrolyte, to the aluminum, and back to the positive of the voltage source. In a short time, however, the aluminum rod becomes coated with a thin layer of aluminum oxide or hydroxide. Over this solid layer a thin gas film of oxygen is generated by the electrolytic action. The resistance of these two layers to the flow of current is very high and the current flow soon drops to a very low value.

It should be observed that this combination has all the requirements of a condenser. There are two conductors, one the aluminum rod, the other the electrolyte. They are separated by an insulator, which in this case is the aluminum oxide and the oxygen film. The thickness of these two films should be expressed in molecular dimensions rather than in a small decimal part of an inch. In the case of a condenser rated at 500 volts breakdown, the film is from .00001 to .000001 inch thick. The two conductors have very large surface areas, since every side of the aluminum electrode is in contact with the electrolyte. Also, the dielectric is of an extreme thinness. The capacity of a condenser is inversely proportional to the thickness of the dielectric; or the thinner the dielectric, the greater is the capacity of the condenser for plates of a given surface area. And so, it is evident that the capacity obtained per square inch of aluminum electrode is very high, especially when sheet aluminum is used as the positive electrode of the condenser cell. It is, therefore, possible to construct an electrolytic condenser with a large capacity in a very compact form.

The great difference in the thickness of this dielectric film as compared with the thickness of paper and mica dielectrics accounts for the much higher capacity obtainable for a given space with an electrolytic type of condenser.

Aluminum is always used as the positive electrode in these condensers, while the electrolyte is usually a solution of borax and boracic acid. When the condenser is out of the circuit, there is a tendency for the gas film to dissolve in the electrolyte and form aluminum hydroxide in the solution. When a voltage is again placed across the condenser, a new film forms under the influence of the leakage current to replace that which dissolved.

It should be noticed that electrolytic condensers have a definite polarity; that is, the aluminum electrode must always be connected to the positive terminal of the voltage source, while the can or container must be connected to the negative terminal.

[1] An electrolyte is any solution which will conduct electricity.

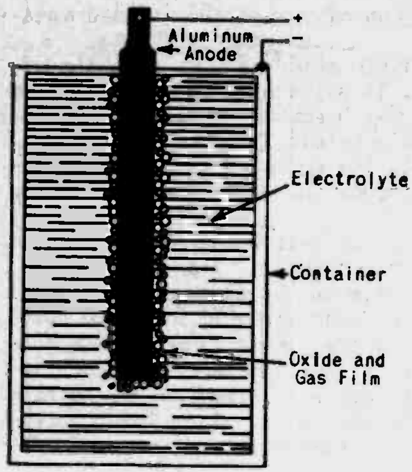


Fig.12 Illustrating the Essential Parts of an Electrolytic Condenser.

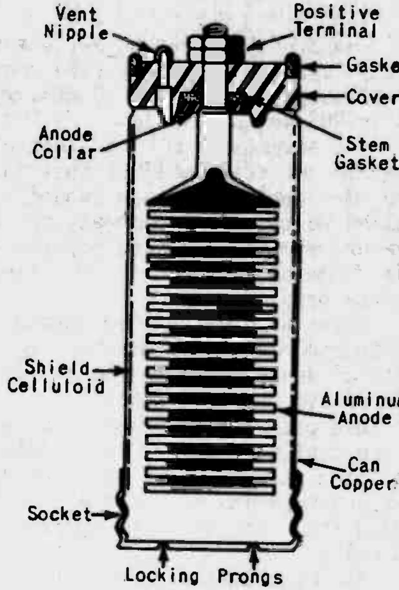


Fig.13 One Commercial Form of Electrolytic Condenser Using a Corrugated Aluminum Electrode to Increase Surface Area.

Thus, it is evident that these condensers may be used only with direct or pulsating direct current. If you were to connect an electrolytic condenser with the wrong polarity, a very high current would flow through the dielectric and the condenser effect would be lost.

The container which holds the electrolyte is ordinarily made of copper or some other metal with which the electrolyte does not react chemically, or which does not form a film. The electrolyte is in direct contact with the inner surface of the container.

The greater the surface area of the aluminum electrode, the greater is the capacity obtained. Many schemes have been devised for increasing this surface area. One of them is to wind sheet aluminum into a loose roll. Thus, the aluminum electrode has more sides or surfaces to contact the electrolyte. Another idea is to make the aluminum electrode hollow and to crimp or corrugate it, thus increasing its surface area. A condenser of this type is shown in Fig. 13.

The aluminum electrode or anode[1] is supported by a hard rubber cover; the stem of the anode protrudes through a tight fitting hole in the cover and is threaded to receive terminal nuts for the anode connection. To prevent leakage of the electrolyte around the anode stem, there is provided a rubber stem gasket. The cover also contains a soft rubber check valve having a needle hole. This permits the escape of gases, but does not allow dust to enter the can or liquid to escape.

It is usual to provide a perforated shield of insulating material between the anode and the can to prevent accidental contact and a short circuit between them.

[1] The term "anode" is used to describe the positive terminal of a device. Thus the anode of an electrolytic condenser is the aluminum electrode; the anode of a vacuum tube is its plate; etc.

Compared to other types, electrolytic condensers have a relatively high leakage loss. The amount of leakage current is several milliamperes for each 10 mfd. of capacity when the applied voltage is 300 volts.

One advantage of the electrolytic condenser is that its dielectric is self-healing; that is, it suffers no permanent injury when the applied voltage exceeds the breakdown voltage. If the applied voltage is too great, the dielectric film is broken down. However, when the voltage returns to its normal value, the dielectric film again forms on the electrode and the condenser is as good as before.

After an electrolytic condenser has been constructed, it must be "formed" before it may be used in a circuit. This forming consists of depositing the dielectric film on the aluminum electrode. A direct voltage is applied to the condenser for 8 or 10 hours and this causes the formation of the oxide and gas film. The greater the applied voltage, the thicker is the film and, consequently, the lower the capacity. Most condensers are formed so as to have a breakdown voltage around 450 volts DC. It is, therefore, recommended that such units be operated at peak voltages not exceeding 450 volts.

It is essential that the temperature of the air surrounding the electrolytic condenser does not exceed 140 degrees F. Temperatures higher than this cause an increased leakage current, resulting in a reduced useful life.

The type of condenser just discussed is known as the "wet" electrolytic condenser. In the last few years, "dry" electrolytic condensers have become popular. Those of you who have taken a dry cell apart know that it is not really "dry". The electrolyte is not in liquid form, but is composed of a damp paste. This is also true of the dry type electrolytic condenser. Its construction is shown in Fig. 14. The anode consists of a thin sheet of pure

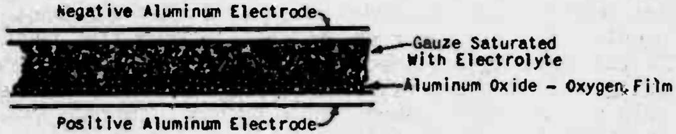


Fig.14 Cross-Section of "Dry" Electrolytic Condenser.

aluminum on the surface of which is formed a film of aluminum oxide and oxygen gas acting as the dielectric. Another aluminum sheet on the opposite side serves merely as a convenient means of making contact with the electrolyte, which is soaked up in the cotton gauze between them. A strip of this absorbent gauze is placed between the aluminum sheets and is rolled up with them. The gauze is saturated with the electrolyte solution and holds it much as a sponge holds water. This roll is then wrapped in heavy paper. Two wires are brought out, one of which connects to the positive aluminum electrode on which the oxide film is formed, and the other to the aluminum electrode which conducts the current to the electrolyte. The positive terminal is ordinarily a wire with red insulation, while the negative terminal has black insulation.

Dry electrolytic condensers have the advantage of being lighter in weight and less bulky than the wet type. However, if they are used in a receiver in a place where the temperature is allowed to rise fairly high, they will in time dry out, and their useful life is not as long as the wet type. An additional advantage is, of course, that there is no electrolyte to be spilled by jarring or vibration.

Electrolytic condensers range in capacity from about 1 mfd. to 20 mfd. or more for use with moderate voltages, and as high as 2,000 mfd. for use with lower voltages.

12. CONDENSERS IN PARALLEL AND SERIES. When condensers are connected in parallel, the effect is to increase the total surface area connected to each side of the line. As an example, let us consider Fig. 15, which shows two condensers connected in parallel.

Fig. 15 (A) Two Condensers with Plate Areas of 10 Sq. In. Each Connected in Parallel. (B) One Condenser with Plate Area of 20 Sq. In.; Equivalent to Circuit (A).

Each plate of the two condensers has a surface area of 10 square inches. The total surface area connected to the positive side of the line is 20 square inches. Likewise, the total surface area connected to the negative side of the line is also 20 square inches. Thus, the effect is the same as though one condenser, each of whose plates has a surface area of 20 square inches, were connected across the line as shown at B in the figure. If each of the condensers shown at A has a capacity of 1 mfd., the total capacity connected across the line is their sum, or 2 mfd. The total effective capacity of condensers connected in parallel is equal to the sum of their individual capacities or:

$$C_t = C_1 + C_2 + C_3, \text{ etc.}$$

Where: C_t is the combined capacities of all the condensers in parallel.
C_1, C_2, C_3, etc., are the individual capacities of the condensers.

Let us work an example using this formula. Suppose three condensers are connected in parallel. The capacity of the first is .01 mfd.; the second, .005 mfd.; and the third, .25 mfd. Their total capacity is:

$$C_t = .01 + .005 + .25 = .265 \text{ mfd.}$$

Assume that the .01 mfd. condenser used in the example has a voltage breakdown of 200 volts, while the other two condensers have a voltage breakdown of 600 volts. It is evident that a voltage greater than 200 volts could not be applied to the combination, else the .01 mfd. condenser would be broken down. Therefore, the voltage breakdown of condensers connected in parallel is equal to that of the condenser having the lowest voltage breakdown.

Connecting condensers in parallel increases the total effective capacity, but it decreases the capacitive reactance of the circuit. For example, the capacitive reactance of each of the two 1 mfd. condensers of A, Fig. 15, at a frequency of 120 cycles, is 1,327 ohms. The capacitive reactance of the equivalent circuit B, Fig. 15, at the same frequency, is the capacitive reactance of a 2 mfd. condenser, which is 663 ohms.

When condensers are connected in series, the effect is to increase the total dielectric thickness. As an example, consider A in Fig. 16, which shows two condensers connected in series. Assume

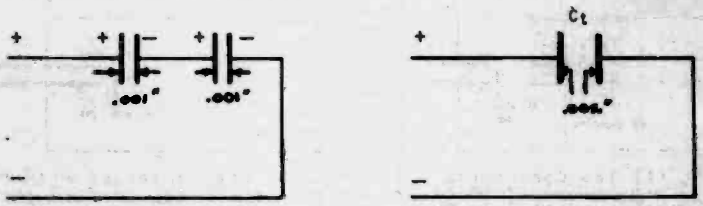


Fig.16 (A) Two Condensers with Dielectric Thickness of .001 inch each, Connected in Series. (B) One Condenser with Dielectric Thickness of .002 inch; Equivalent to Circuit (A).

that each condenser has the same capacity, and that the surface area of the plates of one condenser is equal to that of the other. The total thickness of the dielectric between the positive and the negative sides of the line is .002 inch, since the dielectric thickness of each condenser is .001 inch. This circuit, therefore, is equivalent to one which contains one condenser of the same size plates with a dielectric thickness of .002 inch, as shown at B in the figure. By placing the condensers in series, the total dielectric thickness has been increased; therefore, the total effective capacity must have been reduced. If the capacity of C_1 and C_2 are each 1 mfd., the capacity of the equivalent condenser C_t, as shown at B in the diagram, is .5 mfd. When the circuit shown at A is connected to a direct voltage source with the polarity indicated in the diagram, electrons flow from the left plate of C_1 toward the positive terminal of the voltage source, which makes this plate positive. At the same time, electrons flow from the negative terminal of the source toward the right plate of C_2, thereby charging this plate negatively. The negative charge on the right plate of C_2 drives an equal number of electrons from the left plate of C_2 toward the right plate of C_1. This charges the left plate of C_2 positively and the right plate of C_2 negatively. Thus, both left plates are charged positively and both right plates negatively. The two inner plates do not add to the total capacity in any way, since the charges produced on them is electrically opposite and, therefore, neutralize each other.

The general rule which applies to condensers connected in series is: *The total capacity of the combination is less than the lowest capacity in the combination.* If the condensers so connected are all of equal capacities, the total capacity of the circuit is equal to the capacity of any one of the condensers divided by the total number of condensers so connected; that is, if three 1 mfd. condensers are connected in series, the total capacity of the circuit is $\frac{1}{3}$ mfd. Or, if four 4 mfd. condensers are connected in series, the total capacity is the capacity of one of them (4), divided by the total number of condensers so connected (4), which is $\frac{4}{4}$ or 1. Therefore, the total capacity of this circuit is 1 mfd.

Since the total dielectric thickness is increased when condensers are connected in series, the combination will stand a greater voltage than any one of the condensers connected by itself would stand. For example, if two 1 mfd. condensers with a voltage breakdown of 400 volts each are connected in series, the combination has a voltage breakdown of 800 volts.

When condensers of unequal capacity are connected in series, the total capacity of the circuit can be found by using the inverse formula. This formula is the same as the one used for calculating the effective resistance of resistors connected in parallel. (Also for parallel inductors.) This formula is as follows:

$$C_t = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \ldots, \text{etc.}}$$

Where: C_t is the total effective capacity.
C_1, C_2, C_3, etc., are the individual capacities.

If three condensers having capacities of 2, 3, and 4 mfd., respectively, are connected in series, the total effective capacity can be found by this formula. (It is not necessary to convert these capacities into farads to use this formula.)

$$C_t = \frac{1}{\frac{1}{2} + \frac{1}{3} + \frac{1}{4}}$$

$$= \frac{1}{\frac{6}{12} + \frac{4}{12} + \frac{3}{12}}$$

$$= \frac{1}{\frac{13}{12}}$$

$$= \frac{12}{13} \text{ or } .923 \text{ mfd.}$$

Notice that the total capacity is less than the capacity of any of the condensers connected in the circuit. If a condenser of a particular capacity and voltage breakdown is needed in a circuit and that condenser is not available, it can sometimes be built up from condensers with a lower voltage breakdown. For example, let us assume that a condenser of 1 mfd. with a voltage breakdown of 1,000 volts is needed but is not on hand. There is, however, a plentiful supply of 1 mfd. condensers with a voltage breakdown of 500 volts available. Let us connect two of these condensers in series as shown at A in Fig. 17. The total capacity of this circuit is .5

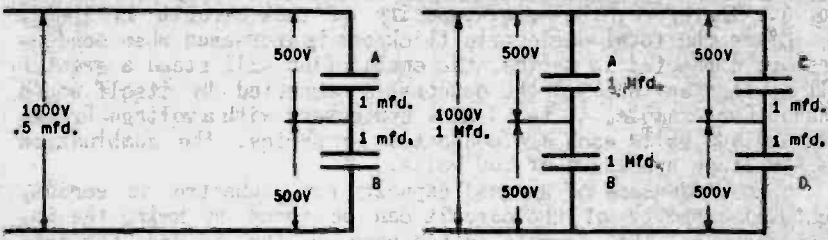


Fig. 17 (A) Two 1 mfd. Condensers in Series Having an Equivalent Capacity of .5 mfd. and a Voltage Breakdown of 1000 Volts.

(B) Four 1 mfd. Condensers in Series-Parallel, Arrangement Having an Equivalent Capacity of 1 mfd. and a Voltage Breakdown of 1000 volts.

mfd. and its breakdown voltage is 1,000 volts. Now assume that two more of these condensers are connected in series and placed across the line as shown at B in the figure. The combined capacity of condensers A and B is .5 mfd. These are in parallel with the combination C and D, which also have a capacity of .5 mfd. The total capacity across the line is, therefore, 1 mfd. with a voltage breakdown of 1,000 volts. Notice that each condenser has not more than 500 volts across it.

Connecting condensers in series reduces the total effective capacity of the circuit, but increases the total capacitive reactance. For example, each of the two 1 mfd. condensers of Fig. 16 at A have a capacitive reactance at 120 cycles of 1,327 ohms. The total effective capacity of this circuit is .5 mfd.; which has a capacitive reactance at this frequency of 2,654. The total capacitive reactance of condensers connected in series may be found by calculating the total capacity of the circuit using the inverse formula, and then calculating the capacitive reactance of this total capacity. It can also be determined by calculating the capacitive reactance of each of the condensers connected in series and then taking the sum of all these capacitive reactances to find the total of the circuit.

In a previous example there were three condensers with capacities of 2, 3, and 4 mfd., respectively, connected in series. The total effective capacity of the circuit found by the inverse formula was .923 mfd. At a frequency of 120 cycles, the total capacitive reactance is:

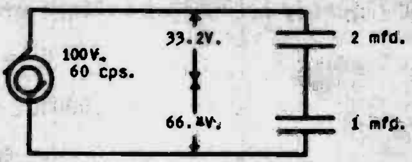
$$X_{C_t} = \frac{1}{6.28 \times 120 \times .000000923} = 1,437 \text{ ohms.}$$

Now let us calculate the capacitive reactance of each of these three condensers separately. They are found to be 663 ohms, 442 ohms, and 332 ohms for the 2, 3, and 4 mfd. condensers, respectively. The sum of these capacitive reactances is:

$$663 + 442 + 332 = 1,437 \text{ ohms.}$$

And so it is seen that either method may be used to determine the total capacitive reactance of the circuit. Let us connect a 1 mfd. condenser in series with a 2 mfd. condenser and then place an alternating voltage of 100 volts, 60 cycles, across the combination. This circuit is shown in Fig. 18. Which condenser will have the

Fig. 18 Illustrating the Voltage Drop Across Two Condensers of Unequal Capacity Connected in Series.



larger voltage drop across it? From the table in Fig. 11, it is found that the capacitive reactance of a 1 mfd. condenser at 60 cycles is 2,654 ohms, while that of a 2 mfd. condenser is 1,327 ohms. The total capacitive reactance connected across the line is:

$$2,654 + 1,327 = 3,981 \text{ ohms}$$

From the formula $I = E \div X_c$, the current which flows can be calculated.

$$I = \frac{100}{3981} = .025 \text{ ampere} = 25 \text{ ma.}$$

To find the voltage drop across each condenser, the formula $E = IX_c$ is used. Thus, the voltage drop across the 2 mfd. condenser is:

$$E = .025 \times 1,327 = 33.2 \text{ volts}$$

And the voltage drop across the 1 mfd. condenser is:

$$E = .025 \times 2,654 = 66.4 \text{ volts}$$

The preceding example shows that when two condensers of unequal capacity are connected in series and placed across an alternating voltage source, the condenser of smaller capacity has the greater voltage drop across it, since this condenser has the larger capacitive reactance.

When a direct voltage source is applied to two or more condensers connected in series, the voltage drop across each condenser depends not upon the capacity of the condenser as much as it does upon the leakage resistance of its dielectric. For example, suppose that two 1 mfd. condensers are connected in series. The leakage resistance of the first is 50 megohms, and the second is 200 megohms. The total resistance of the circuit is:

$$200 + 50 = 250 \text{ megohms}$$

The potential of the direct voltage source applied to the combination is 250 volts. To find the amount of direct current that flows, use Ohm's Law.

$$I = \frac{E}{R} = \frac{250 \text{ volts}}{250,000,000 \text{ ohms}}$$

$$= .000001 \text{ ampere}$$

$$= 1 \text{ microampere}$$

This 1 microampere, in flowing through the leakage resistance of 50 megohms, produces a voltage drop of:

$$E = I \times R$$

$$= .000001 \times 50,000,000$$

$$= 50 \text{ volts}$$

Likewise, the voltage drop across the 200 megohms is:

$$E = I \times R$$

$$= .000001 \times 200,000,000$$

$$= 200 \text{ volts}$$

If the voltage breakdown of each condenser is 150 volts, it would naturally be assumed that the combination would withstand a potential of 300 volts. It is seen, however, that when the applied voltage is only 250 volts, there is a 200-volt drop across one condenser. Since the voltage breakdown of this condenser is exceeded, it breaks down, thus applying the full 250 volts across the other condenser which also breaks down.

To eliminate this possibility, it is customary to place resistors of ½ to 1 megohm across each condenser connected in series when a direct voltage is to be applied to the combination. This is illustrated in Fig. 19. These resistors are known as equalizing resistors, since they tend to keep the voltage drop across any one

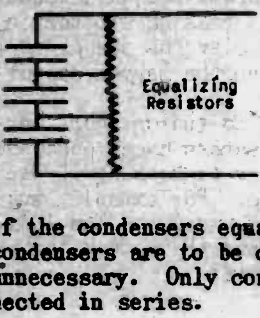


Fig.19 Illustrating Condensers in Series Across a DC Voltage with Equalizing Resistors.

of the condensers equal to that across any of the others. If the condensers are to be connected to an AC source, these resistors are unnecessary. Only condensers of equal capacity are ordinarily connected in series.

13. CONSTRUCTION OF MICA AND PAPER CONDENSERS. Condensers with a breakdown voltage as high as 5,000 volts and with capacities ranging from .00005 to .05 microfarad commonly employ mica as the dielectric. Mica has a relatively high dielectric constant and a high breakdown voltage. If the condenser is to withstand only moderate voltages, a very thin piece of mica may be used for the dielectric. Thus, for a given capacity the surface area of the plates need not be very large and the condenser is very compact. The plates of the condenser are made of tinfoil. The layers of mica and tinfoil are arranged as shown in Fig. 20. Alternate layers of tinfoil are connected together to form one plate of the condenser. The other layers of tinfoil are connected together on the opposite side to form the other plate and are brought out to a separate terminal. The unit is then bolted in a bakelite casing to keep out moisture and prevent a variation in capacity with age. Since mica cannot be rolled, the capacities larger than .05 mfd. are not practical, because they are not compact.

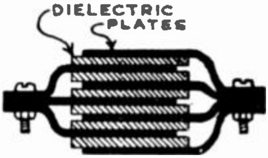


Fig.20 Cross-Section of Mica Condenser.

Condensers using paper as the dielectric are made in capacities ranging from .0001 to several microfarads. Paper does not have as high a dielectric constant as mica, nor is its voltage breakdown as great. Therefore, to withstand the same amount of voltage, a condenser would need a greater thickness of paper than it would of mica. Since the thickness of the dielectric must be greater, the plates must have considerably more surface area to produce the same capacity.

Paper condensers are manufactured by automatic machines. The tinfoil, as well as the paper for the dielectric, is supplied to the machine in large narrow rolls. The machine uses two rolls of tinfoil and two or more rolls of paper. The ends of the tinfoil strips are placed alternately between the ends of the paper strips, and the machine automatically rolls up the combination until a sufficient plate area has been reached to give the desired capacity. This is illustrated in Fig. 21. A flexible metal soldering tab is

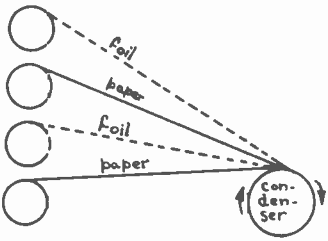


Fig.21 Method of Construction of Paper Condensers.

fastened to each tinfoil plate for connection purposes. The condenser must now be impregnated. This consists of pumping all of the air out of the empty spaces and completely filling them with paraffin. This results in an increase in the breakdown voltage and also prevents moisture from entering the condenser during its normal life.

After the condensers have been impregnated, they are sealed in cardboard or metal containers which protect them from moisture or mechanical injury. The voltage which a piece of paper will stand depends not only upon its thickness, but upon the grade of paper used. Paper condensers usually have two or more sheets of very thin paper between the sheets of tinfoil rather than just one sheet of paper of the desired thickness. This is due to the fact that a sheet of paper has microscopic pinholes in it which might cause a voltage breakdown. By using several sheets of the paper, this difficulty is eliminated, since it is unlikely that the pinholes in the several sheets will be in line.

Suppose that a condenser having a capacity of 2 mfd. and a voltage breakdown rating of 1,000 volts is to be constructed. In order for the dielectric to stand 1,000 volts, it must be rather thick. With a thick dielectric, the plates must have a very large surface area to produce a capacity of 2 mfd. This results in a very bulky condenser and, of course, increases the manufacturing cost. For example, a 1 mfd. paper condenser with a voltage breakdown of 400 volts costs in the neighborhood of fifty cents, while a 1 mfd. paper condenser built to withstand 5,000 volts costs approximately forty dollars.

Paper condensers may be wound in two different ways; inductively or non-inductively. In the inductive type of winding, the foil used is narrower than the paper and contact is made to the foil plates by brass or copper strips inserted into the winding at one end as shown at A in Fig. 22. Each strip makes contact with its

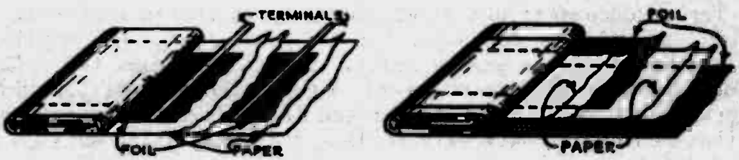


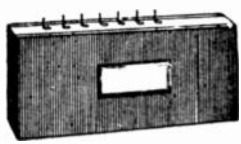
Fig. 22 (A). Inductive Condenser. (B) Non-Inductive Condenser.

foil plate at only one point. Since some of the foil plates may be as long as 50 feet or more, it is obvious that the current must enter the plate from one end and flow around the many turns of tinfoil in order to distribute the charge over the entire plate surface. It may be seen that this is practically the same as sending the current in and out of a coil of wire; therefore, this type of condenser will possess considerable inductance.

The non-inductive type of condenser is wound with foil that is usually the same width as the paper. The winding is staggered so that a condenser plate is visible from each end as shown at B in Fig. 22. When the condenser is rolled up, one plate will protrude from one end of the roll, and the other plate from the opposite end. Each terminal consists of a flexible lead joined to a metal strip soldered to the entire edge of the foil extending across the end. Thus, each terminal makes contact with each turn of the foil and causes the condenser to be non-inductive since the current enters each turn of the coil and is not required to flow around and around in order to distribute the charge. This method of construction short-circuits every "turn" in the condenser. All modern paper-type condensers are wound non-inductively.

It is common practice to construct several condensers in the same case. In this arrangement, a single terminal is connected to one plate of each condenser. This is called the common terminal. The other plates of the condensers are brought out to separate terminals. Thus, to use any particular condenser, one connection is made to the common terminal and the other to that terminal connected to the other plate of the condenser.

Such an arrangement is known as a condenser bank or condenser block. An illustration of and a symbol for a condenser bank are shown in Fig. 23.



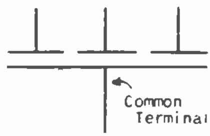
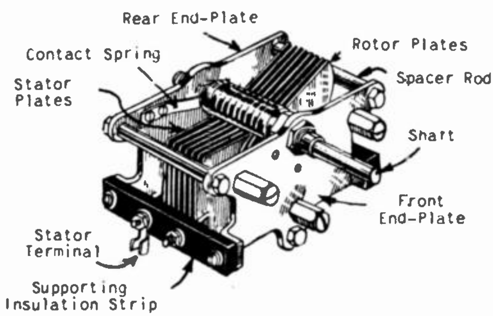


Fig.23 (A) View of Condenser Bank. (B) Symbol for Condenser Bank.

14. CONSTRUCTION OF VARIABLE CONDENSERS. Variable condensers usually employ air as the dielectric. Variation is made continuous from the minimum capacity of the condenser to its maximum capacity. Fig. 24 shows the construction of a variable condenser,

Fig.24 Illustrating Parts of a Variable Condenser.



the various parts being clearly marked. A variable condenser consists of one set of metal plates which are stationary and are known as the stator plates, and another set of metal plates connected to a rotating shaft in such a manner that the rotating plates (called the rotor) may be moved in to and out of the spaces between the stator plates without touching them. When the plates are completely enmeshed, the full areas of the plates are exposed to each other and a maximum capacity exists. When they are completely out of mesh, a minimum capacity exists, and it is possible to obtain any intermediate capacity by intermeshing the plates the required amount. The plates are made of thin, hard brass or aluminum, stamped out on punch presses. Brass plates have the advantage of being easily soldered to the rotor shaft or stator block for good electrical connection, and of requiring less thickness of a plate for the proper stiffness. Brass is subject to corrosion, and if the plates are to be made of this material, they must be given a coat of lacquer. Aluminum, on the other hand, is lighter in weight and not as subject to corrosion. Soldering to aluminum, however, is much more difficult. The stator plates are wedged into grooves cut on the stator support block. The blocks are fastened to two, small strips of hard rubber or bakelite, which in turn are fastened to the metal frame. The bakelite strips serve to insulate the stator assembly from the rotor. The rotor plates are wedged into accurately cut grooves on the rotor shaft. This shaft turns in bearings set into the end plates. Care must be taken that the rotor plates do not at any point of their rotation make contact with the stator plates, for this would result in a short circuit. Contact is made to the rotor plates by means of a contact spring fastened to one of the end plates, as shown at A in Fig. 25. The other end of the

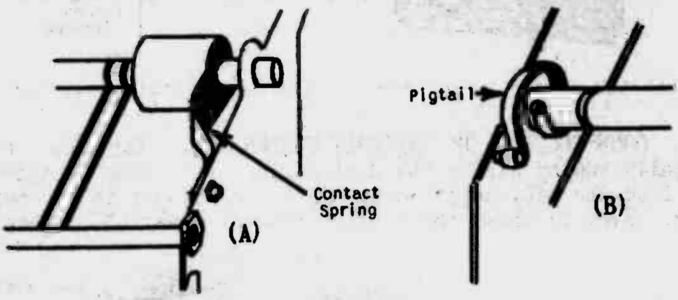


Fig. 25 (A) Using a Contact Spring to Make Connection to the Rotor of a Variable Condenser.
(B) Using a Pigtail to Connect to the Rotor.

spring rests firmly upon one end of the rotor shaft. Another method, illustrated at B in Fig. 25, is to use a pigtail, a conductor made of braided, flexible copper wire. One end of this pigtail is soldered to an end plate and the other is wrapped half way around the rotor shaft and soldered to this shaft. The pigtail must be long enough so that the rotation of the rotor plates does not place any tension upon the pigtail. Also, stops must be provided so that the rotor plates cannot be rotated through more than 180 degrees.

The spacing between a rotor plate and a stator plate is dependent upon the voltage the condenser is required to withstand. Thus, to withstand a voltage of 12,000 volts, the distance between one rotor plate and the adjacent stator plate must be .5 inch. Such a condenser would be used in a very high-powered transmitter.

In a receiver where the voltages are ordinarily low, the spacing between adjacent plates is small. However, enough mechanical clearance must be left so that the rotor plates will not touch or scrape against the stator plates if they should become slightly bent out of shape.

Variable air condensers are manufactured in a wide variety of capacities ranging from 3 or 4 mmfd. to 500 mmfd. or higher.

Another type of variable condenser consists of two small sheets of spring brass separated by a piece of mica (see Fig. 5A). The two sheets of brass and the mica are firmly fixed on one side. An insulated screw extends through the center of the brass and mica. When the screw is turned to the right, the sheets of spring brass are forced closer together, thus increasing the capacity of the condenser. When the screw is turned to the left, not so much tension is put upon the sheets of brass and they spring apart of their own accord, thereby reducing the capacity. Such condensers were used for neutralizing in some of the older-type neutrodyne receivers. They are called trimmer or padding condensers and are used extensively in modern receivers to align the various circuits to the same frequency.

Variable air condensers are also made in what is known as condenser gangs. Several variable condensers are placed in the same frame and the rotor plates of all of them are joined to a common shaft. The rotor plates of all the condensers are, of course, connected together, while separate terminals are provided for each set of stator plates. The symbol for a condenser gang is shown in Fig. 26. The dotted lines indicate that all of these condensers are varied by a common control. As many as six condensers are sometimes ganged together by this method. Fig. 27 shows an illustration of a two-gang condenser.

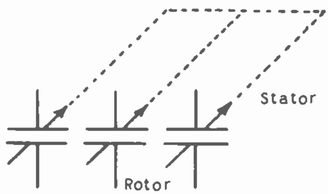


Fig.26 Symbol for Three-Section Ganged Condensers.

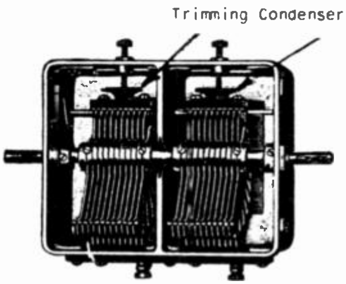
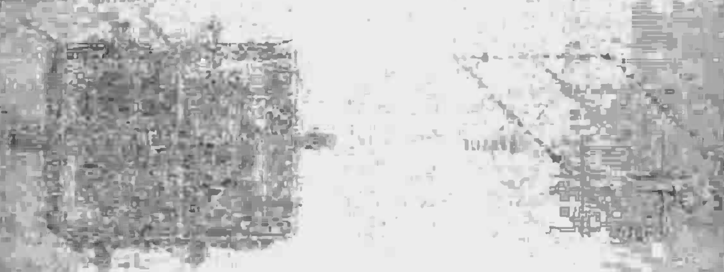


Fig.27 View of Two-Section Ganged Condensers.



Notes

(These extra pages are provided for your use in taking special notes)

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UNIT NO. 1

VACUUM TUBE CHARACTERISTICS

LESSON NO. 12

THOMAS ALVA EDISON (CONTINUED)

.......and he fought his way to success!

After the development of a device that made it possible to employ a single submarine cable for two circuits, Edison opened a small workshop so that he could continue his experiments with electricity. To further his knowledge, he bought all of Faraday's works on electricity, spent much time in second-hand book shops and the public library and became so fired with enthusiasm and ambition that he devoted but little time to eating and sleep. In 1869, he took out his first patent for an electrical voting machine, but his hopes were doomed to disappointment, for the Massachusetts Legislature failed to adopt it. However, he did not become discouraged, but continued his grim, yet fascinating, search for new electrical discoveries.

Even though Edison was devoted to study and serious thought, amusing incidents found their way into his life. On one occasion, he was invited to deliver an address on telegraphy before an academy. When the appointed hour arrived, he was nowhere to be found. Diligent search revealed that he was dressed in his working clothes and putting telegraph wires on the top of a house. Hurrying to the academy without changing clothes, he was astonished to discover that instead of a group of boys, his audience was composed of young ladies dressed in beautiful clothes.

In 1869, Edison tired of telegraph operating, quit his job and went to New York. Although his mind was full of plans for new inventions, his pocketbook and stomach were empty. How easy it would have been for him to "give up" and say, "Oh, what's the use." And how fortunate for civilization that he did not do this, for if he had, we might be without many of the electrical conveniences that we enjoy today. When things looked darkest for Edison, fate intervened with startling abruptness. He happened into a broker's reporting office at a most opportune time. The stock quotation printer had broken down and several hundred brokerage offices were without service. Edison was asked if he could repair the printer. He tackled the job, repaired the printer, restored the vital service and the dark clouds of destitution rolled away. Edison was offered the position of service manager at a salary of $300.00 a month.

But this was only the beginning. He invented several stock quotation printers and other devices, and was asked what he would accept for these inventions. He said that he did not know what they were worth. When he was offered the sum of $40,000.00, his astonishment was tremendous. Thomas Alva Edison's determination to "stick" when things were blackest had started him on the high road to fame, fortune and world-wide acclaim.

Let this incident in Edison's life be an inspiration to you. Remember, "when life seems dark and gloomy and discouragement blocks the way, a little more fight on your part can bring you to the success that lies just ahead"!

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Lesson Twelve

VACUUM TUBE CHARACTERISTICS

"During your study of Radio and Television, I do not believe that you will find any subject of greater interest than the study of vacuum tubes. As you progress with your training, you will encounter a great many interesting uses for this delicate and amazing device.

"In this lesson, you will learn the construction and fundamental operation of a vacuum tube, as well as one of its most important commercial applications.....amplification. Study this lesson well, for much of your advanced training will be based upon the following pages."

1. CONSTRUCTION OF VACUUM TUBES. The study of a vacuum tube is greatly enhanced and made more interesting if the construction of the device is understood. Whereas our modern vacuum tube represents the ultimate in engineering precision and years of painstaking research, the actual physical construction of a vacuum tube isn't difficult to understand. At the present time, there are about 350 different types of vacuum tubes on the market, which are used in the construction of radio receivers. A rough estimate of approximately 150 tubes would comprise those used in the construction of radio transmitters. In addition to those tubes used for radio purposes only, there are several hundred varieties which are applicable to television, telephone, AC power control, DC power control and photoelectric relay services.

Each of the hundreds of different vacuum tubes available on the market are constructed differently; hence, they possess different characteristics relative to internal resistance, amplifying ability, power handling capacity, etc. These different characteristics make it possible to select exactly the type of tube necessary to perform a particular job. A design engineer always selects the type of tubes he is going to use in the receiver or transmitter which he is designing, then proceeds to arrange the connecting circuits between these tubes in such a manner as to secure the maximum performance from each of them. When a certain job is to be performed and it is found that there is no tube available which is capable of performing that job, then, generally, the tube manufacturers are notified and they in turn set their engineers to work on the design of a new tube which will meet with the specified requirements. Therein, a new vacuum tube is born, which possesses different characteristics from all of those preceding it and one which is capable of accomplishing a certain job which no other tube on the market was capable of doing. Nearly all of the vacuum tubes available at the present time have been introduced to the industry in this manner. Of course, this same system will be effective in yielding new tubes in the future.

Considering the hundreds of tubes available at the present time and realizing that there will be any number of newer tubes introduced in the next few years, we realize that it is virtually impossible for any one individual to know the exact characteristics and the use for each type of tube. The well-informed Radio-Television engineer, however, should have a good foundational knowledge of the characteristics of those vacuum tubes which are used in the more common radio and television receiver and transmitter circuits. The tube manuals supplied by manufacturers of receiving and transmitting tubes make it possible for the engineer to have complete data of all tubes on hand, which can be used for quick reference. Even though this information is available in reference form, a general knowledge of vacuum tube characteristics is very essential when attempting to understand the design of a radio or television circuit.

Whereas the electrical characteristics of vacuum tubes differ in all cases, the general physical construction follows along similar lines. The student should become acquainted with the method generally followed in constructing a typical glass vacuum tube. A type 58 pentode tube has been selected for this purpose. A pentode vacuum tube is one which possesses three grids; namely, the control grid, the screen grid and the suppressor grid. These grids are in addition to the heater, cathode and plate. We shall not attempt to explain the electrical function of a pentode tube at this time. It is being used merely as an example for the method of manufacturing a typical glass tube.

Referring to Fig. 1, the glass tube shown at A serves as the main support for the elements. At B, this same glass tube is shown after it has been partially molded. The supporting posts, the lead-in wires and the long glass tube are shown separated from the glass support at C; at D, they are shown assembled. The supporting glass tube is heated, then the supporting posts and lead-in wires are inserted through the supporting tube. A small hole is drilled through the supporting glass tube, then the long, thin glass tube shown at the bottom in C is fused into this hole. The top of the thin tube is left open. While the supporting glass tube is still hot, it is pressed together at the top. After cooling, all of these wires are very securely held in the molded glass.

The long, thin, glass tube which extends down below the lead-in wires at D is hollow and open at both ends. Later in the process, air will be pumped from the inside of the glass envelope by means of this tube. At E in Fig. 1, the supporting wires have been cut and bent to the proper shape so as to hold the elements of the tube in their proper positions. At F, the small pieces of insulating material to be used in the assembly of the tube are shown. These small insulators assist in holding the elements in their proper positions and, at the same time, prevent electrical contact. At G (from bottom to top), the heater wires, the cathode, grid number

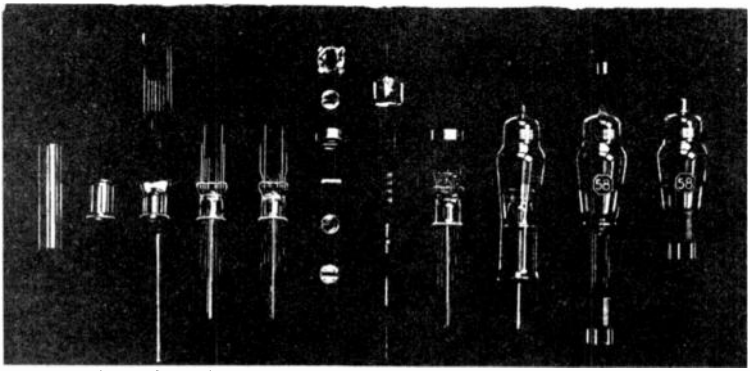


Fig. 1 Various parts and assembly of a type 58 tube.

one, grid number two, grid number three and the plate are shown. After the small insulators and elements have been placed in their proper positions and securely welded, the appearance of the tube is as shown at H. A small, metal cup (not shown) is attached to one of the supporting wires and the cup is filled with a chemical called the "getter". This "getter" will be used for a particular purpose later in the construction of the tube. The getter's cup is generally welded to the wire which supports the plate of the tube. After the glass envelope has been placed over the assembled unit as shown at I, it is cut and fused to the bottom flange of the glass tube which supports the element. Great care must be taken in the glass sealing process, because, if not done in the proper manner, small cracks are very apt to result. The connection protruding through the top of the tube (grid number one connection) must also be sealed; then the only connection between the inside of the bulb and the outside atmosphere is through the long, thin, hollow tube protruding from the bottom.

Next, the inside of the glass envelope must be evacuated. It is necessary to pump out nearly all of the air and other gases inside the space enclosed by the glass bulb and also to drive out any gases which might be contained in the metal elements themselves or the glass envelope. Even after a tube is thoroughly exhausted by means of a vacuum pump, it will give indications of the presence of gases which gradually come out of the interior parts. At ordinary temperatures, these gases are released slowly; hence, the length of time necessary for complete evacuation of the bulb would be prohibitive. In order to rapidly drive out all of the gases from the walls of the tube and from the elements, the entire tube is heated to a high temperature during the process of exhaustion. When the desired degree of vacuum is obtained, the long, thin, glass tube protruding from the bottom is fused off and the tube is then permanently sealed.

To make certain that any gases which might be given out from the glass envelope and metal elements do not cause improper operation of the tube at some future time, the chemical in the "getter" cup is exploded. This is done by means of a high-frequency magnetic field. When the getter is exposed to the high-frequency field, the heat generated causes it to evaporate rapidly or explode. As the getter explodes, it condenses in a silvery film on the inside of the glass bulb. This film not only attracts the gases when they are released from the elements, but also tends to seal the gases in the walls of the tube itself.

After the evacuation process and getter explosion, the glass bulb is cemented to an insulating base, at the bottom of which there are small, hollow, metal prongs. The lead-in wires are passed through these prongs, then fastened to them by a drop of solder at the bottom of each prong. These prongs provide the external connections to the elements inside the tube. In the type 58 tube (which we are using as an example), a small metal cap is soldered to the wire protruding through the top of the glass bulb. This is the connection to grid number one.

After the construction of the tube has been completed, it is necessary to put the tube through various factory tests and, in addition, production samples must be taken out for a test of the tube's characteristics. When testing the characteristics, every electrical detail of the tube is accurately measured to assure a long and useful life.

Several views of tube manufacturing operations are shown in Figs. 2 to 7, inclusive. These are reproduced through the courtesy of the RCA Radiotron Manufacturing Company.

A cut-away drawing showing the internal construction of a four-element tube and indicating the approximate dimensions of the various components is shown in Fig. 8. Fig. 9 illustrates the structure of an all-metal radio tube. A more thorough and detailed description of the operation of metal radio tubes will be given in later lessons.

2. CHARACTERISTIC CURVES. The electrical characteristics of a vacuum tube are in no way apparent from its external appearance. In other words, it is impossible to accurately determine the electrical characteristics of a tube by just looking at it. There are a few characteristics of a vacuum tube which can be estimated from its physical size, but these characteristics are of no importance at the present time.

The performance of a vacuum tube to be used in Radio and Television may be conveniently studied by the use of "curves", which show its electrical characteristic properties. These are known as "characteristic curves". They may be secured from the tube manufacturer or can be constructed from experimental data.

Since the operation of a two-element vacuum tube is the easiest to understand, it is advisable that we should begin our study of characteristic curves, using a tube of this type.

Fig. 10 shows a two-element vacuum tube circuit with 180 volts applied to the plate of the tube and a milliammeter in series with the plate lead to measure the plate current. The negative side of the B battery (180 volts) is connected to the negative side of the filament, thus completing the plate circuit. The rheostat R is in series with the positive lead to the filament of the tube; hence, an adjustment of the rheostat will introduce more or less resistance in the filament circuit, thus varying the filament current accordingly. A voltmeter is connected directly across the filament prongs in order to measure the voltage actually applied across the resistance of the filament wire. If all the resistance possessed by the rheostat R is introduced into the filament circuit, the voltage drop across the filament of the tube will be very low and, likewise, if all the resistance of the rheostat R is taken out of the filament circuit, the voltage across the filament prongs of the tube will be 7 volts. By varying the position of the movable contact arm on the resistance R, it will be possible to change the voltage drop across the filament of the tube from maximum (7 volts) to a very low value.

Suppose that we have this circuit set up using the actual apparatus and proceed to obtain a collection of data from which we shall plot a "filament-voltage, plate-current" characteristic curve for this particular tube.

To begin the compilation of data, suppose we first disconnect the wire which connects the movable arm on the rheostat to the positive terminal of the 7-volt battery. With this lead disconnected, there will be no current passing through the filament circuit; hence, there will be no electron emission from the filament and no plate current will flow. This gives the first pair of related values for the filament voltage and the plate current; that is, with zero filament voltage, we will have zero plate current. Replace the wire from the 7-volt battery to the movable arm on the rheostat, then insert sufficient resistance by moving the arm on the rheostat to the left until the voltmeter connected across the filament prongs measures .5 volt. With .5 volt applied across the resistance of the filament wire, there will be a slight current flow through the filament wire, raising its temperature slightly and resulting in a very weak emission of electrons. Since there are 180 volts applied to the plate of the tube, a few of the sparsely emitted electrons from the filament wire will be attracted to it. We shall assume that there is a sufficient number of electrons reaching the plate to constitute .5 milliampere of plate current flow. This amount of current will barely show an indication on the milliammeter in the plate circuit. These two values give the second pair of figures to be tabulated; that is, with .5 volt applied to the filament, there is .5 ma. of current flowing in the plate circuit.

Next, suppose the variable arm of the rheostat R is moved to the right until the voltmeter connected across the filament prongs reads 1 volt. With this additional voltage applied across the filament, there will be a greater current passing through the filament, raising the temperature of the filament to a higher degree and causing more electron emission. With the increased emission, the 180

VARIOUS STEPS IN MAKING RADIO TUBES

By Courtesy of RCA Radiotron

Fig.2 Carbonizing interior walls of glass bulbs--This machine places a band of carbon dust within the bulb, then neatly cleans the top and bottom section of the bulb.

Fig.3 Gauging bulbs--Uniform bulb dimensions are essential for making quality tubes with modern high-speed equipment.

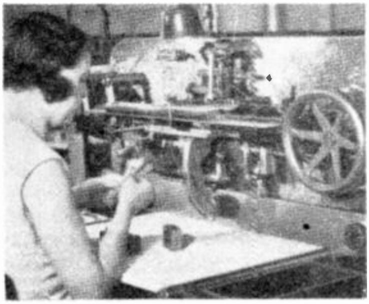


Fig.4 Winding grids--Grid-winding machines automatically wind the correct number of turns for each grid.

Fig.5 Gauging grids--Inside and outside diameters are measured to 0.001 inch.

Fig.6 Assembling tube mounts--All metal connections are welded to insure high electrical conductivity and sturdy construction.

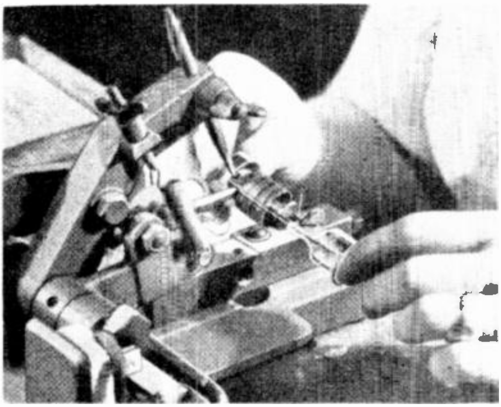
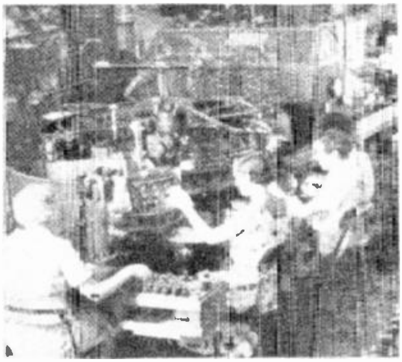


Fig.7 Sealing, exhausting, and basing process--This highly-involved manufacturing unit completes the operations of tube assembly.



volts applied to the plate is capable of pulling more electrons over to it and, let us say, the milliammeter in the plate circuit is reading 1 ma. These two values give the next pair of points to be tabulated; that is, 1 volt filament voltage causes 1 ma. of plate current flow. Continuing, decrease the resistance of the rheostat until there is 1.5 volts across the filament; there will then be 2 ma. of plate current flowing. With 2 volts across the filament, there will be 4 ma. of plate current flowing, etc. The tabular chart on the right side of Fig. 10 shows the relative filament voltage and

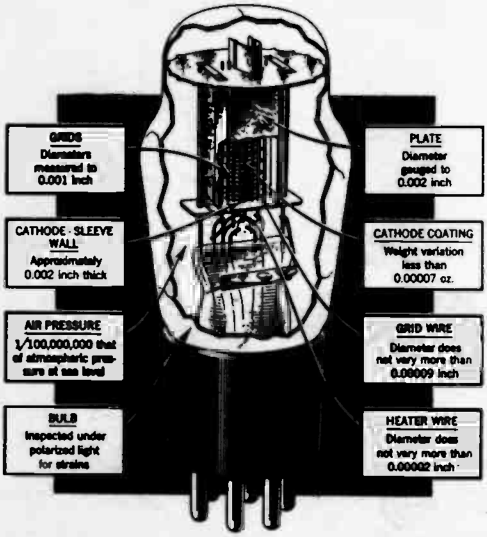


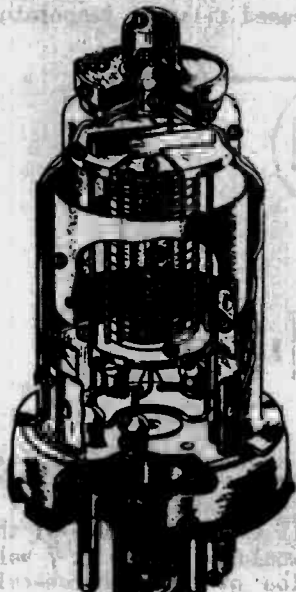
Fig.8 Cutaway view of a four-element glass tube showing internal construction.

Courtesy of RCA Mfg. Co.

plate current values in steps of .5 volt up to the maximum voltage of the filament battery, which is 7 volts in this case. Bear in mind that all of these values are being determined experimentally; that is, the apparatus is actually set up and a test is made on the tube by the use of accurate measuring instruments.

After securing the collection of data experimentally, the next step is to plot the data on a graph. The graph is shown in Fig. 11. In a previous lesson, you were taught how to plot points on a graph, so that information will not be repeated at this time. By inspecting the graph in Fig. 11, you will notice that the various points coincide exactly with the tabulated data. Since this curve illustrates the relationship between the filament voltage and the plate current for this particular type of tube, it is commonly called a "filament-voltage, plate-current characteristic curve".

There are a number of facts pertaining to the operation of this tube made evident from the graph. The collection of data alone is of little importance because it is not until these data are properly placed in graphical form that it is possible to "picture" the operation of the tube. By inspecting the graph, it will be noticed that the plate current is relatively low until the filament voltage reaches about 2.5 volts. At that time, the plate current begins to increase rather rapidly and does so in a nearly straight line characteristic. After passing 5 volts, the relationship between the filament voltage and the plate current is no longer equivalent to a straight line (linear), but, rather, begins dropping off slightly



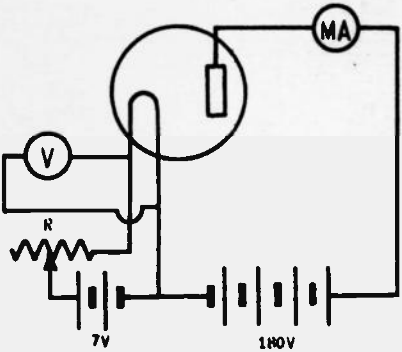
Courtesy of
RCA Mfg. Co.

1—SOLDER
2—CAP INSULATOR
3—ROLLED LOCK
4—CAP SUPPORT
5—GRID LEAD SHIELD
6—CONTROL GRID
7—SCREEN
8—SUPPRESSOR
9—INSULATING SPACER
10—PLATE
11—MOUNT SUPPORT
12—SUPPORT COLLAR
13—GETTER TAB
14—GLASS BEAD SEAL
15—EYELET
16—LEAD WIRE
17—CRIMPED LOCK
18—ALIGNING KEY
19—PINCHED SEAL
20—ALIGNING PLUG
21—GRID CAP
22—GRID LEAD WIRE
23—GLASS BEAD SEAL
24—EYELET
25—BRAZED WELD
26—VACUUM-TIGHT STEEL SHELL
27—CATHODE
28—HELICAL HEATER
29—CATHODE COATING
30—PLATE INSULATING SUPPORT
31—PLATE LEAD CONNECTION
32—INSULATING SPACER
33—SPACER SHIELD
34—SHELL-TO-HEADER SEAL WELD
35—HEADER
36—SHELL CONNECTION
37—OCTAL BASE
38—BASE PIN
39—SOLDER
40—EXHAUST TUBE

Fig.9 Cutaway view of a five-element metal tube showing internal construction.

as evidenced by the curvature of the characteristic at the upper end. Notice that a filament voltage increase from 6 to 7 volts results in a plate current increase of only 3 ma., whereas down on the straight portion of this characteristic curve, a filament voltage increase from 4 volts to 5 volts results in a plate current increase of 17 ma.

The significance of this bend on the upper end of the characteristic is that it is not advisable to apply a voltage higher than 5 volts to the filament of the tube for continuous operation. Increasing the filament voltage above this value does cause a slightly higher plate current to flow, but the increased plate current does not warrant the increased filament temperature which results from



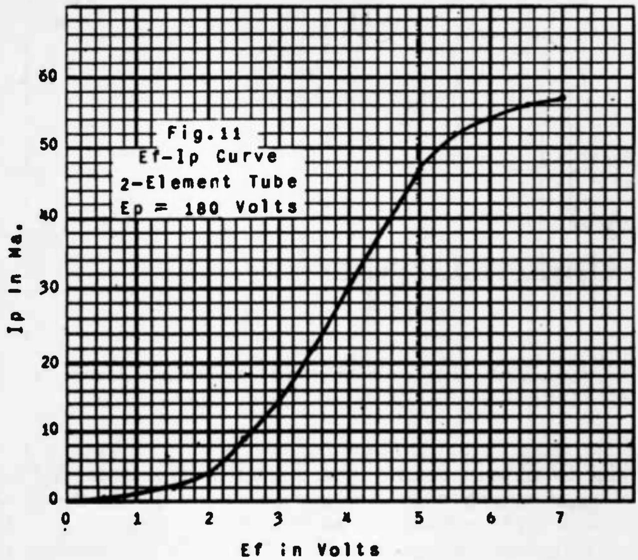
E_F	I_P
0	0
.5	.5
1.	1.
1.5	2.
2.	4.
2.5	9.
3.	14.
3.5	22.
4.	30.
4.5	38.
5.	47.
5.5	52.
6.	54.
6.5	56.
7.	57.

Fig.10 Two-element tube circuit for collecting data to plot a filament-voltage, plate-current (E_f–I_p) curve.

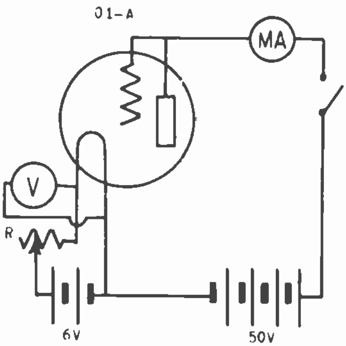
the higher voltage. If the temperature of the filament is run excessively high, as it would be with 6 or 7 volts applied to the filament, the deterioration of the electron-emitting material on the filament occurs more rapidly than normal, resulting in decreased tube life. From the characteristic curve, it is evident that the most satisfactory voltage for continuous operation of the filament is 5 volts.

As the next example, we shall use a vacuum tube which is available on the commercial market. The selected tube is the type 01-A and we shall proceed to plot a characteristic curve of this tube showing the relationship between the filament voltage and plate current. By referring to the table of characteristics for a type 01-A tube, as given in your tube manual, you will find that the specified filament voltage for this tube is 5 volts; the filament current, .25 ampere; the plate voltage, 90 to 135 volts; etc. The circuit to be used for obtaining the necessary data is shown in Fig. 12. You will notice that the grid and plate of the type 01-A tube have been tied together, thus causing the tube to function as a diode, or two-element tube instead of a three-element tube. The plate voltage to be used for this experiment is 50 volts and the filament voltage may be increased to a maximum of 6 volts.

A filament-voltage, plate-current curve is often called an "emission" characteristic curve. An emission characteristic curve is of great importance, especially for transmitter tubes. Transmitter engineers plot an emission curve when they desire to ascertain the condition of the filament in a tube which has been in service for a number of hours. If the emission characteristic curve is found to be satisfactory, the tube will be placed back in the radio or television transmitter and used until it is advisable to plot another emission characteristic curve on it. When the emission characteristic curve indicates that the emission of the tube is below normal, the tube is discarded and a new one is inserted in its place. In view of its relative importance to transmitter tubes, this procedure should be remembered.



Referring to Fig. 12, we shall begin collecting data with no filament voltage applied. With no filament voltage applied, there will be no plate current flowing. Then, by closing the filament circuit and adjusting the position of the rheostat R until there is 1 volt across the filament of the tube, we find there is still no plate current flowing. A point should be placed on the graph coinciding with 1 volt filament voltage and zero plate current. Next, by decreasing the size of the rheostat until the filament voltage is 1.5 volts, we find the plate current has begun to flow and has a value of 1 ma. Decreasing the filament rheostat until the filament voltage is 2 volts, allows 2 ma. of plate current to flow; 2.5 volts applied to the filament allows 2.8 ma. of plate current to flow; 3 volts applied to the filament allows 4 ma. of plate current to flow; etc. All of these figures are tabulated on the right of Fig. 12. It will be noted that this circuit has a switch in the plate circuit. This switch is for the purpose of opening the plate circuit until the filament rheostat is set to the correct value; then, when a reading on the plate current milliammeter is desired, the switch in the plate circuit is closed, the reading taken and the switch immediately opened. As you will notice, the plate current which flows in the plate circuit with the filament voltage of 5.5 volts is 65 ma., whereas the maximum plate current specified by the manufacturer (by referring to the tube manual) is found to be 3 ma. Overloading the tube in this manner for any period of time is certain to damage the tube seriously. When obtaining experimental data for characteristic curves in this manner and



E_F	I_P
0	0
1.	0
1.5	1.
2.	2.
2.5	2.8
3.	4.
3.5	8.5
4.	15.8
4.5	27.
5.	47.
5.5	65.

Fig.12 Circuit for plotting filament-voltage, plate-current (E_f -I_p) curve on a type 01-A tube.

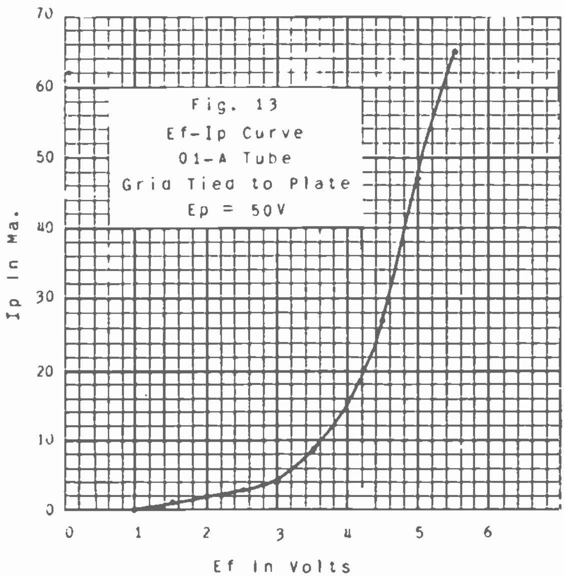
it is desired to obtain points where an exceedingly high plate current will flow, a switch should always be provided in the plate circuit so as to allow a momentary reading to be taken.

After collecting the experimental data, these points are plotted on a graph as shown in Fig. 13 and the points connected by a smooth line. Notice that the bottom of the characteristic is rather curved, but, after passing about 4 volts, it becomes nearly a straight line. The top of the characteristic does not bend to any great extent. When the emission characteristic curve does not bend over at top with high values of plate current, it indicates that the tube is in good condition insofar as the electron emission from the filament is concerned. Suppose you were plotting this characteristic curve on a transmitter tube for the purpose of determining whether or not the tube should remain in use. Since the emission curve does not bend at the top, it indicates that the tube is in good condition and continued use of the tube is permissible. If, upon plotting the curve, you had found that the upper portion had deflected from the normal incline after passing 40 or 50 ma., it would have indicated that the emission characteristics of the tube were poor and that future use of that tube in the circuit is not advisable.

These data and this characteristic curve represent an actual commercial tube. An equivalent characteristic curve could be plotted for any tube if the equipment were available.

As previously stated, a filament-voltage, plate-current characteristic curve is for the purpose of determining whether or not the active material on the filament or cathode is in good condition.

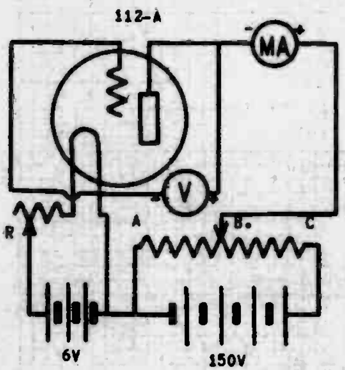
3. PLATE-VOLTAGE, PLATE-CURRENT CHARACTERISTIC CURVES. Throughout the entire course of study, plate-voltage, plate-current curves will be found very beneficial. By use of these characteristic curves it is possible to determine whether or not a tube is capable of functioning properly as a certain type of amplifier, detector, or generator of high-frequency alternating currents. It is also possible to determine the "constants" of a tube which will be discussed later in this lesson. For these reasons, it is necessary to understand how this "picture" of the relationship between the plate voltage and the plate current is obtained.



When collecting the data necessary for plotting a plate-voltage, plate-current characteristic curve, a constant voltage is applied to the filament (or heater) and the grid of the tube. The circuit shown in Fig. 14 has been selected to illustrate the method of collecting data for plotting a plate-voltage, plate-current characteristic curve on a type 112-A vacuum tube. In this circuit, the grid of the tube has been tied to the negative side of the filament, thus making the bias voltage zero. Before starting the collection of data, it is necessary to adjust the rheostat R in the filament circuit until the proper voltage is applied to the filament of the tube. By referring to the manufacturer's specifications, the recommended filament voltage on this tube is found to be 5 volts. Connect a voltmeter across the filament prongs and adjust the rheostat until that voltage is obtained; then do not change the position of the rheostat thereafter.

A 150-volt battery is being used as the plate voltage supply and a potentiometer is shown connected across the battery. The movable arm B on the potentiometer can be changed back and forth across the resistance from A to C, thus changing the voltage applied to the plate from zero to 150 volts. A voltmeter V is shown connected between the plate of the tube and the negative side of the filament to measure the plate voltage.

First, set the movable arm B on the potentiometer at point A, which connects the plate of the tube directly to the negative side of the filament; hence, the plate voltage will be zero. The milliammeter in the plate circuit will be indicating no plate current, so the first values to record will be: plate voltage, 0; plate current, 0. Next, move the arm B to the right until the voltmeter reads 25 volts of plate voltage. By reading the plate current milliammeter carefully, we find it to be 1.25 ma. After tabulating



E_P	I_P
0	0
25	1.25
50	5.
75	9.8
100	16.
125	23.5
150	31.

Fig. 14 Circuit for plotting plate-voltage, plate-current (Ep-Ip) curve on a type 112-A tube.

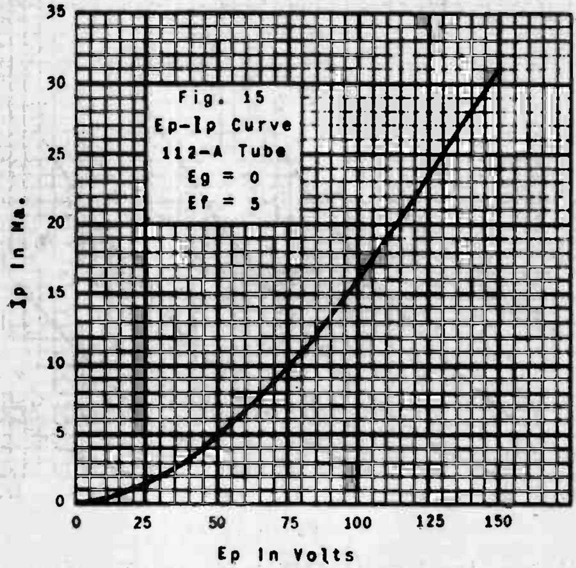
these readings, the movable arm B on the potentiometer is moved to the right until the plate voltage meter is indicating 50 volts. By observing the plate current, we find it has increased to 5 ma. Continuing to increase the plate voltage in 25-volt steps up to a maximum of 150 volts and making note of the plate current flowing with each plate voltage reading, the data listed in the chart on the right side of Fig. 14 is obtained.

The collection of data alone does not clearly indicate the relationship between plate voltage and plate current, so it is advisable to plot these points on a graph. The graph shown in Fig. 15 has these values plotted. As can be seen from the graph, the plate-voltage, plate-current characteristic curve of this tube has a slight bend at the lower end. After passing approximately 75 volts, the relationship between plate voltage and plate current becomes quite linear[1], as evidenced by the straightness of the characteristic from this voltage up to 150 volts. It is possible to collect data at plate voltages higher than 150; however, when the grid bias is zero,

[1] The words, "linear" and "non-linear", are used quite frequently when speaking of characteristic curves. "Linear" means that the relationship between the constant and the variable is such that the graph is a straight line. "Non-linear" means that the graph of a relationship is not a straight line.

the plate current reaches dangerously high values at higher voltages and the tube is apt to be damaged.

In this example, the plate voltage was increased in 25-volt steps. Had the plate voltage been increased in 12.5-volt steps and the plate current recorded each time, twice as many points would have been obtained through which to draw the characteristic curve. Twice as many points would have given a more accurate curve; so, when extreme accuracy is desired, as many points as practical should be placed on the graph before drawing the line. When the relationship between the plate voltage and plate current is quite linear, such as from 75 to 150 volts in Fig. 15, it is not necessary to secure a large number of points before drawing the line. However,



when the relationship between the plate voltage and plate current is non-linear; that is, it is bending or passing through a curve, it is advisable to obtain several points in order to assure greater accuracy. In this particular case (Fig. 15), it would have been advisable to secure at least three additional points between 25 and 75 volts.

It will be noticed that in the graphs plotted so far, the plate or filament voltage values have always been plotted along the base of the graph and the current values have been plotted along the side of the graph. This is the procedure generally followed and you will find that nearly all characteristic curves are plotted in a similar manner. The division of the voltage values along the bottom of the graph and the division of the current values along the side of the graph are always made so that, with the data obtained, the curve will run approximately from the lower left-hand corner to the upper right-hand corner of the graph paper. The greater the area of the sheet occupied by the characteristic curve, the greater will be the accuracy when we desire to use the characteristic for practical application.

4. A FAMILY OF PLATE-VOLTAGE, PLATE-CURRENT CHARACTERISTIC CURVES. The single plate-voltage, plate-current characteristic curve as plotted in Fig. 15 illustrates the tube's operation when zero bias is applied to the grid. This same curve is labeled (1) on the graph in Fig. 16. On this curve, it is indicated that Ec = 0. This notation signifies that when plotting this characteristic curve, the grid bias was zero.

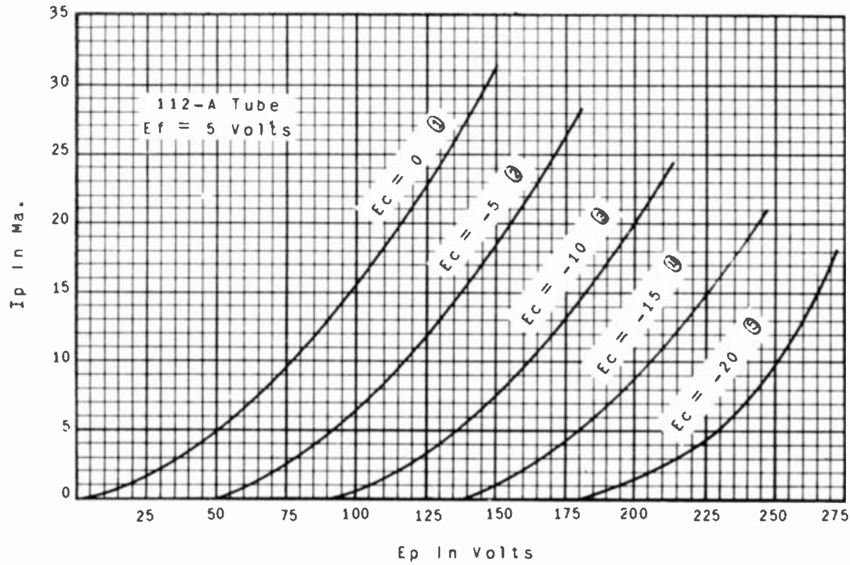


Fig.16 Family of Ep-Ip curves for a type 112-A tube.

More information about the operation of a vacuum tube may be obtained when a "family" of characteristic curves are available instead of just a single characteristic curve. A "family" of plate-voltage, plate-current characteristic curves means several curves plotted on the same graph (using the same tube) when the grid voltage is changed to different values. To obtain the data for plotting a family of plate-voltage, plate-current characteristic curves, it is necessary to provide a method by which the grid bias voltage can be set to different values. This is conveniently done by use of the circuit arrangement shown in Fig. 17. This circuit is the same as Fig. 14, except the value of the plate voltage battery has been increased to 300 volts and a provision is made whereby the bias applied to the grid of the tube may be varied from 0 to -30 volts. The voltmeter V_1 indicates the plate voltage applied to the tube and the voltmeter V_2 measures the negative voltage applied to the grid of the tube. The grid voltage may be varied from 0 to -30 volts by changing the position of the movable arm E on the potentiometer P_2 from D to F. When the movable arm is at point D, the grid of the tube will be connected directly to the negative side of the filament and the voltmeter V_2 will be reading zero grid bias. Then as the movable arm is moved toward F, the voltmeter V_2 will indicate the increasing negative voltage applied to the grid. Upon reaching point F, the grid of the tube will be 30 volts negative with respect to the negative side of the filament.

To obtain the data necessary for plotting a family of plate-voltage, plate-current characteristic curves, we shall start by setting the grid voltage at a value of -5 volts (the filament voltage must be 5 volts). By changing the position of movable arm B on the plate voltage potentiometer P_1, the plate voltage can be increased in 25-volt steps. At each 25-volt interval, the plate current is recorded. The plate voltage is increased to a maximum value of 200 volts.

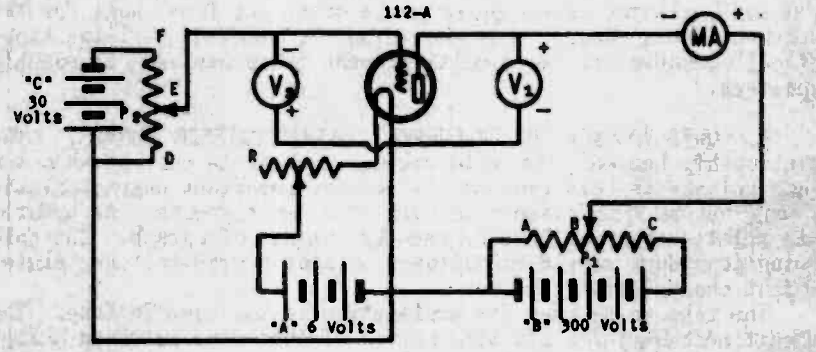


Fig.17 Circuit for obtaining data to plot family of Ep-Ip curves on type 112-A tube.

After securing the data and plotting the plate-voltage, plate-current characteristic, you will notice that the characteristic curve for -5 volts of grid bias (number 2) follows very closely with the curve obtained when the bias voltage was zero, except that in all cases for a given plate voltage, the plate current is lower. This is to be expected because we know that when the grid is made negative with respect to the negative side of the filament, the plate current will be less for a given value of plate voltage.

To obtain the next characteristic curve (number 3), change the movable arm on the grid bias potentiometer until the grid is 10 volts negative with respect to the negative side of the filament. Starting with the movable arm of potentiometer P_1 at the left side (point A), increase the plate voltage in 25-volt steps, noting the plate current at each setting. After tabulating the data, the points are placed on the same graph and the characteristic curve is drawn.

After plotting curve 3, next set the grid voltage to -15 volts. (Move the arm E on potentiometer P_2 until V_2 is reading 15 volts.) Then, increase the plate voltage from 135 to 275 volts. When the plate voltage is less than 135 volts, no plate current is flowing, because of the high negative bias applied to the grid.

Curves 5 and 6 are plotted in a similar manner. After all of the data has been obtained and the curves plotted on the graph, we now have a "family" of plate-voltage, plate-current characteristic curves on a type 112-A tube. By referring to the tube manual, you will find that the family of plate-voltage, plate-current curves for this particular tube may be extended much further when a plate voltage supply of 520 volts and a grid bias supply voltage of 55 volts are obtainable.

Later in this lesson, we shall find several uses for a family of plate-voltage, plate-current characteristic curves and in following lessons where we will be dealing with vacuum tube amplifier, detector and oscillator circuits, these curves will be found to be very beneficial. At this time, the student should inspect the tube manual and become familiar with the appearance of the characteristic curves for 3-element tubes. The characteristic curves for 4, 5, 6 and 7-element tubes appear quite different from those for the 3-element tubes; hence, they should not be studied until the theoretical operation of these multi-element tubes has been thoroughly explained.

5. GRID-VOLTAGE, PLATE-CURRENT CHARACTERISTIC CURVES. The relationship between the grid voltage and plate current when the plate voltage is held constant is a very important characteristic of any vacuum tube possessing more than two elements. As before, this relationship can best be seen by the use of a graph. The following procedure should be followed to plot a grid-voltage, plate-current characteristic curve.

The tube to be used for explanation is the type 76 tube. The circuit necessary for plotting a graph of this kind is shown in Fig. 18. Referring to the tube manual, you will find that the type 76 tube requires a heater voltage of 6.3 volts. This may be supplied by a storage battery or from the secondary of a step-down transformer. This tube is of the indirectly-heated cathode type; hence, the reference point for measuring plate voltage and grid voltage is the cathode. The storage battery or the 6.3-volt secondary winding of a transformer should be connected across the points marked x-x (the heater winding). The cathode of the tube is connected to the negative terminal of the 100-volt plate battery and is also connected to the positive terminal of the 9-volt grid battery. The plate voltage will be held constant throughout this experiment. A milliammeter in series between B plus and the plate of the tube measures the plate current. Voltmeter V_1 connected between the plate and the cathode will measure the plate voltage to make certain that it remains constant. A potentiometer P_1 is connected across the terminals of the 9-volt C battery and the movable arm on the potentiometer is connected through MA_2 to the grid of the tube. Voltmeter V_2 is connected between the grid and the cathode of the tube in order to measure the grid voltage. This voltmeter must be connected with the polarity shown on the diagram when the negative side of the C battery is connected to the grid. When the movable arm on P_1 is to the left side of the potentiometer, there will be 9 volts negative bias on the grid, and the voltmeter V_2 will be reading 9 volts. Under this condition, there will be no plate current flowing. These two values are the first which should be recorded; that is, grid voltage, -9; plate current, 0. There will be no grid current flowing when the grid is negative with respect to the cathode. By moving the potentiometer arm to the right until the voltmeter V_2 reads 8 volts, the plate current meter MA_1 will show an indication of .5 ma. Making the grid voltage less negative (in two volt steps) allows the plate current to rise as shown in the tabular chart to the left of Fig. 18. When the grid voltage is zero, the potentiometer arm will be completely to the right of P_1. At this point, you will find 12.5 ma. of plate current flowing as indicated on MA_1 and also a very, very slight indication of grid current on MA_2. The measured grid current is found to be approximately .2 ma.

Eg	Ip	Ig
-9	0	
-8	.5	
-6	2.	
-4	4.5	
-2	8.	
0	12.5	.2
+2	17.5	.3
+4	23.+	.45
+6	27.5	.8
+8	30.	1.25
+9	31	

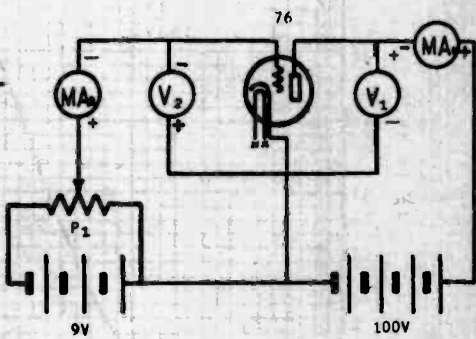


Fig.18 Circuit for obtaining data to plot grid-voltage, plate current (Eg-Ip) and grid-voltage, grid-current (Eg-Ig) curves on type 76 tubes

It is now necessary to reverse the connections to the 9 volt C battery. Connect the negative terminal of the C battery to the cathode and connect the positive terminal of the C battery to the left side of the potentiometer P_1. Also reverse the connections to the voltmeter V_2. It will now be possible to increase the grid voltage into the positive region by changing the position of the movable arm on the potentiometer P_1. Starting with the grid at 2 volts positive, we find the plate current to be 17.5 ma., as indicated on MA_1 and the grid current to be approximately .3 ma., as indicated on MA_2. By further increasing the grid voltage in 2-volt steps, the collection of data as shown in the tabular chart on the left side of Fig. 18 is obtained. It is not safe to increase the grid voltage above 9 volts positive, because the plate current is reaching dangerously high values. An excessive grid current is also beginning to flow, which is very apt to damage the small grid winding within the tube. To obtain readings when the plate current of this tube is over 25 ma., the plate circuit should be closed only momentarily so as not to damage the tube.

With the collection of data secured experimentally, it is next necessary to plot these values on a graph in order to obtain a picture of the relationship between the grid voltage and the plate current. On the same graph, it is possible to plot the grid-voltage, grid-current curve.

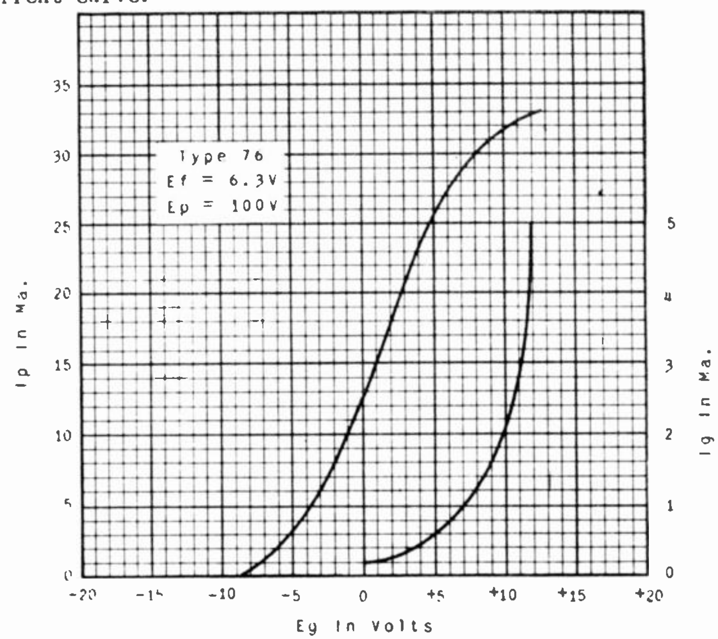


Fig.19 Eg-Ip and Eg-Ig curves for type 76 tube.

The graph should be constructed as shown in Fig. 19. Zero grid voltage is placed at the center of the graph. The positive values of grid voltage are to the right and the negative values of grid voltage to the left. The plate current is plotted on the left side of the graph in 5 ma. steps and the grid current is shown on the right side of the graph with each small division representing .2 ma. of grid current. To plot the graph, start with the most negative value of grid voltage. This was -9 volts and, at that time, the plate current was zero. Next, plot the plate current values for -8 volts, -6 volts, etc., up to the maximum of +9 volts. Drawing a smooth line connecting these points, we obtain a curve such as shown in Fig. 19. After drawing the grid-voltage, plate-current characteristic curve, plot the grid-voltage, grid-current characteristic curve on the same graph.

There are several facts pertaining to the operation of this tube which may be determined from the grid-voltage, plate-current characteristic curve. First, notice that the characteristic curve is fairly straight between -4 volts and +5 volts. Between the grid voltages of -4 and -9 volts, the characteristic is distinctly curved. Likewise, on the upper positive end, from 5 volts to 12 volts, there is a curvature in the characteristic. The upper bend in the characteristic curve is of little consequence in vacuum tube operation because we never apply a high positive grid voltage to a tube of this type. We are mainly interested in the straight portion of the characteristic curve above -4 volts and in the curvature of the characteristic between -4 volts and -9 volts. These are commonly referred to as "the straight portion of the grid-voltage, plate-current characteristic" and "the curved portion of the grid-voltage, plate-current characteristic", respectively.

It is possible to plot a family of grid-voltage, plate-current characteristic curves for different values of plate voltage in a manner similar to the method used for plotting the family of plate-voltage, plate-current characteristic curves with different values of grid voltage in Fig. 1b. Manufacturers' tube manuals generally give the family of plate-voltage, plate-current characteristic curves for different values of grid voltage on a tube, but seldom show the grid-voltage, plate-current family. Whereas a family of grid-voltage, plate-current characteristic curves would be useful in certain cases, they are not sufficiently important to warrant their addition to a tube manual.

6. STATIC AND DYNAMIC TUBE CHARACTERISTICS. *Static characteristics are those relationships which exist between the tube's voltages and currents when only a DC grid-bias voltage is applied to the grid circuit.* The relations which exist between the tube's voltages and currents when the tube is operating in a circuit are determined not only by the characteristics of the tube itself, but also by the apparatus used with the tube. In actual vacuum tube operation, there will generally be an alternating voltage applied to the grid of the tube in addition to the DC bias voltage.

The relationships between the tube's voltages and currents under actual operating conditions are called the dynamic characteristics. Dynamic characteristics, therefore, indicate the performance of a tube under actual working conditions, whereas the static characteristics show only the voltage and current relations when the circuit operation is disregarded. The graphs plotted in this lesson are all static characteristics, because in each case, we assumed that a DC voltage was applied to each electrode of the tube. This does not include the heater or filament voltage. When determining the static or dynamic characteristics of a tube, the heater supply may be either AC or DC, because the only purpose of the filament or heater is to supply the source of electrons.

7. AMPLIFICATION FACTOR. The amplification factor is one of the most important constants of a vacuum tube, because the usefulness of the tube as an amplifier depends to a great deal (not entirely) upon it. Before explaining how the amplification factor of a tube is determined, let us see just exactly what is meant by the expression "a vacuum tube amplifies a voltage".

The illustration shown in Fig. 20 will serve to explain this. Referring to A, suppose that 1 millivolt (representing an audio-frequency voltage) is applied across the two terminals, A and B, of the loudspeaker. With 1 millivolt applied across the windings of the loudspeaker, a very slight current will flow and the vibration of the loudspeaker's diaphragm will be over such an exceedingly **short** distance that the sound waves emanating from the loudspeaker are hardly audible. This is an example showing that the input voltage is not of sufficient amplitude to properly vibrate the diaphragm of the loudspeaker and produce sound waves that can be heard. To remedy this condition, it is necessary to place a "vacuum tube amplifier" between the 1-millivolt input and the terminals of the loudspeaker. This arrangement is shown at B in Fig.

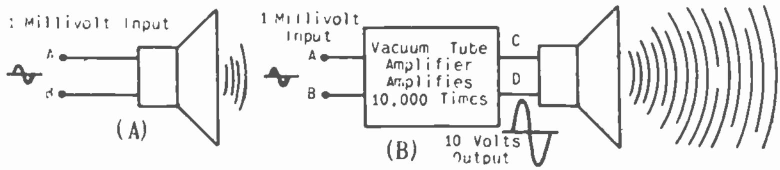


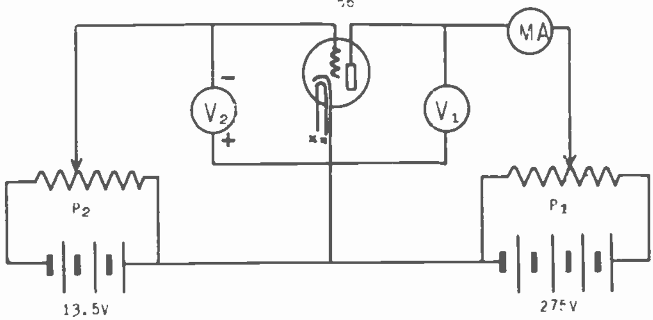
Fig. 20 (A) One millivolt applied to the speaker directly will not produce much diaphragm vibration. (B) One millivolt is amplified 10,000 times by vacuum tube amplifier then applied to speaker. Greater diaphragm vibration is produced because the amplified voltage has a higher amplitude.

20. The 1 millivolt is applied to the input of the amplifier, which is capable of amplifying the voltage 10,000 times. The result is an output voltage of 10 volts and when this higher voltage is applied across the loudspeaker, it will force a sufficient current through the windings to cause the diaphragm to vibrate over a greater distance and thus set up sound waves which are easily audible. The 10-volt output has exactly the same waveform as the 1-millivolt input. The only difference is that it is higher in amplitude; that is, **it has been amplified.**

In this illustration, the vacuum tube amplifier is capable of amplifying the input voltage 10,000 times. Of course, this vacuum tube amplifier circuit consists of several tubes connected in such a manner that the output of each tube is fed to the input of the following tube, etc.; that is, one tube is not sufficient to produce all of the amplification that has been obtained. Considering a one-tube circuit, *if the output voltage secured from the vacuum-tube circuit is higher in amplitude than the input voltage applied to the vacuum-tube circuit, it is said that the vacuum tube has amplified the voltage.* As previously stated, the amount of amplification obtained depends largely upon the amplification factor of the tube.

To determine the amplification factor of a tube from experimental data, the procedure would be as follows. An amplifier circuit using a type 56 tube is set up as shown in Fig. 21. A plate-voltage supply of 275 volts and a grid-bias supply of 13.5 volts is being used. A potentiometer must be connected across each of these batteries to provide a means of varying the plate voltage and grid voltage. A milliammeter MA is connected in series with the plate circuit and a voltmeter V_1 must be connected from plate to cathode so as to accurately measure the plate voltage. The voltmeter V_2 is connected from grid to cathode to measure the grid-bias voltage.

First, set the plate voltage to exactly 250 volts and the grid-bias voltage to exactly 13.5 volts. Under these conditions, we will find there will be exactly 5 ma. of plate current flowing. (Refer to tube manual.)



TRIAL FOR Eg CHANGE

Ep	Eg	Ip
250	13.5	5.
250	12.	7.5
A 1.5 Eg Change Produces a 2.5 Ma. Ip Change		

TRIAL FOR Ep CHANGE

Ep	Eg	Ip
250	13.5	5.
270.7	13.5	7.5
A 20.7 Ep Change Produces a 2.5 Ma. Ip Change		

$$Mu = \frac{20.7}{1.5} = 13.8$$

Fig. 21 Circuit for experimentally determining the mu of a type 56 tube.

One of the two things determining the amplification factor of a tube is the effect of a variation in plate voltage on the plate current. The other is the effect of a change in grid voltage on the plate current.

With the experimental apparatus assembled, first make a test to determine the effect of a grid voltage change on the plate current. We know that if the grid-bias voltage is made less negative, the plate current will increase. Let us move the potentiometer arm P_2 until the grid bias voltage is exactly 12 volts. We will find that the plate current increases from 5 ma. to 7.5 ma. This test has shown that a decrease in negative grid voltage of 1.5 volts causes an increase in plate current of 2.5 ma. Replace the grid voltage to 13.5 volts after making the test.

Next test the effect of a plate-voltage change on plate current. This is done by increasing the plate voltage with potentiometer P_1 until we have exactly 7.5 ma. of plate current flowing. Upon accurately reading voltmeter V_1, we will find it to be 270.7 volts. This test has shown that a plate voltage change of 20.7 volts is required to produce a plate current increase of 2.5 ma.

From the data obtained, it is now possible to calculate the amplification factor of the type 56 tube. The amplification factor is simply the ratio between the ability of the plate to the ability of the grid to control the plate current. This is expressed in the following formula:

$$\text{Amplification Factor} = \frac{E_p \text{ change required to produce a given } I_p \text{ change}}{E_g \text{ change required to produce the same } I_p \text{ change}}$$

Expressed in shorter form, this is:

$$\text{Amplification Factor} = \frac{E_p \text{ change}}{E_g \text{ change}}$$

Since we found that a 20.7-volt change in plate voltage was necessary to produce the same plate-current change as 1.5-volt change in grid voltage, we shall substitute these values in the formula and will obtain:

$$\text{Amplification Factor} = \frac{20.7}{1.5}$$

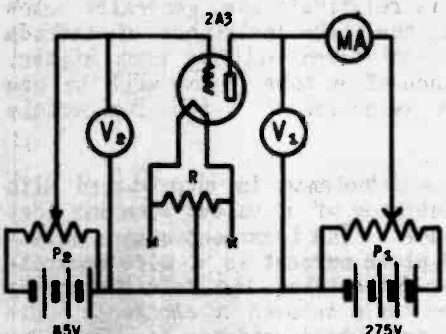
$$= 13.8$$

By referring to the tube manual, we will find that the amplification factor specified by the manufacturer for a type 56 tube is 13.8! *This factor is merely a number which expresses the ability of a tube to amplify a voltage.* It is not to be assumed that whenever a type 56 tube is used in an amplifying circuit the input voltage will always be amplified exactly 13.8 times. **The actual amount of amplification** received from a tube depends not only upon its amplification factor, but also upon the conditions under which the tube is operated in the circuit. Even under the most favorable conditions, it is impossible to ever secure an actual amplification from a tube equal to its amplification factor. This means that the amplification which will ordinarily be obtained from a type 56 tube when it is used in a properly designed circuit will be somewhat less than 13.8 times.

The amplification factor is often called the "mu". The Greek letter "μ" is nearly always used in formulas to represent the amplification factor. The amplification factor is also called the "amplification constant". All three of the phrases, mu, amplification factor, and amplification constant, refer to the same characteristic of a vacuum tube.

8. PLATE RESISTANCE. The plate resistance of a vacuum tube is abbreviated in formulas by "R_p". *The plate resistance of a vacuum tube is the opposition of the path between the cathode or filament and the plate to the flow of a changing current.* The plate resistance may be secured from the manufacturer or may be determined with experimental apparatus, the same as the amplification factor.

To illustrate the procedure for determining the plate resistance of a vacuum tube with experimental apparatus, we shall use the circuit shown in Fig. 22. A type 2A3 tube is being used for this purpose. A plate-supply voltage of 275 volts and a bias-supply voltage of 45 volts will be required. In this circuit, you will notice that the filament leads are marked x-x, which indicates that they are to be connected across a 2.5-volt transformer secondary winding. In tubes of this type, when AC is being used as the filament supply, to secure the electrical center of the filament circuit, it is necessary to place a center-tapped resistor across the filament leads. This center-tapped resistor is marked R in Fig. 22. The exact center of this resistance will never change in



TRIALS FOR Rp

Ep	Eg	Ip
250	-45	60
275	-45	91.25

A 25-Volt Ep Change Produces a 31.25 Ma. Ip Change

$$R_p = \frac{25}{.03125} = 800\ \omega$$

Fig.22 Circuit for experimentally determining the Rp of a type 2A3 tube.

potential regardless of the changes in AC voltage across it; hence, it is used as the reference point when measuring the plate and grid voltages. The negative side of the plate battery and the positive side of the grid battery are both connected to the center tap of the filament resistance.

To determine the plate resistance of this tube, it is necessary to find the effect of a plate voltage change on the plate current. Set the potentiometer P_1 until the plate voltmeter V_1 is reading exactly 250 volts, then set the potentiometer P_2 until the grid voltmeter V_2 is reading exactly 45 volts. Under these conditions, a plate current of 60 ma. will be flowing. (Refer to the manufacturer's specifications on the type 2A3 tube to verify these operating conditions.) Now increase the plate voltage to exactly 275 volts. We find that the plate current meter increases to 91.25 ma. In the collection of data of this kind, it is necessary that the meters be read accurately to obtain the proper results.

To calculate the plate resistance of the tube, it is only necessary to calculate the ratio between the change in plate voltage and the change in plate current which it produced. We increased the plate voltage 25 volts and found that the plate current increased 31.25 ma. The ratio between the plate voltage change and the plate current change which it produces may be expressed as follows:

$$R_p = \frac{25}{.03125}$$

$$= 800 \text{ ohms.}$$

By referring to the manufacturer's specifications for a type 2A3 tube, you will find the plate resistance to be 800 ohms. The plate resistance of all other tubes could be found in a similar manner with experimental apparatus. The plate resistance of nearly all triode (3 element) vacuum tubes is relatively low, generally below 15,000 ohms. As a general rule, the plate resistance of tetrode (4 element) and pentode (5 element) tubes will be much higher. Whether or not the plate resistance of a tube is low will be one of the factors entering into the selection of a tube for certain types of circuits.

9. **TRANSCONDUCTANCE.** Transconductance is abbreviated with the letters "S_m". The transconductance of a vacuum tube was formerly called the "mutual conductance". The transconductance existing between the grid voltage and plate current is a more accurate measure than any other factor for determining the relative merits of a tube. It is defined as *the ratio between a change in plate current and the change in grid voltage which produces it*. The number obtained by this ratio is taken as a "figure of merit" whereby one tube may be compared with other tubes of the same type as to its deserving usefulness in a certain type of circuit. This means that if several tubes are available, each of which can be used in a particular circuit, the decision or selection is most easily made by comparing their transconductance values. The tube possessing the highest transconductance is nearly always the most satisfactory. Since transconductance is secured by dividing a current by a voltage, the ratio represents conductance, not resistance. Conductance is measured in mhos; however, since the transconductance of all tubes is fairly low (much less than 1 mho), the common unit of measurement is the micromho.

The transconductance of a vacuum tube may be determined experimentally the same as the amplification factor and plate resistance. To determine the transconductance of a tube, we shall use the type 45 tube in a circuit such as shown in Fig. 23. The potentiometer P_1 must be connected across the 50-volt grid battery. The voltmeter V_1 connected between the grid and the center tap of the filament winding will indicate the grid voltage. First, let us start with the following values: plate voltage, 250 volts; grid voltage, -50; plate current, 28 ma. The student should refer to the characteristic curve for the type 45 tube in the tube manual to verify these values. With the plate voltage remaining constant at 250 volts, change the grid voltage from -50 to -40 volts. Upon making this voltage change, the plate current is found to rise to 49.75 ma.

With the data obtained, it is now possible to calculate the transconductance of the type 45 tube. The transconductance is expressed in a formula as follows:

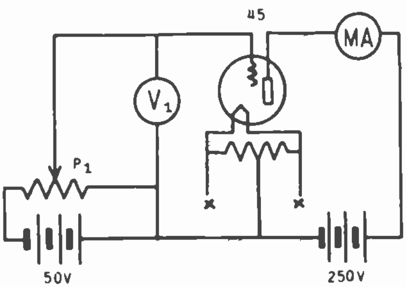
$$\text{Transconductance} = \frac{\text{Change produced in plate current}}{\text{Grid voltage change producing } I_p \text{ change}}$$

Substituting the values found in this formula, we have:

$$S_m = \frac{.02175}{10}$$

$$= .002175 \text{ mho, or } 2175 \text{ micromhos}$$

By referring to the table of characteristics for the type 45 tube, you will find that the transconductance specified by the manufacturer with 250 volts plate voltage and 50 volts grid bias is 2175 micromhos.



Ep	Eg	Ip
250	-50	.028
250	-40	.04975
A 10-Volt Change in Eg Produces a 21.75 Ma. Ip Change		
$S_m = \frac{.02175}{10} = .002175$ mhos or 2,175 micromhos		

Fig.23 Circuit for experimentally determining the Sm of a type 45 tube.

In the table of manufacturer's characteristics, you will find that two additional columns of characteristics headed with different values of plate voltage are also given. For example, on the type 45 tube, the first column gives the characteristics for a plate voltage of 180 volts. The second column is a list of the characteristics for a plate voltage of 250 volts and the third column gives a list of characteristics for 275 volts. These characteristics vary with different plate voltages because of the different conditions under which the tube is being operated. When selecting voltages for the operation of any vacuum tube, one should always attempt to apply one of the plate voltages recommended by the manufacturer so that he may be absolutely certain of the tube's characteristics which result from that plate voltage.

10. **RELATION BETWEEN THE TUBE CONSTANTS.** The three tube constants just discussed were all found to depend upon the relationship between the grid voltage, plate voltage and plate current. Since

the grid circuit of a tube is entirely separated from the plate circuit except for the controlling effect of the grid on the plate current, it is quite evident that there should be some relationship between the amplification factor, the plate resistance and the transconductance. There is a very definite relationship between the ability of the grid to control the plate current (transconductance), the ability of the tube to amplify a voltage applied to its grid circuit (amplification factor) and the opposition offered between the plate and cathode or heater to the passage of a changing current (plate resistance). This relationship may be expressed as:

$$S_m = \frac{Mu}{R_p} \qquad (1)$$

To prove this relationship, let us consider each of the three constants separately, then substitute them in the above equation.

We have found:

$$Mu = \frac{E_p \text{ change}}{E_g \text{ change}} \qquad (2)$$

$$R_p = \frac{E_p \text{ change}}{I_p \text{ change}} \qquad (3)$$

$$S_m = \frac{I_p \text{ change}}{E_g \text{ change}} \qquad (4)$$

According to formula (1), the transconductance should equal the amplification factor divided by the plate resistance. We may substitute in formula (1) as follows:

$$S_m = \frac{Mu \text{ or } \dfrac{E_p \text{ change}}{E_g \text{ change}}}{R_p \text{ or } \dfrac{E_p \text{ change}}{I_p \text{ change}}}$$

Here we have two fractions, one of which is to be divided by the other. According to the fundamental rule for the division of fractions, invert the divisor, then multiply. Performing this operation, we have:

$$S_m = \frac{E_p \text{ change}}{E_g \text{ change}} \times \frac{I_p \text{ change}}{E_p \text{ change}}$$

Cancelling the E_p change in the numerator and denominator, we have:

$$S_m = \frac{I_p \text{ change}}{E_g \text{ change}} \qquad (5)$$

From the fundamental definition of transconductance, formula (5) is true; hence, the relationship as expressed in formula (1) is correct. Having proved formula (1), it may now be transposed to the three different forms:

$$S_m = \frac{Mu}{R_p}, \qquad R_p = \frac{Mu}{S_m}, \qquad Mu = R_p \times S_m$$

Where: R_p is the plate resistance in ohms.
S_m is the transconductance in mhos.
Mu is the amplification factor expressed as a number.

11. DC PLATE RESISTANCE. The DC plate resistance of a vacuum tube is defined as *the opposition offered to the passage of a direct current from the cathode or filament to the plate.*

The DC plate resistance of a tube should not be confused with the aforementioned plate resistance of the tube. These are two entirely separate and distinct constants. The plate resistance was previously defined as the opposition offered to the passage of a changing current from the cathode to the plate, whereas the DC plate resistance is the opposition offered to the passage of a DC current from the cathode to the plate. The method for calculating the plate resistance of a vacuum tube was covered in detail in a preceding paragraph. The plate resistance of a vacuum tube is sometimes called the "plate impedance". The word, "impedance", is used in this case because it means an opposition to a changing current, not to a DC current. When the expression "plate impedance" is used, it is not so easily confused with the DC plate resistance.

To find the DC plate resistance of a tube, it is only necessary to divide the DC plate voltage by the DC plate current. This is expressed as follows:

$$DC\ R_p = \frac{E_p}{I_p} \qquad (6)$$

Referring to the family of characteristic curves for the type 112-A tube as shown in Fig. 16, let us select any point on any one of the five curves shown and calculate the DC plate resistance at that point. For example, on curve 1, suppose we choose the point coinciding with a plate voltage of 75 volts and plate current of 9.5 ma. The DC plate resistance at this point is:

$$DC\ R_p = \frac{75 \text{ volts}}{.0095 \text{ ampere}} = 7,894+ \text{ ohms}$$

On curve 3, at 200 volts plate voltage, we find the plate current to be 20 ma. The DC plate resistance at this point will be:

$$DC\ R_p = \frac{200 \text{ volts}}{.02 \text{ ampere}} = 10,000 \text{ ohms}$$

In a similar manner, the DC plate resistance of this tube under different operating conditions could be calculated at any point desired on any one of the five curves.

Notice that the DC plate resistance of a tube varies with any change in plate voltage or any change in grid voltage. This fact allows a vacuum tube to be used as a variable resistance or potentiometer; that is, if desired, a vacuum tube may be employed in a circuit to function as a variable resistance because each time the grid voltage is varied, the DC resistance of the tube will change. The range of resistance variation secured from a certain tube is limited by the physical construction of the tube; that is, an excessively high plate voltage cannot be applied, nor can an exceedingly high plate current be allowed to flow without causing considerable damage to the tube itself. In later lessons, we shall find applications for using a vacuum tube as a variable resistance. The performance of a vacuum tube in this capacity will depend upon the variation of the DC plate resistance whenever the plate voltage or grid voltage is changed.

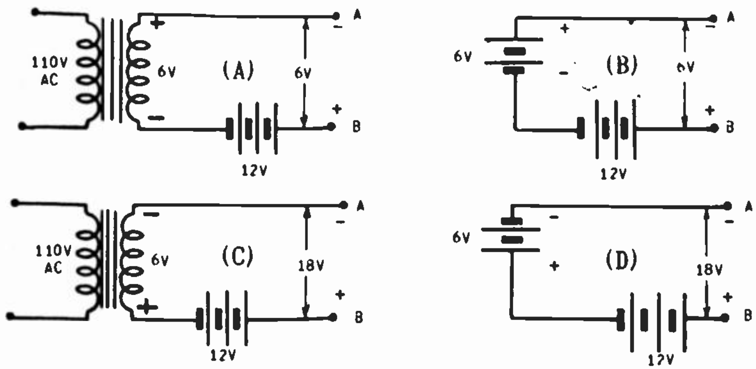


Fig.24 Simple circuits illustrating how two voltages buck against each other (A and B) when - is connected to - and how they add together (C and D) when - is connected to +.

12. ADDING AND BUCKING VOLTAGES. In preparation for the explanation of how a vacuum tube amplifies a voltage, it is necessary to become familiar with a certain phenomenon which affects the operation of the grid circuit.

At A in Fig. 24, we have shown a stepdown transformer which reduces the 110-volt AC applied to the primary to 6 volts AC across the secondary side. In series with one lead on the secondary side, a 12-volt battery is inserted with the polarity as shown. We have learned that the AC current passing through the primary of the step down transformer will induce a 6-volt AC voltage across the secondary terminals. First, let us consider the instant when the top of the secondary winding is positive and the bottom of the secondary winding is negative. This instant is shown at A in Fig. 24. The secondary voltage will be bucking against the 12 volts produced by the series battery, resulting in only 6 volts being available across the two terminals A and B. (Remember this is only an instantaneous condition.) The circuit shown at B represents this condition in a more definite manner. This drawing shows a 6-volt battery inserted with the proper polarity instead of the 6-volt AC voltage induced in the secondary. It may be seen that the negative terminal of the 12-volt battery is connected to the negative terminal of the 6-volt battery; hence, these two voltages will not add to each other, but rather will buck against each other, resulting in only 6 volts being available across the terminals A and B. This 6 volts is the difference between the 12-volt battery and the 6-volt battery (or secondary).

When there is no current passing through the primary winding, there will be no voltage induced across the secondary of the stepdown transformer and there will be a voltage of 12 volts available across AB, with A negative and B positive.

Next, let us consider the instant when the current passing through the primary is in the opposite direction. The voltage produced across the secondary side will be of opposite polarity as shown at C in Fig. 24. To make this a little more clear the equivalent circuit is shown at D. Notice that the negative terminal of the 12-volt battery is now connected to the positive terminal of the 6-volt battery, thus placing them in series. We have previously learned that when batteries are connected with the positive terminal of one to the negative terminal of the next, their individual voltages will add, resulting in the total voltage being equal to the sum of the individual voltages. When adding the 12-volt battery to the 6 volts, a total of 18 volts is secured across the two terminals A and B with A negative and B positive.

These illustrations serve to explain the manner in which the grid circuit of a vacuum tube operates when the voltages applied to the grid circuit are of an AC nature. In this explanation we have disregarded the intermediate voltage values which will appear across the terminals A and B during all parts of the AC sine wave. We have considered only the voltage at the maximum amplitude of the positive alternation and the maximum amplitude of the negative alternation.

Since the 12-volt battery is causing a potential of 12 volts to exist across the terminals A and B when there is no voltage induced in the secondary, we should consider this 12 volts as being equivalent to the zero line drawn through the center of an AC sine wave. This may be understood by referring to Fig. 25. At A in Fig. 25, one cycle of an AC voltage is shown varying above and below the zero line, attaining a maximum of 6 volts on each of its alternations. This would be the voltage across the two terminals A and B in Fig. 24 if the 12-volt battery were not present. Due to the fact that the battery is connected in series with one of the secondary leads, the voltage appearing across the two terminals A and B will actually be as shown at B in Fig. 25. The 12-volt battery merely causes a displacement of the reference line for the AC voltage, moving it down to a value of -12 volts. Now, the secondary voltage will first add to, then subtract from this steady 12-volt potential of the battery, thus causing the voltage across A and B to vary from -6 volts to -18 volts.

This explanation should be studied thoroughly in order to secure a clear conception of the action taking place in the grid circuit of a vacuum tube.

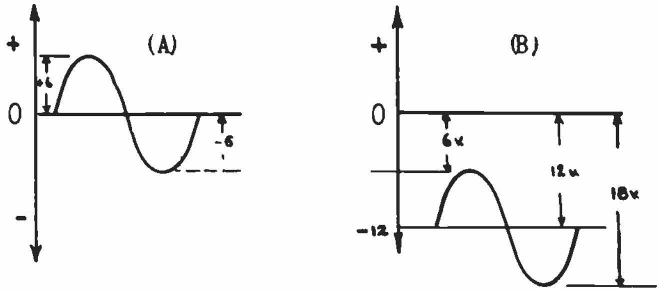


Fig.25 (A) Six volts AC varying above and below 0.
(B) Six volts AC varying above and below -12.

19. HOW A VACUUM TUBE AMPLIFIES A VOLTAGE. To explain the function of a vacuum tube as a voltage amplifier, we shall use the circuit arrangement shown in Fig. 26. A type 76 tube is being used with 140 volts plate supply and a bias voltage of 2 volts. The positive terminal of the 140-volt battery is connected through the resistance R (and the milliammeter) to the plate of the tube, and the negative terminal of the 140-volt battery is connected directly to the cathode. The plate voltage (difference in potential between the plate and cathode) will be 140 volts minus the voltage drop across resistance R. The negative terminal of the grid bias battery is connected through the iron core coil S to the grid of the tube, and the positive terminal of this battery is connected directly to the cathode. The grid bias voltage will be exactly 2 volts because there is no grid current passing through the coil; hence, there will be no voltage drop across it. By referring to the grid-voltage, plate-current characteristic curve for a type 76 tube as shown in Fig. 19, it will be found that under the conditions of 100 volts plate voltage and 2 volts negative grid bias, there will be a plate current of 8 ma. flowing. Since it will be necessary to use this grid-voltage, plate-current characteristic to explain the process of voltage amplification, it is reproduced again in Fig. 28 for convenience. In Fig. 28, notice that at -2 volts grid bias on the curve, the letter X is placed. This point on the characteristic is commonly called "the operating point". When 100 volts is applied to the plate of a type 76 tube and 2 volts negative bias applied to the grid, there will be a plate current flowing of 8 ma. This coincides exactly to the operating point on the curve. Notice particularly that the operating point is on the straight portion of the grid-voltage, plate-current characteristic. *When working a vacuum tube as a voltage amplifier, it is very essential that it be operated on this portion of the static grid-voltage, plate-current characteristic curve.* If the bias were increased to -6 or -8 volts, we would then be operating on the curved portion of the characteristic

and the result would be an output voltage which does not coincide (in wave form) with the input voltage. This is called "distortion".

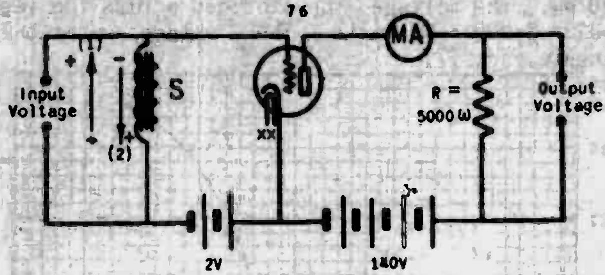


Fig.26 Circuit to explain "how a vacuum tube amplifies a voltage".

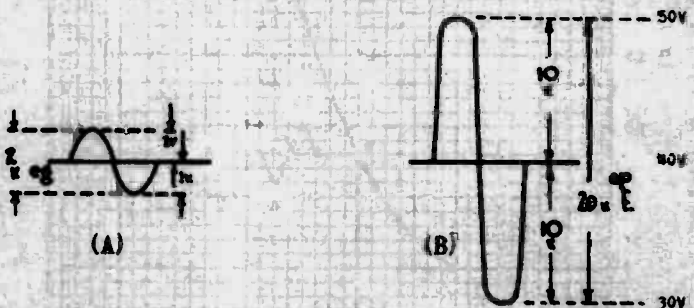


Fig.27 (A) 2-volt variation of voltage applied to grid circuit.
(B) 20-volt variation of voltage produced in plate circuit.

	Eg	Ip	E Across R
No Voltage Across S	-2	8	40V
Positive Alternation	-1	10	50V
Negative Alternation	-3	6	30V

Voltage Change Across Grid Circuit = 2V
" " " Plate " = 20V

Voltage Amplification = $\frac{20}{2}$ = 10 Times

Since we know there is 8 ma. of plate current flowing, we can calculate the voltage drop across the 5,000 ohm resistance R in the plate circuit; 8 ma. × 5,000 ohms produces a voltage drop of 40 volts. In the chart below Fig. 27, the static conditions (conditions of the circuit before a signal is applied to the grid circuit) are tabulated. The grid voltage is -2, the plate current is 8 ma. and the voltage drop across the resistance R is 40 volts.

On the positive alternation of the voltage to be amplified, let us assume that the voltage produced across the coil S is in the direction as shown by the arrow marked 1 (Fig. 26). This will make the top end of the coil positive and the bottom end negative. When the voltage across the coil is in this direction, it will buck against the 2-volt battery, thus causing the instantaneous voltage difference between the grid and the cathode to decrease to a value of -1 volt. From the characteristic curve on this tube shown in

Fig. 28, it may be seen that when the grid is made 1 volt negative, the plate current will rise to 10 ma. When the plate current increases to 10 ma., the voltage drop produced across the resistance R will be .01 × 5,000 = 50 volts. These values are tabulated in the chart beneath Fig. 27.

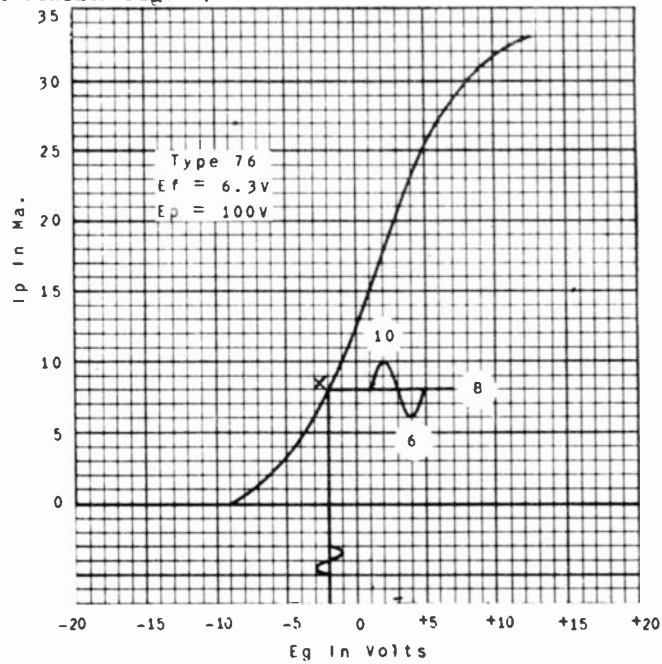


Fig.28 Graphical analysis of relation between grid voltage and plate current when the operating point is on the straight portion of the curve below zero grid bias.

Next, let us consider the function of the circuit on the negative alternation of the voltage to be amplified. When the voltage produced across the coil S is in the direction of the arrow marked 2, the bottom of the coil will be positive and the top will be negative. This voltage is in such a direction as to add to the 2 volts of the C battery, thus making the instantaneous voltage difference between the grid and the cathode equal to -3 volts. From the characteristic curve of the tube shown in Fig. 28, it may be seen that when the grid is made -3 volts negative, the plate current will decrease to 6 ma. As the plate current falls to 6 ma., the voltage drop produced across the resistance R in the plate circuit will decrease to .006 × 5,000 or 30 volts. These values are also tabulated in the chart beneath Fig. 27.

To review briefly the action of the tube so far, we have found that when the grid is made less negative, the plate current increases, thus causing an increased voltage drop across the resistance R in the plate circuit. When the grid is made more negative, the plate current decreases, thus causing a decreased voltage drop across the the resistance R in the plate circuit.

In Fig. 27 at A, we have shown the voltage variation which was applied to the grid circuit of the tube. Starting from 2 volts negative, the grid was first made 1 volt negative, then returned back to 2 volts, only to change again in the opposite direction and become -3 volts, then reduced back to -2 again. We had a 1-volt change on each alternation of the signal voltage, thus making an over-all voltage change across the grid circuit of 2 volts. This is the voltage applied to the grid circuit of the tube which we desired to amplify. Now let us analyze the changes which have occurred in the plate circuit and thereby determine whether or not amplification has been obtained. With the normal plate current of 8 ma. passing through the resistance R, the voltage drop was 40 volts. When the grid was made less negative, the plate current increased and the voltage across the resistance went up to 50 volts. When the grid was made more negative, the current through the plate circuit decreased, causing the voltage drop across resistance R to decrease to 30 volts. Referring to B in Fig. 27, we see the total voltage variation which has occurred across the resistance R. Starting with a normal voltage drop of 40 volts, it first increased 10 volts, then decreased 10 volts, thus causing an over-all voltage change of 20 volts across the plate circuit resistance.

Since we applied only a 2-volt variation to the grid circuit of the tube and have secured a 20-volt variation across the plate circuit of the tube, it is quite apparent that the tube has amplified the original voltage. To determine exactly the number of times which the applied voltage has been amplified, it is only necessary to take a ratio between the voltage variation across the plate circuit to the voltage variation applied to the grid circuit. This will be 20 ÷ 2 or 10 times.

From the graphical analysis of this action in Fig. 28, it is apparent that the grid voltage changes have produced plate current changes which vary in direct proportion. When the grid was made 1 volt less negative, the plate current increased 2 ma. and when the grid was made 1 volt more negative, the plate current decreased 2 ma. This linear relationship must exist between grid voltage and plate current if we are to obtain amplification without causing a distortion of the original waveform of the voltage applied to the grid. It is for this reason that the operating point was originally placed at point X. Suppose the operating point were moved down on the curve to around -8 volts; since the characteristic curve is not a straight line in this vicinity, the grid voltage changes would not have produced corresponding plate current changes. Distortion of the original voltage would have resulted, which would be very undesirable. Distortion means that the output voltage (or current in the plate circuit) does not have exactly the same waveform as the input voltage applied to the grid circuit. Several other factors enter into the operation of a vacuum tube which must be taken into consideration to prevent distortion. These will be discussed in later lessons. For the present, the student should remember that a voltage amplifier must be operated on the straight portion of the grid-voltage, plate-current characteristic curve. The grid must always be kept negative in this type of amplifier, so the operating point must be below zero grid bias.

Voltage amplification represents one of the most important functions of a three-element vacuum tube for commercial purposes. The amount of voltage amplification obtained from a tube will always be the ratio of the voltage variation produced across the plate circuit to the voltage variation applied to the grid circuit. For undistorted amplification, the voltage variations across the plate circuit must have the same waveform as the voltage variations applied to the grid circuit. It should be understood that the amplification obtained in any case is due to the controlling action which the grid has on the plate current. The voltage applied to the grid has caused the grid to control the plate current and the plate current in turn causes the voltage variations across the resistance in the plate circuit. Quite often, instead of using a resistance in the plate circuit, a coil (air core or iron core) is inserted. A coil will have an effect similar to a resistance; that is, the current changes created in the plate circuit (by the grid voltage changes) will cause varying voltage drops to occur across it and the applied grid voltage changes will be amplified.

The method we have just used to explain how a vacuum tube amplifies a voltage is not similar to the method previously employed to determine the amplification factor of a tube. It should be kept in mind that the amplification factor is merely a number specified by the manufacturer denoting the ability of a tube to amplify a voltage. The actual amount of amplification obtained from a vacuum tube depends not only upon the amplification factor, but also the conditions existing in the associated circuits. In this particular case, if the size of the resistance R was decreased, the amount of amplification which would have been obtained would have been less. Likewise, if the resistance R were increased (also increased battery voltage to keep the plate voltage the same), the amount of amplification would have been greater.

The actual voltage amplification obtained from any tube may be found by use of the following formula:

$$\text{Voltage Amplification} = \frac{\text{Amplification factor} \times \text{Plate load resistance}}{\text{Plate load resistance} + \text{Plate resistance}}$$

Or: $$V.A. = \frac{Mu \times R_L}{R_L + R_p}$$ [1]

Where:
Mu is the amplification factor
R_L is the load resistance
R_p is the plate resistance

This formula is very useful and should be remembered. *The plate load resistance is that opposition (resistance or inductive reactance in ohms) in the plate circuit across which voltage variations are produced, due to the plate current changes.* In Fig. 26,

[1] The derivation of this formula involves the use of information contained in later lessons. It will be explained in Lesson 28.

the plate load resistance was 5,000 ohms. In order to accurately determine the voltage amplification using this formula, it is necessary to know the exact plate resistance of the tube at the operating point. The plate load resistance may be determined by actual measurement and the mu or amplification factor of the tube may be secured from manufacturer's specification. Exceedingly accurate determination of the plate resistance of the tube with experimental apparatus is not practical, so in order to use this equation to any degree of accuracy, it is necessary to apply the voltages specified by the manufacturer in the tube manual.

As an example, we shall use the type 6F5 all-metal tube. When this tube is operated in a circuit with 250 volts on the plate and 2 volts negative grid bias, the plate resistance will be 66,000 ohms and the amplification factor 100. Let us assume that we are operating this tube in a typical amplifier circuit as shown in Fig. 29.

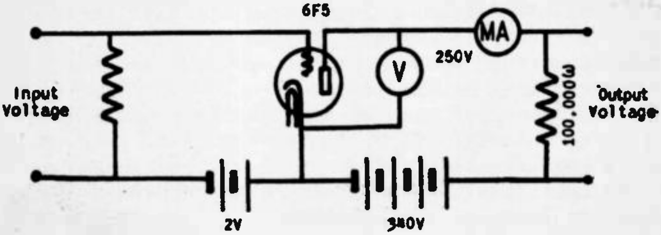


Fig.29 Circuit to illustrate the effect of the plate load resistance on voltage amplification.

In this circuit, the plate load resistance is 100,000 ohms and since .9 ma. of plate current will be passing through this resistance, it will be necessary to employ a plate voltage supply of 340 volts in order to maintain the plate 250 volts positive with respect to the cathode.

Instead of using a coil in the grid circuit as was done in the preceding example, a resistance is shown. Whether a coil or resistance is used is immaterial as long as there is some type of opposition in the grid circuit across which it is possible to develop a voltage.

Using the formula just given to calculate the voltage amplification which will be obtained from this circuit, we will have:

$$V.A. = \frac{100 \times 100,000}{100,000 + 66,000}$$

$$= \frac{10,000,000}{166,000}$$

$$= 60.2 \text{ (approx.)}$$

Notice that the amount of voltage amplification actually secured from this typical circuit is not equal to the amplification factor of the tube. As previously stated, the amplification factor is merely the manufacturer's specifications as to the ability of a tube to amplify and that the voltage amplification actually secured depends not only upon the amplification factor, but also upon the associated circuit. In this circuit, if the plate load resistance had been made greater than 100,000 ohms, the amplification obtained would have been greater, and likewise, if the plate load resistance were made less than 100,000 ohms, the amplification would decrease accordingly.

When it is said that the voltage amplification produced by a tube is 60, it means that if 1 volt is applied to the input or grid circuit, 60 volts will be secured across the output or plate circuit. Similarly, if 2 volts was applied to the input, 120 volts would be obtained across the output, etc.

The voltage amplification secured from a tube can be calculated by the use of formulas other than the one just given. These other formulas are not of sufficient importance to necessitate their study at this time.

Notes

(These extra pages are provided for your use in taking special notes)

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UNIT NO. 1

ALERNATING CURRENT CIRCUITS

LESSON NO. 13

KNOWLEDGE IS YOUR MERCHANDISE

.....see that you have plenty of it to sell.

When you are in need of some new shirts, and you go to your merchant who sells men's clothing, you enter his store with the thought that you are going to get the most for your money. You look over the different shirts that Mr. Merchant shows you, examine the texture of the material of which they are made and finally select those shirts that appeal to you the most and that seem to be the best buy.

In other words, you select your merchandise very, very carefully. You do not buy "just anything" that is shown you, for you are paying out hard-earned money and you want the best there is.

Now, then, let us suppose that the manager of a radio broadcasting station is in need of an operator. Several young men, including yourself, have applied for the job, submitted applications and have been interviewed. During such interviews, the manager will make careful note of the extent of the knowledge each applicant possesses. The reason that he does this is because he wants to get the most for the money that he pays out in salary ...so...he naturally selects the applicant who knows the most.

In other words, Mr. Student, when you applied for the job mentioned above, you put your merchandise (knowledge) on display. The other applicants did the same. When you were buying your shirts, you make your selections with care. You wanted high-grade, full-value merchandise. The knowledge that you have tucked away in your brain is YOUR MERCHANDISE. If Mr. Manager feels that he will get MORE knowledge for his money if he employs YOU....YOU WILL GET THE JOB. On the other hand, if your merchandise (KNOWLEDGE) is not as outstanding as one of the other fellows who applied for the job......YOU WON'T GET THE JOB.

So, to make sure that YOUR MERCHANDISE (KNOWLEDGE) is going to be so extensive and complete that YOUR SERVICES WILL BE A GOOD "BUY", see that you study EVERY SINGLE LESSON THOROUGHLY......see that you COMPLETE EVERY SINGLE EXPERIMENT CORRECTLY.......STICK TO YOUR TRAINING AND COMPLETE IT WITH HIGH GRADES.....

AND YOU WILL HAVE PLENTY OF BIG VALUE, QUALITY MERCHANDISE (KNOWLEDGE) TO SELL......AND YOU'LL GET A HANDSOME PRICE FOR IT, TOO....SUBSTANTIAL, REGULAR "PAY CHECKS" EVERY MONTH, YEAR IN AND YEAR OUT. YOU'RE GOING TO BE A WINNER AND WE ARE GOING TO HELP YOU WIN.

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Lesson Thirteen

ALTERNATING CURRENT CIRCUITS

"This lesson takes you into one of the more advanced phases in the study of Electricity. Since the function of most Radio and Television circuits is based primarily on constitutional electrical principles, it is necessary that you obtain a thorough training in the more fundamental electrical theories.

"The study of Alternating Current constitutes a very interesting portion of your work. Throughout your future studies and your home laboratory experiments, the knowledge you secure from this lesson will be of great value to you."

1. ALTERNATING CURRENT CIRCUITS. Having secured a fundamental knowledge of the resistor, the coil and the condenser, it is now necessary to point out certain facts pertaining to the function of these three parts in alternating current circuits. Some information on this subject has been given in preceding lessons when discussing the inductive reactance of a coil and the capacitive reactance of a condenser. This information will not be repeated; however, the important facts which must be recalled at this time are:

1. A pure resistance, having no inductive or capacitive effects, will offer the same number of ohms opposition to an alternating current as to a direct current.
2. An alternating current meets with more opposition than a direct current when passing through a coil.
3. A direct current will not pass through a condenser (assuming no leakage), but an alternating current will pass through a condenser with comparative ease.

In AC circuits, several conditions exist which are not true in a DC circuit. Among these are, *first*, the total current flowing through an alternating current circuit will not be equal to the applied voltage divided by the resistance of the circuit. The reactance (inductive and capacitive) in the circuit must be taken into consideration before applying Ohm's Law. *Second*, the true power in an AC circuit may not be equal to the product of the applied voltage and the current flowing through the circuit. In a pure DC circuit, W = E × I. This same relationship is true in an AC circuit if it contains only pure resistance, but if the AC circuit contains either inductance or capacity, the "power factor" of the circuit must be taken into consideration.

The material of this lesson explains why these facts are true.

2. GENERATING AN ALTERNATING VOLTAGE. An AC voltage is produced by a machine known as an AC generator, or, as it is more commonly known, an "alternator". A fundamental knowledge of the construction and operation of an alternator is of great importance in order to understand the various actions of an alternating current. The principle of an AC generator is based on the simple process of induction. From the Law of Induction, it is known that a voltage will be induced in a conductor when it is rotated through a magnetic field, the voltage depending upon the speed of the conductor and the number of lines of force cut per unit of time. Fig. 1 illus-

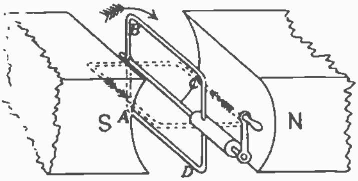


Fig.1 Outline drawing illustrating the fundamental construction of an alternator.

trates the fundamental construction of an alternator. A single loop of wire (labeled A-B-C-D) is arranged on a shaft with a crank attached and supported in such a manner that the loop of wire may be rotated through the magnetic field existing between the north and south poles of the permanent magnet. The rotation of the loop of wire through the steady magnetic field will cause the generation of a voltage in the loop.

A comprehensive understanding of the alternating voltage generator may be secured by reference to Fig. 2. The permanent magnet has been omitted in this figure to simplify the diagram. The magnetic lines of force are represented by the arrows drawn from left to right. The loop of wire has been drawn in two colors; one-half of the loop is black and the other half is white. The object of the different colors is to clearly indicate the position of each side of the loop at various instants during its revolution through the magnetic field. To conduct the voltage generated in the loop of wire to an external circuit, it is necessary to equip each end of the loop with a separate connection, these two connections being insulated from each other. Ordinarily, each end of the loop is connected to an individual slip ring as shown in Fig. 3. The slip ring marked X is connected to the side of the loop marked AD, and the slip ring Y is connected to the side of the loop marked BC. The two brushes, B' and B'', are resting on the slip rings so as to make contact with them, thus conducting the voltage generated to the external circuit, which, in this case, consists of resistance R.

Referring to Fig. 2 again, the black side of the loop is connected directly to the shaft with the brush B resting upon it. The white side of the loop is connected to the slip ring with the brush W resting upon it. The external load resistance R is connected across the two brushes W and B. An alternating current will flow through this resistance when an alternating voltage is induced in the loop.

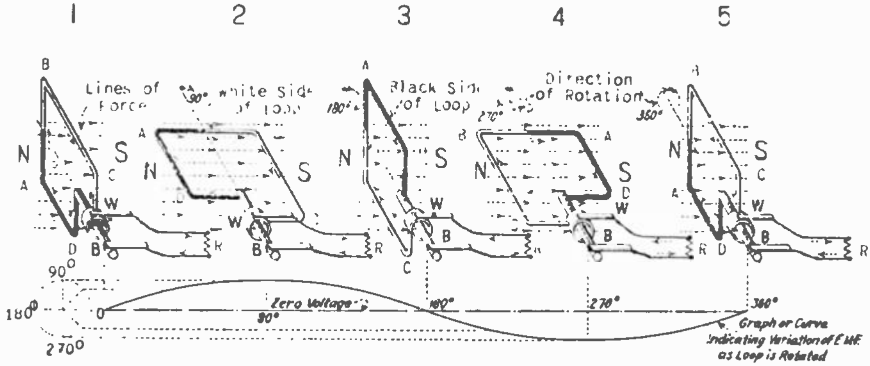
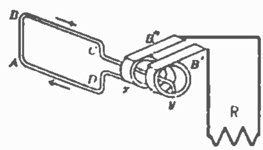


Fig.2 Illustrating the relation of the values of a sine wave to the voltages induced at different instants during the revolution of a conducting loop.

Let us start with position 1, where the black side of the loop is at the bottom and the white side of the loop is at the top. This represents a point of zero voltage. There will be no voltage induced at this instant because a very slight movement of the shaft in either direction will cause the two sides of the loop to move parallel to the magnetic lines of force; hence, there will be no voltage induced. Now assume that the loop is rotated 90 degrees, in a clockwise direction from position 1 to position 2. As the white side of the loop comes down in front of the S pole, it is

Fig.3 Diagram to illustrate the slip rings on either end of the conducting loop. The load resistor R constitutes the external circuit.



cutting through an increasing number of lines of force; hence, the voltage induced in that side of the loop gradually increases from zero to maximum. Likewise, as the black side of the loop comes up in front of the N pole, it is cutting through an increasing number of lines of force; hence, the voltage on that side of the loop gradually increases from zero to maximum. Since the white side of the loop is moving *down* in front of the S pole and the black side of the loop is moving *up* in front of the N pole, the voltage induced in the two sides of the loop will be in such directions as to add together, resulting in the total voltage across brushes W and B being equal to the voltage induced in the black side of the loop plus the voltage induced in the white side. A slight movement of the loop in either direction when it is in the 90-degree position will result in a high voltage being generated because both conductors will be moving perpendicular to the lines of force.

As the rotation is continued from the 90-degree position (2) to the 180-degree position (3), the white side of the loop will be cutting through a decreasing number of lines of force and, likewise, the black side of the loop will be cutting through a decreasing number of lines of force. This will cause the induced voltage in both sides of the loop to gradually decrease from maximum (position 2) to zero (position 3). Again at position 3 it can be seen that a slight movement of the loop in either direction will not generate a voltage because both sides of the loop will be moving parallel to the magnetic lines of force.

Continuing the rotation of the loop from position 3 to position 4, the white side of the loop is now coming up in front of the N pole and the black side of the loop is going down in front of the S pole. Both sides of the loop will be cutting through an increasing number of lines of force, resulting in the voltage gradually increasing from zero to maximum. Notice that the *direction* of the voltage induced in the loop is opposite to that induced when the loop was rotated from position 1 to position 2. The reason for this is that the white side of the loop is now coming *up* in front of the S pole, whereas before, it was going *down* in front of the N pole, and the black side of the loop is now going *down* in front of the N pole, whereas before, it was moving *up* in front of the S pole. Since the sides of the loop are cutting through the magnetic field in opposite directions, the voltage induced in one side will be opposite to that induced in the other in accordance with fundamental laws previously learned.

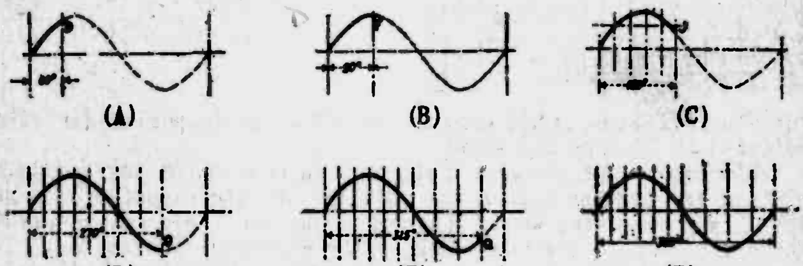
As the loop rotates from the 270-degree position (4) to the 360-degree position (5), both sides of the loop are cutting through fewer lines of force; hence, the voltage induced will gradually decrease back to zero (position 5).

From 1 to 5, the loop has completed one revolution and one cycle of alternating voltage has been induced in the loop. If the rotation of the loop were continued, the process would be repeated; that is, one cycle of alternating voltage would be induced in the loop for each complete revolution. The alternating voltage produced across the two brushes W and B causes a corresponding AC current to pass through the resistance R.

Since the frequency of an alternating current or voltage means the number of cycles per second, it can be seen that the speed of revolution of the loop through the magnetic field determines the frequency of the alternating voltage produced. A rapid rotation results in a high frequency and a slow rotation results in a low frequency. A rapid rotation of the loop through the magnetic field also results in the generation of a *higher voltage*. The reason for this is based on one of the fundamental factors determining the induction of a voltage in a single conductor. This law states that *the voltage induced in a conductor depends upon the speed with which the magnetic lines of force cut through the conductor.* The value of the alternating voltage can also be increased by increasing the strength of the magnetic field. Since electromagnets supply a much stronger magnetic field than permanent magnets, electromagnets are always used in powerful commercial alternators.

A higher output voltage would result if there were more turns of wire on the loop, providing these turns were so arranged that the voltage induced in each turn would add to the voltage induced in the others. In commercial AC generators, there are several hundred turns wound on this portion of the machine and it is commonly called the "armature winding". The electromagnetic coils used to supply the strong magnetic field through which the conductors on the armature rotate are called the "field coils". All AC generators consist fundamentally of these two portions; the field coils and the armature winding.

To generate an AC voltage in the armature winding, it is necessary that a relative motion be established between the magnetic field produced by the field coils and the turns on the armature winding. This can be done by rotating the armature with the field stationary, or by rotating the field with the armature stationary. Ordinarily, the armature winding is held stationary and the field coils are rotated in the larger commercial machines.



(A) (B) (C) (D) (E) (F)

Fig. 4 Illustrating the designation of various points on a sine wave in degrees.

3. THE DEGREES IN A SINE WAVE. It is common practice to refer to various places on an AC sine wave by designating the number of degrees between the starting of the cycle and the point under consideration. For example (see Fig. 4), if it is desired to refer to point D on the sine wave at A, we would say "60 degrees". Likewise, point F is 90 degrees, J is 150 degrees, O is 270 degrees, Q is 315 degrees and the complete cycle consists of 360 degrees.

In Fig. 5, a more representative illustration is given to show the degrees in a sine wave. It is well known that a circle consists of 360 degrees. Suppose that the arm OA, which is equal in length to the radius of the circle, has one end fixed at O, and is revolved in a counter-clockwise direction. The degrees through which the arm passes causes the point A to be a definite distance above or below the horizontal diameter of the circle. This distance corresponds to a definite point on the sine wave which is the same number of degrees from the starting point X. A complete revolution of the arm OA constitutes a 360-degree movement and likewise one cycle consists of 360 degrees.

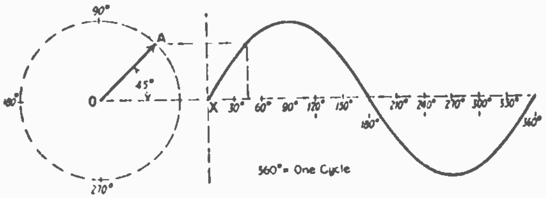


Fig.5 The relation of degrees in a sine wave to degrees in a circle.

4. INSTANTANEOUS AND PEAK VALUES. *The instantaneous value of an AC current or voltage is the value at some designated instant on the sine wave.* This instant is always specified in degrees. For example, in Fig. 6, the instantaneous value at 22.5 degrees is 13 volts, the instantaneous value at 135 degrees is 22 volts and the

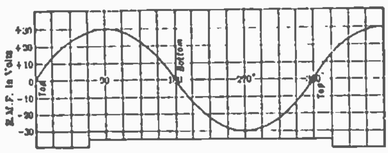


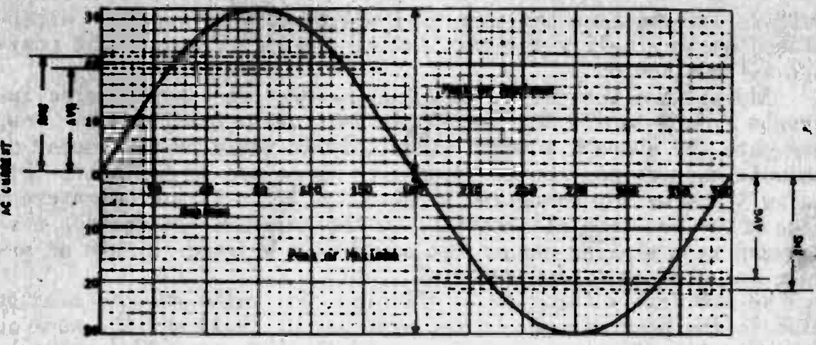
Fig.6 Calibrated sine wave to illustrate the use of "instantaneous" and "peak" values.

instantaneous value at 315 degrees is -22 volts (opposite direction indicated by a minus [-] sign).

The peak value of an AC voltage or current is the maximum value to which it rises on either the positive or the negative alternation. In a pure sine wave, the peak value on the positive alternation is equal to the peak value on the negative alternation. Referring again to Fig. 6, the peak value of the AC voltage is 30 volts at the 90-degree position (positive alternation) and is again 30 volts at 270 degrees (negative alternation). The words "peak" and "maximum" are both used to designate this highest value to which an AC voltage or current rises during either its positive or negative alternation.

5. THE AVERAGE VALUE OF AN AC SINE WAVE. Upon inspecting a sine wave, it can be seen that the value of the represented alternating current or voltage does not remain constant for any length of time throughout the entire cycle. An AC current or voltage is always changing in value, either increasing from zero to maximum, or decreasing from maximum back to zero. The instantaneous values throughout the entire cycle are constantly varying. An exception to these statements must be made at the peak of the positive alternation and at the peak of the negative alternation, because at these instants, the value will remain unchanged for a small fraction of a second.

The average value of an AC sine wave means the average of all the instantaneous values throughout one alternation of the alternating current or voltage and is equal to .637 times the maximum or peak value. The derivation of this constant, .637, can be shown



AVERAGE

Degrees	Value
0	0
10	5.2
20	10.4
30	15.
40	19.3
50	23.
60	26.
70	28.2
80	29.6
90	30
100	29.6
110	28.2
120	26.
130	23.
140	19.3
150	15.
160	10.4
170	5.2
Total	343.4

$\frac{343.4}{18} = 19.07$ (.04 error)

$\frac{19.11}{30} = .637$

$.637 \times 30 = 19.11$

R.M.S.

Degrees	Value	Value Squared
0	0	0
10	5.2	27.04
20	10.4	108.16
30	15	225.
40	19.3	372.49
50	23	529.
60	26	676.
70	28.2	795.24
80	29.6	876.
90	30.	900.
100	29.6	876.
110	28.2	795.24
120	26.	676.
130	23.	529.
140	19.3	372.49
150	15.	225.
160	10.4	108.16
170	5.2	27.04
Total		8118.18

$\frac{8118.18}{18} = 451.01$

$\sqrt{451.01} = 21.23$

$\frac{21.23}{30} = .707$

$30 \times .707 = 21.21$ (.02 error)

Fig. 7 Derivation of the "average" and "R.M.S." values of a pure sine wave.

graphically by referring to Fig. 7. In this figure, one cycle of an AC current having a peak value of 30 amperes will be analyzed. To secure the average value of the current changes over the positive alternation, we shall start with zero degrees. The value of the current at this instant is zero. Advancing 10 degrees to the right, we find the instantaneous value to be 5.2 amperes. At 20 degrees, the instantaneous value is 10.4 amperes, etc. The instantaneous values at 10-degree intervals from 0 to 170 are shown in the chart on the left, below Fig. 7. At 180 degrees, the AC current is again zero; however, this zero value should not be included in the calculations because, in reality, it is the starting point of the negative alternation. By inspecting the graph, you will notice that the negative alternation of the AC sine wave is exactly the same as the positive alternation; hence, if we find the average of the positive alternation, the same will be true for the negative alternation, so to simplify the calculations, we will consider the positive alternation only.

Add all the instantaneous values secured at the 90-degree intervals from 0 to 170 degrees. This is shown to total 343.4! Now, to secure the average, or mean value, divide 343.4 by the number of instants considered. Counting, we find there are 18 instants. Dividing 343.4 by 18, we obtain 19.07.[1] 19.11 is the actual average value of the positive alternation. If the negative alternation were analyzed in a similar manner, it would also be found to have an average value of 19.11 amperes.

We are next interested in finding the ratio of the average value to the peak value. If the average is 19.11 and the peak is 30, the ratio of average to peak is 19.11 ÷ 30, or .637 (approx.). The .637 as found in this manner is the constant which specifies the relationship between the average and the peak value of any pure sine wave.

When we know the peak value of any AC voltage or current (true sine wave), it is possible to find the average value by multiplying the peak value by .637!

By dividing the peak value of 30 amperes by the average, 19.11, we secure the constant, 1.57! This division is exactly opposite to the division used to secure the constant .637, so the constant, 1.57, expresses the ratio of peak to average value instead of the ratio of average to peak value. Hence, if the average value is known, the peak value can be found by multiplying the average value by 1.57! Both of these constants, .637 and 1.57, should be remembered because they illustrate the relationship existing between the peak and average value in an AC sine wave.

6. **THE R.M.S. VALUE OF AN AC SINE WAVE.** The average value of an AC sine wave is of little consequence in most electrical work. For practical applications, the "root mean square", or "effective" value is far more important. The root mean square value is often abbreviated with the letters "R.M.S."

The R.M.S. value of an AC current is defined as that value which will produce the same heating effect as will the same value of direct current. For instance, in Fig. 8, if one ampere of DC current is required to flow through the heating resistor for one hour to raise the temperature of the water 10 degrees, then one ampere of AC current (expressed in R.M.S. value) passed through the resistor for one hour will also raise the temperature of the water 10 degrees. This "heating effect" comparison between the R.M.S. value of an AC current and a DC current has been adopted by general agreement. The ampere was used as the unit of measuring direct current before alternating currents were employed. When it became necessary to measure alternating current values, instead of adopting a new unit, it was decided to use the unit "ampere" for AC current measurements and to have it equivalent to the ampere as used for DC as closely as possible. The most satisfactory method for

[1] This number is in error by .04, due to graphical inaccuracies.

defining the AC ampere in terms of the DC unit was found to be a comparison as to their "heating effects". The above example serves to illustrate the comparison and, as stated previously, one ampere of AC current will produce the same amount of heat as one ampere of DC current, when the current is expressed in its R.M.S. or effective value.

The effective, or R.M.S., value of an AC current is equal to .707 times the peak value when the AC current is in pure sine wave form. It will be noticed that the R.M.S. value is slightly higher than the average value of an AC sine wave, the average value being

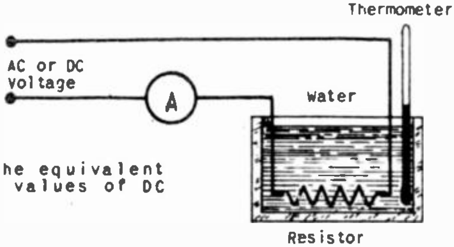


Fig.8 Demonstrating the equivalent heating effect of equal values of DC and AC current.

.637 of the maximum. By a graphical analysis of the sine wave shown in Fig. 6, we proved the derivation of the constant, .637, for the average value . It is also possible to use this same method to prove the derivation of the constant, .707, for the effective or R.M.S. value. Since we have previously stated that the unit ampere as used for measuring an AC current is based on its heating effect, it is necessary to consider the instantaneous power throughout each alternation instead of the instantaneous voltage or current values alone.

When a DC current passes through a resistor, the amount of heat (power) generated is found by squaring the current, then multiplying by the value of the resistor (I^2R Law). Since a DC current remains at a constant value, the amount of heat generated in a resistor, due to the passage of a DC current through it, will remain constant. If the current passing through the resistor is varied in any manner, either increased or decreased, the amount of heat generated will change. The change in the heat produced, however, will not be in direct proportion to the current change, but rather will be proportional to the *square* of the current change. This can be illustrated by the following example. In Fig. 9 at A, an applied voltage of 10 volts is forcing a current of 2 amperes through a 5-ohm resistance. The amount of heat generated in this case will be $2^2 \times 5 = 20$ watts. At B, the applied voltage is increased to 20 volts, thus forcing twice as much current (4 amperes) through the 5-ohm resistance. To calculate the heat generated in the resistance, we will apply the I^2R Law; $4^2 \times 5 = 80$ watts. Notice that the power has been increased four times, whereas the current was only doubled. This illustrates that the amount of heat generated in a resistor will increase proportional to the *square of the current* increase, because $2^2 = 4$.

By uniting the fundamental formula for power and Ohm's Law, it is also possible to show that the power increase in a circuit will be proportional to the square of the voltage increase. This is done as follows:

$$I = \frac{E}{R}$$

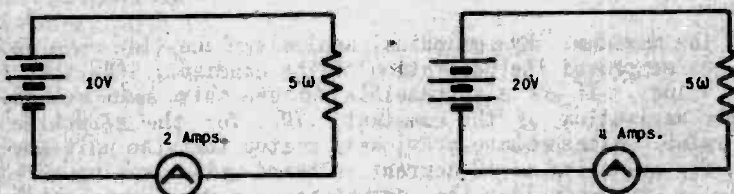
Substituting $\frac{E}{R}$ for I in the power formula $W = E \times I$, we have:

$$W = E \times \frac{E}{R}$$

or:

$$W = \frac{E^2}{R}$$

From this formula, it can be seen that the power increase in a circuit will be proportional to the square of the voltage increase. This may be illustrated with the values given in Fig. 9. In this circuit, the voltage was increased two times in order to double the



(A) (B)

FORMULA USED	CIRCUIT (A)	CIRCUIT (B)
$W = I^2R$	$2^2 \times 5 = 20W$	$4^2 \times 5 = 80W$
$W = \frac{E^2}{R}$	$\frac{10^2}{5} = \frac{100}{5} = 20W$	$\frac{20^2}{5} = \frac{400}{5} = 80W.$
$W = E \times I$	$10 \times 2 = 20W$	$20 \times 4 = 80W$

Fig. 9 Circuit to illustrate the relationship between current, voltage and power.

current (the resistance in the circuit remained constant). The resulting power increase was four times; hence, doubling the applied voltage increased the power four times. If the power increased 4 times when the voltage was only doubled, it is apparent that the power increase in a circuit is proportional to the square of the voltage increase.

It is also shown in Fig. 9 that when the formula $W = E \times I$ is used, the power will be four times greater in circuit B than in circuit A.

In these examples, it was assumed that the current and voltage were increased. It is also true that if the current passing through a circuit, or if the voltage applied to a circuit is decreased, the power decrease will be proportional to the square of the current or voltage decrease. Every change of current or voltage in a circuit will cause a change to occur in the power which is proportional to the *square* of the current or voltage change.

Having learned that the power in any AC circuit depends on the squared values of the current or voltage, let us return to Fig. 7 and proceed to derive the constant, .707! The chart on the right beneath the sine wave shows the degrees (at 10-degree intervals) over one alternation, the instantaneous values corresponding to these degrees and the instantaneous values squared. It is desired to find the value of this current which will be just as effective in producing heat as a corresponding value of DC current. To do this, find the average of the squared values, then extract the square root. The total of the instantaneous squared values is 8,118.18 and the average is this number divided by 18 (number of instants). According to the chart, this average of the squared (mean square) values is 451.01! Extracting the square root of this number, gives 21.23! This 21.23 is the square *root* of the *average* of the *squared* values, or as it is often called, the "root mean square" value (abbreviated R.M.S.). *This means that if the peak value of an AC current is 30 amperes, it will have exactly the same effect in producing heat as 21.23 amperes of DC current.* If 21.23 is the R.M.S. value when the peak value is 30, the ratio of 21.23 to 30 will give a constant which will express the relationship between the R.M.S. value and the peak value for any pure sine wave. Dividing 21.23 by 30, the constant .707 is obtained. Due to the fact that only 18 instants were considered and due to the inaccuracy of a graphical solution, some of the values given in this derivation are slightly incorrect; however, for all practical purposes *the R.M.S. value of a pure sine wave is definitely accepted as .707 of the peak value.*

An AC voltmeter is always calibrated to read the effective or R.M.S. value of the AC voltage when it is placed across an AC circuit.[1] Likewise, an AC current meter is always calibrated to read the effective or R.M.S. value. If the average or peak value is desired, it will be necessary to measure the R.M.S. value with a meter, then use the necessary conversion factors.

The conversion factor or constant to be used to find the peak value of an AC current or voltage when the R.M.S. value is known is 1.414! This number is the square root of 2 and it can be remembered as $\sqrt{2}$ if the student finds it easier. If the R.M.S. value of a pure sine wave is measured to be 21.23 amperes, the peak value is found by multiplying 21.23 by 1.414; thus, 21.23 × 1.414 = 30 amperes (approx.).

The conversion factors given in the preceding paragraphs are tabulated to facilitate their use:

Peak or Maximum Value = 1.414 × R.M.S. or Effective Value
R.M.S. or Effective Value = .707 × Peak or Maximum Value
Average Value = .637 × Peak or Maximum Value
Peak or Maximum Value = 1.57 × Average Value

[1] This statement does not apply to vacuum tube voltmeters. Most V. T. voltmeters read the peak value.

Also, by simple mathematics:

Average Value = .901 × R.M.S. Value
R.M.S. Value = 1.11 × Average Value

The following problems illustrate the use of these conversion factors.

Problem 1: By connecting an AC voltmeter across a power supply line, it is found to read 110 volts. What is the peak voltage across the AC line?

Solution: The 110 volts read on the meter is the R.M.S. or effective value of the line voltage. In order to find the peak voltage across the line, the effective value, 110, must be multiplied by the factor, 1.414! Multiplying, we have 110 × 1.414 = 155.54 volts.

Problem 2: The current flowing through an AC circuit is measured and found to be 30 ma. What is the peak value of the AC current?

Solution: If the AC meter is reading 30 ma., the peak current flowing through the circuit will be 30 × 1.414 = 42.42 ma.

Problem 3: A mica condenser has a voltage breakdown rating of 500 volts DC. What is the maximum R.M.S. AC voltage which may be applied across the condenser without breaking it down?

Solution: Since a peak voltage of over 500 volts will damage the condenser, the R.M.S. value of this peak voltage will be 500 × .707 = 353.5 volts. An R.M.S. voltage higher than 350.5 would have a peak value over 500 volts, which would damage the condenser.

Problem 4: If the measured voltage of an AC line is 115 volts, what is the average value?

Solution: The measured voltage is 115 volts; this is the R.M.S. value. To find the average value, multiply 115 by .901! This equals 103.61 volts.

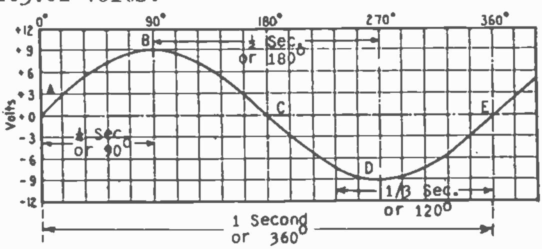


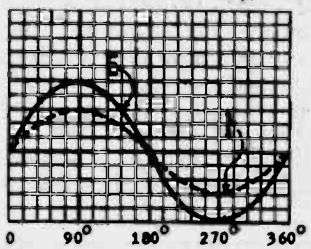
Fig. 10 Illustrating the relation of degrees to time.

7. LEADING AND LAGGING VALUES. In alternating current circuits, degrees are always used to denote the lapse of time. In Fig. 10, the point on the AC sine wave at 270 degrees occurs a fraction of a second later than the point on the same sine wave at 120 degrees. The actual lapse of time in seconds depends upon the frequency of the AC current or voltage represented by the sine wave.

The lapse of time between two points on any sine wave is specified in degrees rather than the actual part of a second merely for convenience. If the sine wave shown in Fig. 10 represents an alternating voltage or current of one cycle per second, the lapse of time between 90 degrees and 270 degrees would be one-half of a second, because 270 - 90 = 180 degrees and 180 degrees is one-half of a cycle. Likewise, the lapse of time from 0 to 90 degrees would be one-fourth of a second and the time from 240 degrees to 360 degrees would be one-third of a second, etc.

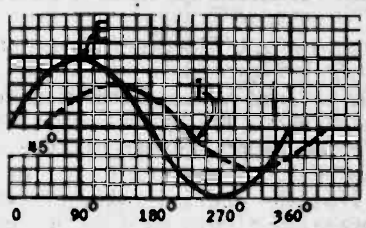
The words "leading" or "lead" and "lagging" or "lag" are commonly used when speaking of AC circuits. In all instances, these words are used as a reference to time. In an AC circuit, it is possible for the current to be passing through the same electrical degree in the same direction as the applied voltage; in which case, current would be said to be "in phase" with the applied voltage. It is also possible for the current to "lead" or to "lag" the ap-

Fig. 11 Current is in phase with the applied voltage.



plied voltage, depending upon the electrical constants in the AC circuit. When it is said that the current is "leading" the voltage, the significance of the statement is that the current reaches its maximum value on each alternation *before* the applied voltage reaches its maximum value. The lapse of time between the instant when the current is maximum and the instant when the voltage is maximum is specified in degrees. Bear in mind that the degree is merely a method of denoting relative time in an AC circuit. Like-

Fig. 12 Current is lagging 45° behind the applied voltage.



wise, if the statement was made that the current flowing through an AC circuit is "lagging" the voltage applied to the AC circuit, the significance of the statement is that the voltage applied to the circuit attains its maximum value *before* the current flowing through the circuit reaches maximum. In this case it will also be correct to say that "the voltage is leading the current" and the statement would have the same meaning as "the current is lagging".

By general agreement, it has become common practice to always specify the position of the current in an AC circuit with reference to the voltage. In other words, it is seldom said that the voltage is "leading" or "lagging" the current; but, rather, the current is said to be "lagging" or "leading" the voltage. For example, in Fig. 11 it will be noted that the AC voltage applied to the circuit and the AC current flowing through the circuit are starting from zero at the same time, attaining their maximum value of the positive alternation at the same time, completing the first alternation at the same time, etc., throughout the entire cycle. In this case, the current is said to be "in phase" with the applied voltage.

In Fig. 12 it will be noticed that the current starts from zero on its positive alternation 45 degrees after the voltage starts from zero. To maintain this condition, the frequency of the current must be the same as the frequency of the applied voltage. If the electrical characteristics of the circuit remain constant, the current will always lag behind the applied voltage the same number of degrees. With the voltage as a reference, the current is said to be lagging the applied voltage 45 degrees. In a single phase[1] AC circuit, it is possible to produce a current lag of nearly 90 degrees (never more than 90 degrees) behind the applied voltage.

In Fig. 13, the diagram shows that the current is 45 degrees ahead of the applied voltage. Of course, it is impossible for current to start flowing through any circuit before the voltage is applied, but by certain electrical characteristics the current may be made to lead the applied voltage after the switch in the circuit is closed and a few cycles have been completed. The electrical characteristics of the circuit are such that the voltage is caused to drop behind the current, or in other words the current is caused to lead the applied voltage. Instead of saying a "voltage lag" the expression always used is a "current lead". In Fig. 13, the current is leading the applied voltage 45 degrees. It is possible to produce a current lead in a single phase AC circuit nearly equal to 90 degrees, but the current lead can never be greater than 90 degrees.

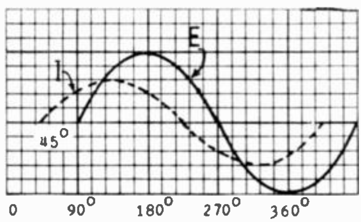


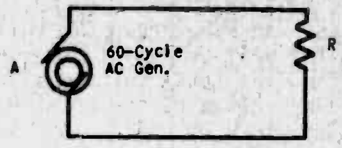
Fig. 13 Current is leading the applied voltage 45°.

8. **SINE WAVES IN PHASE.** In Fig. 14, the 60-cycle AC generator marked A is applied across the resistance R. Assuming that the

[1] All of the AC circuits discussed in this lesson are "single phase". Later lessons will give information on "polyphase" circuits.

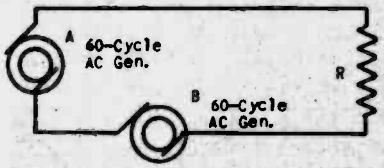
peak voltage output of the generator is 100 volts, the R.M.S. value of the voltage will be 70.7 volts.

Fig.14 The output of the 60-cycle AC generator (A) is 100 volts peak.



Now suppose that another generator is connected in series in the same circuit as shown in Fig. 15. This generator is marked B and has the same frequency as generator A; that is, 60 cycles. The peak voltage output of generator B, however, is only 80 volts. Let us assume that upon connecting the series generator B in the circuit, we made the necessary adjustments so that the voltage output

Fig.15 The peak voltage output of generator A is 100 volts and the peak voltage output of generator B is 80 volts.

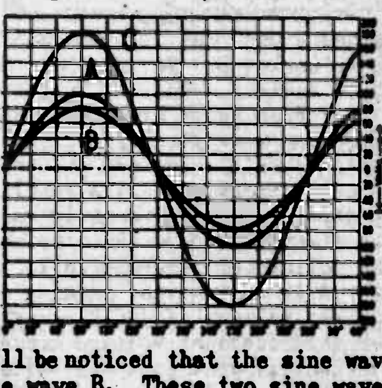


of generator B was directly in phase with generator A. The process of adjusting two generators possessing the same frequency so that their voltage outputs are directly in phase with each other is called "synchronizing" the generators.

When the generators have been synchronized, let us see what the total voltage across the resistance R will be.

To understand how these voltages combine, refer to the graph shown in Fig. 16. The 100-volt output of generator A is shown by the curve marked A and the 80-volt output of the generator B is

Fig.16 Illustrating that voltages directly in phase with each other will add together. Resultant voltage is equal to the sum.



shown by the curve marked B. It will be noticed that the sine wave A is directly in phase with the sine wave B. These two sine waves should be drawn in phase with each other because we assumed that when connecting generator B in the circuit, it was synchronized or put in step with generator A.

The total voltage produced across the resistance R at every instant can now be found by adding the instantaneous voltages produced by A and B. Thus, at 30 degrees, the instantaneous voltage of generator A is 50 volts and the instantaneous voltage of generator B is 40 volts. Adding, the total voltage is approximately 90 volts. At 90 degrees the voltage output of generator A is 100 volts and the voltage output of generator B is 80 volts. Adding these, we find the total voltage at that instant to be 180 volts. Corresponding values of the total voltage can be secured throughout the entire cycle by adding the instantaneous values of the two generators.

From this, the statement may be made that when two voltages in series are in phase with each other, the resultant total voltage will be equal to the sum of the two voltages.

9. **SINE WAVES OUT OF PHASE.** Referring again to Fig. 15, let us assume that generator B was not properly synchronized with generator A before it was connected in the circuit. In this case, the voltage output of A is not in phase with the voltage output of B and the resultant total voltage is not equal to 180 volts. In Fig. 17, the voltage output of generator A is indicated by the curve

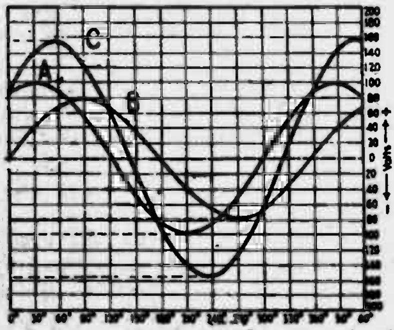


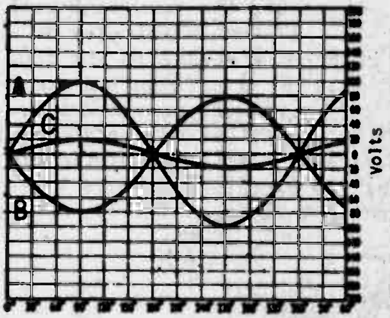
Fig.17 Illustrating the resultant voltage obtained when two AC voltages are not exactly in phase.

marked A and the voltage output of generator B is shown by the curve marked B. Notice that the two generators are not attaining their maximum values nor crossing the zero axis at the same time. A 60-degree phase difference exists between the two voltages. To determine the voltage resulting from these two "out of phase" voltages, we will again add the instantaneous values to determine the points through which the resultant curve (marked C) must pass. At 30 degrees, voltage B is 40 volts and voltage A is 100 volts. The resultant voltage at that instant will be 140 volts. At 60 degrees, the voltage of generator B is 69.3 volts and the voltage of generator A is 86.6 volts. Adding these two voltages, we have the resultant voltage of 155.9 volts. Notice that this particular value for the resultant voltage is nearly the highest voltage obtained. (The actual peak is 156.2 volts.) This is somewhat less than the 180 volts which was secured when the two voltages were in phase with each other. The resultant voltage has a value of zero when voltage A and voltage B are exactly equal but opposite in direction. This is seen to be approximately 146.3 degrees. At the instant designated by 146.3 degrees, voltage A is -44.3 volts and voltage B is +44.3 volts. Adding +44.3 to -44.3, the sum is zero.

From this example, it can be seen that when two AC voltages in series are applied to the same circuit and *differ in phase*, the resultant voltage produced in the circuit will be somewhat less than the voltage produced when the two voltages are *in phase* with each other. The exact amount of voltage reduction depends entirely upon the phase difference between the two voltages.

If the two voltages were 180 degrees out of phase[1], the resultant voltage across the circuit would vary as shown by the graph in Fig. 18. In this graph, the voltage output of generator A is rep-

Fig.18 Illustrating that voltages exactly out of phase will buck against each other. Resultant voltage is equal to the difference.



resented by sine wave A and the voltage output of generator B is represented by the sine wave B. Again adding the instantaneous values, we obtain a resultant voltage as represented by the sine wave C. Studying Fig. 18, it is seen that as the voltage of the generator A is increasing in the positive direction, the voltage of generator B is increasing in the negative direction. This means that the two voltages are bucking against each other. The extent of this cancellation depends entirely upon the instantaneous values of the two voltages. For example, at 30 degrees, the value of voltage A is 50 volts in the positive direction and the value of voltage B is 40 volts in the negative direction. The resultant voltage is equal to the algebraic[2] sum of the two. Adding +50 to -40, we obtain +10 volts. Again, at 90 degrees, the instantaneous value of voltage A is 100 volts in the positive direction and the instantaneous value of voltage B is 80 volts in the negative direction. Adding +100 to -80, we obtain a value of +20 volts for the resultant voltage. The negative alternation is treated in a similar manner.

From this example it can be seen that when two voltages are exactly 180 degrees out of phase with each other and applied to the same circuit, the resultant voltage across the circuit will be equal to the difference between the two voltages. If the two voltages were equal in peak value, a complete cancellation would occur and the resultant voltage across the circuit would be zero.

[1] It is possible for two voltages or two currents to be 180 degrees out of phase with each other, but a voltage and a current impelled by that voltage can never be more than 90 degrees out of phase with each other.

[2] To add "algebraically" means to subtract the two numbers (if their signs are opposite), then attach the sign of the larger number. Thus, +10 added to -15 is -5; -8 added to +10 is +2; etc.

Summarizing this information, we have found that:

When two AC voltages or currents are exactly *in phase* with each other, the voltage or current resulting from this combination will be equal to the sum.

If two AC voltages or currents are exactly *out of phase* with each other (180 degrees), the resultant value of the AC voltage or current will be equal to the difference. If they are exactly equal in peak value, a complete cancellation will occur and the resultant will be equal to zero.

If two AC voltages or currents differ in phase by some degree between zero and 180, the resultant voltage or current will be less than the sum of the two and greater than the difference between the two. The exact value will depend upon the extent of the phase difference.

A mathematical solution is possible for determining the value for the resultant voltage instead of a graphical solution; however, such calculations involve the use of higher mathematics.

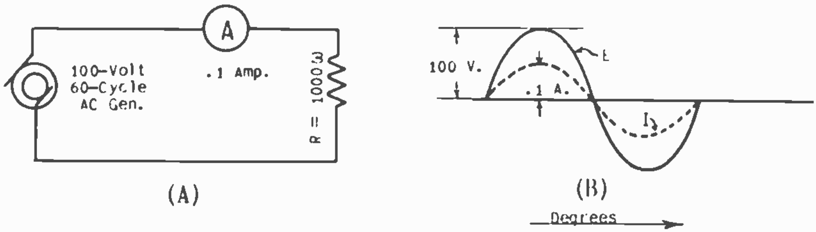


Fig. 19 (A) Pure resistance in an AC circuit.
(B) Current is in phase with the applied voltage.

10. PURE RESISTANCE IN AN AC CIRCUIT. In Fig. 19, the 100-volt output of a 60-cycle AC generator is shown applied across a 1,000-ohm resistor. If the 1,000-ohm resistance does not have any inductive or capacitive effects, the current which passes through the AC circuit will be in direct accordance with Ohm's Law and can be calculated by the formula:

$$I = \frac{E}{R}$$

$$= \frac{100 \text{ volts}}{1000 \text{ ohms}}$$

$$= .1 \text{ ampere}$$

A diagram illustrating the phase relation between the applied voltage and the current passing through the resistor is shown at B in Fig. 19. Notice that at every instant, the current increases as the voltage increases and the current decreases as the voltage decreases. The current and voltage reverse direction at the same time (180 degrees) and both the current and voltage complete the cycle at exactly the same time. When only pure resistance is contained in an AC circuit, the current flowing through the circuit is directly in phase with the applied voltage.

The opposition offered to the passage of the AC current through a pure resistance circuit consists only of the physical properties of the 1,000-ohm resistor. As stated previously, this type of opposition is often called "ohmic" or "frictional" resistance.

Power will be dissipated in the form of heat when the alternating current passes through the resistance. This power can be calculated by direct application of the I^2R Law. The number of watts dissipated in the form of heat in this particular example will be:

$$W = I^2R$$

$$= .1^2 \times 1000$$

$$= .01 \times 1000$$

$$= 10 \text{ watts}$$

All these statements are true *only* when a pure resistance is contained in the AC circuit. If there are any inductive or capacitive effects in the circuit, the above statements will *not* be true and the current flowing through the circuit, as well as the power dissipated in the circuit, cannot be calculated by the methods just given.

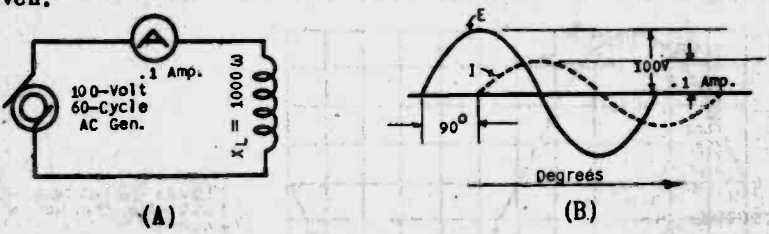


Fig.20 (A) Pure Inductance in an AC circuit.
(B) Current is lagging applied voltage 90°.

11. INDUCTANCE IN AN AC CIRCUIT. The circuit shown at A, Fig. 20 shows the 100-volt, 60-cycle generator connected across a *pure inductance*. It is called "pure" because we are assuming that the coil has no resistance and there are no capacitive effects between the coil turns. Of course, it would be impossible to construct such a coil, because all coil windings consist of conductors and all conductors have resistance. This theoretical coil is being considered only for the purpose of explanation and it should be understood that such a piece of apparatus is not possible from a practical standpoint.

Assuming that the inductive reactance of this coil is 1,000 ohms, the current flowing through the coil can be found by substituting X_L for R in Ohm's Law. Thus:

$$I = \frac{E}{X_L}$$

$$= \frac{100}{1000} = .1 \text{ ampere}$$

The current which passes through a pure inductance will not be in phase with the applied voltage, but rather will lag behind the applied voltage 90 degrees.

Assuming that there is no resistance in the circuit shown at A, Fig. 20, the opposition offered to the passage of the alternating current through the circuit is due entirely to the inductive reactance of the coil. In Lesson 10 we learned that when a changing current passes through a coil, a counter voltage will be induced within the coil and that this self-induced counter voltage always opposes any change in the current. Since the current passing through the coil in Fig. 20 is an alternating current, every *change* of the alternating current will cause a counter voltage to be induced within the coil. When the current is rising, the self-induced counter voltage within the coil attempts to prevent the rise, thus causing the current to attain its maximum value *later* than the applied voltage. As a result, the current increase through the coil will lag behind the voltage increase during the time elapsing from zero to 90 degrees. From 90 to 180 degrees, the applied voltage is decreasing. As the current attempts to fall, the counter voltage of self-induction opposes the decrease and tends to maintain the current above zero. As a result, the current decrease will lag behind the voltage decrease from 90 to 180 degrees.

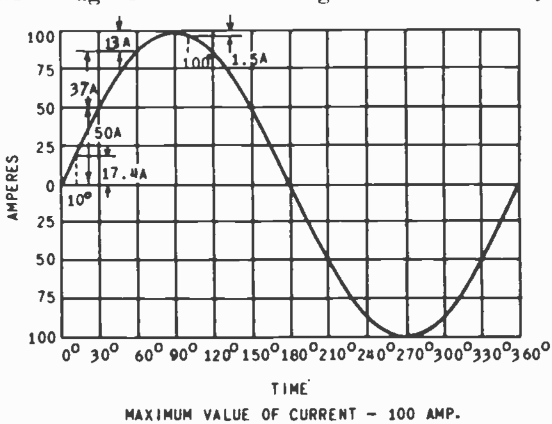


Fig. 21 Diagram to illustrate "rate of change".

12. WHY THE CURRENT LAG IN A PURE INDUCTIVE CIRCUIT IS 90 DEGREES. If it were not for the self-induced counter voltage within the coil, this current lag behind the applied voltage would not occur. In Fig. 19, where the only opposition in the circuit was pure resistance, the current and voltage were directly in phase with each other. Due to the complete absence of resistance and the presence of nothing except inductive reactance in Fig. 20, the current is caused to lag 90 degrees behind the applied voltage. Let us see why the counter voltage produced in a pure inductance causes the 90-degree phase difference between the current and voltage. First, we must learn what is meant by the expression "rate of change".

The single sine wave shown in Fig. 21 will be used to illustrate "rate of change". The rate of current change is defined as "the change in amperes per degree". By inspection, it is apparent that the instantaneous value of the current is constantly changing. The change from zero to 30 degrees is 50 amperes, the change from 30 to 60 degrees is approximately 37 amperes and the change from 60 to 90 degrees is approximately 13 amperes. It will be noticed that as the current progresses from 0 to 90 degrees, the change in amperes per degree is gradually decreasing. Upon reaching 90 degrees, the instantaneous rate of change is zero, which means that for the small fraction of a second elapsing at the peak of the positive alternation, the current remains steady. After passing 90 degrees, the current begins decreasing slowly at first, then gradually gains speed during each succeeding degree. Upon reaching 180 degrees, the current is changing in value at a very rapid rate. The greatest rate of current change occurs at 180 degrees and 0 degrees. To illustrate, during the 10-degree interval from 0 to 10 degrees, the current changes from 0 to 17.4 amperes, and during the 10-degree interval from 90 to 100 degrees, the current changes from 100 amperes to 98.5 amperes. The total current change from 90 to 100 degrees is 1.5 amperes and the change from 0 to 10 degrees is 17.4 amperes. Since an equal number of degrees was considered in each case, upon dividing 17.4 by 1.5, it is found that the current changes 11.6 times as fast (as an average) when it is near 0 than it does when it is near 90 degrees. Hence, the rate of current change (change in amperes per degree) is fastest when the current is passing through zero and slowest when the current is passing through the peak of the positive alternation. These same statements apply to the negative alternation.

One of the fundamental laws of induction states: *The strength of an induced voltage depends upon the speed of the magnetic field change.* Since the magnetic field around a coil winding depends upon the current and, since any current change will cause a corresponding magnetic field change, it follows that the magnetic field around a coil will be changing fastest when the current is passing through zero and will be changing slowest when the current is passing through its maximum amplitude on either the positive or negative alternation. Having previously learned that the self-induced voltage depends on the speed of the magnetic field changes, we now conclude that the counter voltage generated within a coil will be *maximum* when the current is passing through zero and that the self-induced counter voltage will be zero when the current is at its peak value on the positive or negative alternations.

A counter voltage produced by self-induction in a coil will always lag 90 degrees behind the current passing through the coil. The preceding example, wherein it was illustrated that the counter voltage depends upon the rate of current change, should be sufficient to prove this fact. Reference to Fig. 22 will show the relationship between the applied voltage, the current and the counter voltage in a coil when the resistance of the coil is zero. *With zero resistance, the counter voltage will always be exactly 180 degrees out of phase with the applied voltage;* that is, the counter voltage will be bucking against or opposing the effect of the applied voltage at every instant.[1] Also, since the counter voltage lags 90 degrees behind the current passing through the coil, it follows that the current through a pure inductance always lags 90 degrees behind the applied voltage. Bear in mind that the coil must not have any resistance or capacitive effects for these statements to be true.

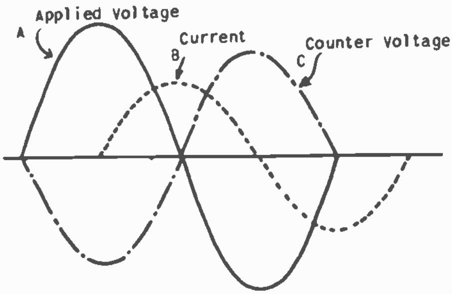


Fig.22 Illustrating the relationship between the applied voltage, the current and the counter voltage when pure inductance is present in an AC circuit.

The insertion of resistance in series with a coil has the effect of decreasing the phase difference between the applied voltage and the cou.ter voltage. For example, if a certain value of resistance were inserted in series with the coil shown at A in Fig. 20, the counter voltage would be less than 180 degrees out of phase with the applied voltage. Since the counter voltage *always* lags the current passing through the coil by 90 degrees, this will cause the phase difference between the applied voltage and the current passing through the coil to be less than 90 degrees. Adding more resistance in series with the coil will decrease the phase difference still further between the counter voltage and the applied voltage, thus moving the current more nearly in phase with the applied voltage. If a sufficiently high resistance were inserted in series with A in Fig. 20, the effect of the inductance would be almost entirely overcome and the current flowing through the circuit would be nearly in phase with the applied voltage. Taking the inductance out entirely and leaving only the pure resistance in the circuit would allow the current to be directly in phase with the applied voltage and the circuit would perform according to the facts stated in Section 10 of this lesson.

Since the current passing through an AC circuit containing a coil is never in phase with the applied voltage, the power cannot be calculated as though pure resistance alone were in the circuit. To calculate the power in this type of AC circuit, it is necessary to take "the power factor" into consideration. The method of determining the power factor will be discussed later in this lesson.

13. **CAPACITANCE IN AN AC CIRCUIT.** A condenser, as previously explained, functions in an electrical circuit as though it were a "storage house" for electricity. A voltage impressed across a condenser will cause the condenser to become charged. A charged con-

[1] This fact is a direct application of Lenz's Law.

denser has a quantity of electricity (coulombs) stored within it. Upon discharge, the condenser releases this stored energy back into the circuit. This "storage" action of a condenser is the important electrical function of it and, in all cases when a condenser is inserted in an electrical circuit, its purpose will be to store and expend electrical energy as the voltage across it varies.

A brief review of the action of a condenser in an AC circuit is advisable at this time. Referring to A in Fig. 23, when brush 1 of the generator is positive and brush 2 negative, current will be forced into the lower plate B of the condenser and drawn from the upper plate A. The condenser will become charged to the peak voltage of the generator when a sufficient amount of current has passed from A to B. This is 100 volts. Now as the applied voltage decreases, the condenser discharges and current flows from plate B around through the generator to plate A. The amount of current which flows during the charge and discharge depends upon the rate of the voltage change. In Fig. 21, the "rate of current change" was illustrated. It was found that the current changed most rapidly when passing through zero and changed slowest when at the peak of the alternation. The same is true with an AC voltage. An AC voltage is changing slowest at its maximum amplitude and changing fastest as it passes through zero (0, 180 and 360 degrees).

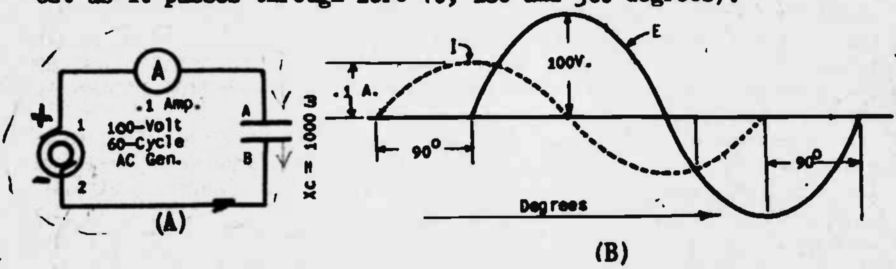


Fig. 23 (A) Pure capacity in an AC circuit.
(B) Current is leading the applied voltage 90°.

The amount of AC current effectively flowing through a condenser depends upon the *rate of voltage change* when the condenser is charging and when it is discharging; hence, the current will be zero when the voltage is maximum, because at this instant there is no voltage change. Likewise, the current will be maximum when the applied voltage is passing through zero, because at this instant the voltage is passing through its greatest rate of change. It follows that: *In a pure capacitive circuit (one containing no inductance or resistance), the current will be 90 degrees out of phase with the applied voltage.*

In a pure inductive circuit, the current lags the applied voltage 90° due to the opposition offered by the counter voltage to the *current changes*. In a circuit containing a condenser, the capacitive reactance causes an opposition to the *voltage changes* across the condenser. *In a pure capacitive circuit, the opposition offered to these voltage changes causes the voltage to lag 90 degrees behind the current flowing through the circuit.* This statement is the same as: *In a pure capacitive circuit, the current will be leading the applied voltage 90 degrees.*

The phase relations in a pure inductive and in a pure capacitive circuit should be carefully studied and remembered. It will be noticed that inductance and capacitance produce exactly opposite effects on the phase difference between the current flowing through the circuit and the applied voltage. Whereas pure inductance causes a 90-degree *current lag*, pure capacitance causes a 90-degree *current lead*. A sine wave illustrating the phase difference between the applied voltage and current flowing through a pure capacitive circuit is shown at B in Fig. 23. This illustration should be compared with B in Fig. 20 and the difference between the position of the current with respect to the voltage should be noticed.

When discussing the pure inductive circuit, it was stated that the circuit will always have a certain amount of resistance because the coil winding is composed of conductors; hence, it is impossible in practical circuits to ever secure a current lag of exactly 90 degrees. This same is true in a capacitive circuit. The plates of the condenser offer a slight resistance to current flow and the connecting wires from the condenser to the generator also possess resistance. Since a slight amount of resistance will *always* be present in any capacitive circuit, it is impossible to secure an exact 90-degree current lead. It is possible to approach the 90-degree limit much more closely in a capacitive circuit than in an inductive circuit, because the slight amount of resistance due to the connecting wires and the resistance of the condenser plates is nearly negligible.

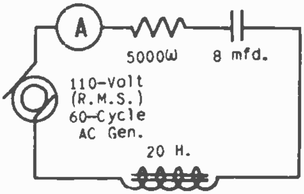
The counter voltage and applied voltage in a pure inductive circuit were shown to be exactly 180 degrees out of phase. The same is true in a pure capacitive circuit; that is, the counter voltage, due to the back pressure exerted by the charging and discharging condenser, will always be 180 degrees out of phase with the applied voltage if the circuit contains nothing but pure capacity. The insertion of resistance in series with a capacitive circuit tends to reduce the phase displacement between the applied voltage and the counter voltage to somewhat less than 180 degrees. Since the counter voltage in a capacitive circuit *always* leads the current by 90 degrees, the phase difference between the applied voltage and the current will be somewhat less than 90 degrees when resistance is inserted.

14. RESISTANCE, INDUCTANCE AND CAPACITANCE IN AN AC CIRCUIT. Since resistance, inductance and capacitance all have different effects on the phase displacement between the applied voltage and the current, let us see what the combined effects will be when all three of these are introduced into the same electrical circuit. If the inductive reactance in the circuit is predominating over the capacitive reactance in the circuit, the effect of the inductance (which is to cause a current lag) will be greater than the effect of the capacitance (which is to cause a current lead). The result will be that the current flowing through the circuit will be lagging the applied voltage. Similarly, if the capacitive reactance is higher

than the inductive reactance, the current flowing through the circuit will be leading the applied voltage. It is to be understood that the relative effects of inductance and capacitance are determined by their relative reactances.

When the reactance of the condenser in a circuit happens to be equal to the reactance of the coil ($X_L = X_C$), the effect of one will cancel the effect of the other; then only the pure resistance in the circuit will oppose the current passing through the circuit. If resistance alone is offering opposition, the current will be directly in phase with the applied voltage and the relationship as expressed by Ohm's Law ($I = E \div R$) will be true. As long as there are reactive effects in the circuit in addition to the resistance, Ohm's Law cannot be applied directly in this form because of the difference in nature between the opposition offered by a resistance and the opposition offered by either an inductance or capacitance.

Fig.24 AC circuit containing inductance, capacitance and resistance.



This information can be more firmly fixed in mind by working out an example. Fig. 24 shows an AC circuit containing an inductance of 20 henries, a capacity of 8 microfarads and a 5,000-ohm resistance. The frequency of the voltage applied to this circuit is 60 cycles. First calculating the inductive reactance of the 20-henry coil, we have:

$$X_L = 6.28 \times F \times L$$
$$= 6.28 \times 60 \times 20$$
$$= 7{,}536 \text{ ohms.}$$

Calculating the capacitive reactance of the condenser, we have:

$$X_C = \frac{1}{6.28 \times F \times C}$$

$$= \frac{1}{6.28 \times 60 \times .000008}$$

$$= 331.7 \text{ ohms}$$

Now since the 7,536 ohms of inductive reactance are tending to cause a current *lag* through the circuit and the 331.7 ohms capacitive reactance are tending to cause a current *lead* through the circuit, it is quite obvious that the greater magnitude of the inductive reactance will overcome the effect of the capacitive reactance resulting in the current through the circuit lagging behind the applied voltage.

In the aforementioned circuit, if the size of the series condenser is decreased, its reactance will become greater and the capacitive reactance will more nearly equal the inductive reactance. Suppose, for example, that the size of the condenser is reduced until the capacitive reactance of the condenser is 7,536 ohms. By calculating the capacitive reactance of a .35 microfarad condenser at a frequency of 60 cycles, it will be found very close to 7,536. When the capacitive reactance in the circuit is made equal to the inductive reactance, the effect of the capacitance, which tends to cause a current lead, will be equal to the effect of the inductance, which tends to cause a current lag. Since they are both equal (and opposite), the result will be that the current flows directly in phase with the applied voltage and only the 5,000-ohm resistance in the circuit will oppose the flow of current.

The condition of an electrical circuit, wherein the reactances of the inductance and capacitance are made equal to each other, is commonly known as "resonance". The importance of "resonance" will be discussed fully in succeeding lessons where applications are necessary.

Continuing with the circuit shown in Fig. 24, if the size of the condenser is decreased to a value less than .35 microfarads, the capacitive reactance in the circuit would be greater than the inductive reactance. With capacitive reactance predominating, the current flowing through the circuit will *lead* the applied voltage. Further calculations involving Fig. 24 will be continued later in this lesson.

Summarizing the foregoing information, the important facts to be remembered are:

1. Resistance in an AC circuit causes no phase displacement between the applied voltage and the current flowing through the circuit.

2. When inductive reactance is predominating in an AC circuit, the current will lag behind the applied voltage.

3. When capacitive reactance is predominating in an AC circuit, the current will lead the applied voltage.

15. **IMPEDANCE.** In some of the previous discussions, we have made the statement that Ohm's Law (I = E ÷ R) cannot be applied directly to an alternating current circuit, when there is a predominance of inductive reactance or capacity reactance in the circuit. The reason for this statement is that the resistance (frictional or ohmic resistance) is not the only opposition offered to the passage of current through a circuit wherein inductance or capacitance exists. The reactive effects of the inductance and capacitance must be taken into consideration as well as the ohmic resistance. When an electrical circuit contains:

1. Inductance and resistance;
2. Capacitance and resistance; or
3. Inductance, capacitance and resistance;

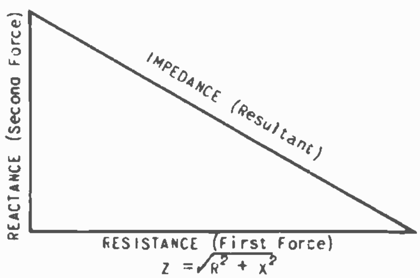
it is necessary to combine these different forms of opposition in order to find the *total opposition* which will be offered to the passage of current through the circuit. *This total opposition offered by reactance and resistance to the flow of an alternating or changing current is called impedance.*[1] The word "*impedance*" is a collective term, meaning that it takes into consideration all of the opposition contained in the circuit.

At first thought it might be assumed that the impedance can be found by computing the sum of the resistance and the reactances. This is a misapprehension and a little reasoning will make it very apparent. The effect of either inductive or capacitive reactance is to displace the current 90 degrees from the applied voltage; whereas, the effect of resistance is to keep the current in phase with the applied voltage. The reactance (capacitive or inductive) and resistance are not *in phase* with each other, insofar as they oppose the current; hence, it is quite obvious that they cannot be added directly to obtain the impedance. Instead of adding directly, it is necessary to consider them as two forces acting at right angles to each other. According to one of the fundamental physical laws: *when two forces are acting at right angles to each other, the resultant force will be equal to the square root of the sum of the squares of the two forces.* This can be expressed as follows:

$$\text{Resultant Force} = \sqrt{(\text{First Force})^2 + (\text{Second Force})^2}$$

The triangle shown in Fig. 25 is generally used to represent this

Fig.25 Triangle illustrating the calculation of impedance.



relation. From the study of high school geometry, the student will recall the Pythagorean Theorem. This theorem states: *The hypotenuse of a right-angle triangle is equal to the square root of the sum of the squares of the other two sides.* The Pythagorean Theorem and the Fundamental Law of Forces both serve to prove that when two forces are at right angles, the resultant will be equal to the square root of the sum of their individual squares.

Applying this principle to the electrical circuit, *the impedance or total opposition offered to the passage of an electric current through an AC circuit will be equal to the square root of the resistance squared plus the reactance squared.*

$$\text{Impedance} = \sqrt{(\text{Resistance})^2 + (\text{Reactance})^2}$$

[1] The letter "Z" is used to abbreviate impedance.

Expressed as a formula, this is:

$$Z = \sqrt{R^2 + X_N^2}$$

Where:
- Z is the impedance in ohms.
- R is the resistance in ohms.
- X_N is the net reactance in ohms.

The net reactance[1] to be used for the calculation of impedance in the above formula is the *difference* between the inductive and capacitive reactance in the circuit. If only inductive reactance is contained in the circuit, then naturally this is the only value to be considered. Likewise, if capacitive reactance alone is present in the AC circuit, its value may be substituted directly for X_N in the impedance formula. But, if both inductive and capacitive reactance are present in the circuit, since they are exactly opposite and tend to cancel each other, the *difference* between them must be substituted for X_N in the impedance formula. Thus:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

Where: $X_L - X_C = X_N$

It will be noted in Fig. 25 that the impedance is represented by the hypotenuse while the resistance and net reactance are represented by the other two sides of the triangle.

16. OHM'S LAW FOR AC CIRCUITS. Since the impedance of an AC circuit is the total opposition in the circuit, considering both resistance and reactance, it may be substituted directly in Ohm's Law for R. This makes it possible to calculate the current flowing through an AC circuit when the applied voltage and the impedance are known. Likewise, if the current passing through an AC circuit is measured by an AC milliammeter and, if the impedance of the entire circuit is calculated, it will be possible to multiply these two values to secure the R.M.S. voltage applied to the circuit. These relations between the voltage, current and impedance in an AC circuit are represented by the following formulas:

$$E = I \times Z$$

$$I = E \div Z$$

$$Z = E \div I$$

Where: E and I are the R.M.S. values of the AC current and voltage.

Example 1: The resistance of a coil is measured by an ohmmeter and found to be 5 ohms. The inductive reactance of the coil is calculated as 25 ohms. Find the impedance.

First, square the 5-ohm resistance, $5 \times 5 = 25$; then square the 25 ohms inductive reactance, $25 \times 25 = 625$. Adding the resistance squared (25) to the reactance squared (625), we have:

[1] The symbol X_n is used to abbreviate net reactance.

$$25 + 625 = 650$$

Extracting the square root of 650:

$$\sqrt{650} = 25.49$$

The impedance of the coil is 25.49 ohms. Notice that the 5 ohms of resistance has not caused much increase above the 25 ohms inductive reactance in the total impedance of the coil. In some cases this slight increase in opposition caused by the presence of the resistance is negligible, while in others it *must* be considered.

Example 2: The resistance of a 2-henry coil is found to be 10 ohms. What is the impedance of this coil to a frequency of 60 cycles?

To solve this problem, it is first necessary to calculate the inductive reactance of the coil. The inductance and frequency are given, so the inductive reactance equals:

$$6.28 \times 2 \times 60 = 753.6 \text{ ohms}$$

To find the impedance, the resistance must be squared:

$$10 \times 10 = 100$$

Then, squaring the inductive reactance, we have:

$$753.6 \times 753.6 = 567{,}912.96$$

Adding the resistance squared to the reactance squared, we have 568,012.96! The impedance will be the square root of this number. Extracting the square root, we find the impedance to be 753.667 ohms. If the voltage applied to the coil were known, it would be possible to calculate the amount of AC current passing through the coil by dividing this impedance value into the applied voltage.

Example 3: The example given in Fig. 24 can be carried further now that we have learned the method of calculating the impedance of a coil. In this circuit, we found that the inductive reactance was 7536 ohms and the capacitive reactance, 331.7 ohms. Before calculating the impedance, it is necessary to find the difference between the inductive and the capacitive reactance. This gives the net reactance in the circuit:

$$7536 - 331.7 = 7204.3 \text{ ohms}$$

The resistance was given as 5,000 ohms in this problem, so to find the impedance, first square the resistance:

$$5{,}000 \times 5{,}000 = 25{,}000{,}000$$

Then square the net reactance:

$$7204.3 \times 7204.3 = 51{,}901{,}938.49$$

Adding these two squared values together, we obtain 76,901,938.49

The impedance is then found by extracting the square root of this number. Taking the square root, we find the impedance to be approximately 8,769 ohms.

$$Z = \sqrt{R^2 + X_L^2}$$

$$= \sqrt{(5,000)^2 + (7204.3)^2}$$

$$= \sqrt{25,000,000 + 51,901,938.49}$$

$$= \sqrt{76,901,938.49}$$

$$= 8,769 \text{ ohms (approx.)}$$

Notice in this example that the resistance is fairly high compared to the reactance and that it does have appreciable effect toward increasing the total impedance above the value of the reactance. Since the applied voltage was given as 110 volts, it is possible to calculate the amount of AC current flowing through this circuit by dividing the total impedance (8,769 ohms) into the applied voltage of 110 volts:

$$I = \frac{E}{Z}$$

$$= \frac{110}{8,769}$$

$$= .0125 \text{ ampere or } 12.5 \text{ ma.}$$

Example 4: The circuit shown in Fig. 26 illustrates capacitance and resistance in the same electrical circuit. The resistance of this circuit is 100 ohms and the capacitance is 6 mfd.

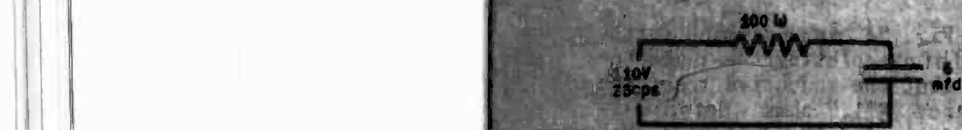


Fig. 26 AC circuit containing capacitance and resistance.

R = 100 ω
Xc = 1062 ω
Z = 1066.6ω
I = .103 Amperes

Calculating the capacitive reactance of the condenser:

$$X_c = \frac{1,000}{6.28 \times .025 \times 6}$$

$$= 1062 \text{ ohms}$$

Squaring Xc and R, we have:

$$X_c^2 = 1062^2 = 1,127,844$$

$$R^2 = (100)^2 = 10,000.$$

Adding reactance squared to resistance squared:

$$1,127,844 + 10,000 = 1,137,844$$

$$Z = \sqrt{1,137,844}$$

$$= 1066.6 \text{ ohms}$$

Now, divide the impedance into the applied voltage to find the current:

$$I = \frac{E}{Z}$$

$$= \frac{110}{1066.6}$$

$$= .103 \text{ ampere}$$

17. POWER IN AN AC CIRCUIT. In a DC circuit, the voltage applied to the circuit and the current flowing through the circuit are always of a constant value. The power at every instant in a DC circuit can be found by taking the product of the voltage and the current. This relationship is expressed by the formula:

$$W = E \times I$$

Where: W is the DC power in watts
E is the DC voltage in volts
I is the DC current in amperes

If the current flowing through a circuit is pulsating or alternating, the instantaneous power will vary at every voltage and current change.

In Fig. 27, the voltage applied to an AC circuit is shown by

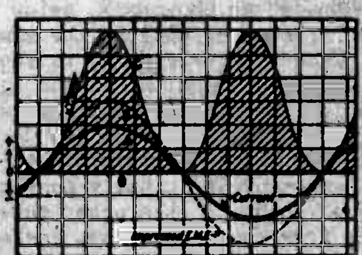


Fig.27 Power (curve C) in an AC circuit when the current (curve A) and voltage (curve B) are in phase.

the sine wave B and the current passing through the same circuit is shown by the sine wave A. As can be seen, the current and voltage are directly in phase with each other, so this represents an AC circuit in which only pure resistance is opposing the current flow. The instantaneous power is always equal to the product of the instantaneous voltage and the instantaneous current. The power in this AC circuit is represented by the shaded curve C. On the negative alternation, when both the current and voltage are in the opposite direction, the power will still be positive. This results from a fundamental rule of mathematics which states: When negative values are multiplied by negative values, the product will be positive.

Fig. 28 illustrates an AC circuit when the current lags 30 de-

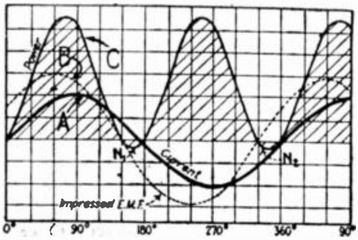


Fig.28 Power in an AC circuit when the current is lagging 30° behind the applied voltage.

grees behind the applied voltage. The current is shown by the solid line A and the voltage is shown by the dotted line B. When the current and voltage are both positive or both negative, their product will be positive; however, when the current is positive and the voltage is negative, or when the voltage is positive and the current is negative, the product of the two numbers will be negative. It will be noticed that from zero to 150 degrees, the current and voltage are both positive; hence, their products result in "positive power" as represented by curve C above the zero line. From 150 to 180 degrees, the current is positive, but, the voltage is negative; hence, the product of the positive current and negative voltage results in "negative power" as represented by the portion of the curve marked N_1 below the zero line. After passing 180 degrees, the current and voltage are both negative so their product gives "positive power" again. From 330 degrees to 360 degrees, the current is negative and the voltage is positive. Their product results in "negative power" as shown by N_2 below the zero line. The succeeding cycles, of course, will be the same.

When the power curve is above the zero line, power is being drawn or taken from the source (generator) and when the power curve is below the zero line, power is being delivered back to the generator. In Fig. 28, 86.5% of the power curve lies above the zero line. This indicates that this percentage of the power taken from the generator is actually consumed in the circuit. The remaining 13.5 per cent of the power curve represents power which has been taken from the source, but instead of being consumed or used in the circuit, it is delivered back to the generator. These percentages have been accurately calculated and cannot be secured easily from a graph.

The power delivered from the circuit back to the generator is not available in the circuit for doing work. This unused power must be deducted from the total power originally taken from the source, if we are to know the exact amount of power available in the circuit for doing work. The effective power in the circuit (power available to do work) is found by use of the "power factor". When expressed as a percentage, *the power factor is defined as the percentage of AC power taken from the source that is actually doing work in the circuit*. There are several methods of calculating the power factor in an AC circuit. In all cases it depends upon the angle of phase displacement between the voltage and the current. We have previously found that the angle of phase displacement (in degrees) depends upon the magnitude of the inductive or capacitive reactance in comparison to the resistance. The angle of phase displacement will be close to zero when the resistance (by comparison) is extremely high. When the inductive or capacitive reactance is extremely high in comparison to the resistance, the angle of phase displacement will be close to 90 degrees.

PHASE ANGLE	POWER FACTOR	PHASE ANGLE	POWER FACTOR
0°	1.0000	46°	.6947
1	.9998	47	.6820
2	.9994	48	.6691
3	.9986	49	.6561
4	.9976	50	.6428
5	.9962	51	.6293
6	.9945	52	.6157
7	.9925	53	.6018
8	.9903	54	.5878
9	.9877	55	.5736
10	.9848	56	.5592
11	.9816	57	.5446
12	.9781	58	.5299
13	.9744	59	.5150
14	.9703	60	.5000
15	.9659	61	.4848
16	.9613	62	.4695
17	.9563	63	.4540
18	.9511	64	.4384
19	.9455	65	.4226
20	.9397	66	.4067
21	.9336	67	.3907
22	.9272	68	.3746
23	.9205	69	.3584
24	.9135	70	.3420
25	.9063	71	.3256
26	.8988	72	.3090
27	.8910	73	.2924
28	.8829	74	.2756
29	.8746	75	.2588
30	.8660	76	.2419
31	.8572	77	.2250
32	.8480	78	.2079
33	.8387	79	.1908
34	.8290	80	.1736
35	.8192	81	.1564
36	.8090	82	.1392
37	.7986	83	.1219
38	.7880	84	.1045
39	.7771	85	.0872
40	.7660	86	.0698
41	.7547	87	.0523
42	.7431	88	.0349
43	.7314	89	.0175
44	.7193	90	.0000
45	.7071		

Fig. 29 Power Factor Table. The angle of phase difference (phase angle) can be determined if the power factor is known and the power factor can be determined if the phase angle is known.

The simplest method of determining the power factor (expressed as a decimal) when the resistance and the impedance of the AC circuit are known is to divide the resistance by the impedance. This is expressed by the formula:

$$\text{Power Factor} = \frac{R}{Z}$$

The power factor is less than 1 (in decimal form);
Where: R is the resistance of the circuit in ohms;
Z is the impedance of the circuit in ohms.

Example: What is the power factor if the impedance of an AC circuit is 100 ohms and the resistance is 10 ohms?

Solution: Dividing 10 (R) by 100 (Z), the decimal .1 is obtained. The power factor is .1, or if expressed in percentage, is 10%.[1]

This means that 10% of the power taken from the generator by this circuit is actually consumed or used in doing work; the remaining 90% is delivered back to the generator. By referring to the Power Factor Table shown in Fig. 29, it can be seen that a phase angle of approximately 84 degrees corresponds to a power factor of .1 (one-tenth). Therefore, in this circuit, the current will be about 84 degrees out of phase with the applied voltage. Whether the current is leading or lagging the voltage is determined by nature of the reactance; that is, whether it is inductive or capacitive.

In Fig. 30, a simple AC circuit, consisting of a coil and resistor in series, is shown. Let us find the current lag through

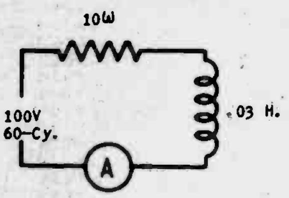


Fig. 30 AC circuit containing inductance and resistance.

this circuit. The procedure is as follows:

Step 1: Find the inductive reactance of the .03-henry coil.

$$X_L = 6.28 \times F \times L$$
$$= 6.28 \times 60 \times .03$$
$$= 11.3 \text{ ohms}$$

Step 2: Find the impedance of the circuit.

$$Z = \sqrt{R^2 + X_L^2}$$

[1] To express a decimal fraction in percentage, multiply the decimal by 100 and attach the % sign. Thus, .78 is 78%; .932 is 93.2%; .0461 is 4.61%.

$$= \sqrt{10^2 + 11.3^2}$$

$$= \sqrt{227.69}$$

$$= 15.08 \text{ ohms}$$

Step 3: Find the power factor of the circuit.

$$P.F. = \frac{R}{Z}$$

$$= \frac{10}{15.08}$$

$$= .6631 \text{ or } 66.31\%$$

Step 4: Find the angle of phase displacement.

Locate the number .6631 in the Power Factor Table. This number is not given exactly, but lies between the given numbers .6561 and .6691. These two numbers correspond to the phase angles of 49 and 48 degrees respectively, so the angle of phase displacement is between 48 and 49 degrees when the power factor is .6631. Since the circuit shown in Fig. 30 is inductive, the current is lagging approximately 48.5 degrees.

When the power factor of a circuit is known, the effective power can be calculated. In Fig. 30, the applied voltage is given as 100 volts. The current flowing through the circuit can be found by dividing this voltage by the impedance of the circuit, thus:

$$I = \frac{E}{Z}$$

$$= \frac{100}{15.08}$$

$$= 6.63 \text{ amperes}$$

The product of the applied voltage and the current gives the power which is being taken from the generator. This is NOT the effective power and, to prevent confusion, we will call it the "apparent power". Thus:

$$W_{app} = E \times I$$

$$= 100 \times 6.63$$

$$= 663 \text{ watts.}$$

Where: W_{app} is the apparent power in watts
E is the R.M.S. voltage
I is the R.M.S. current

The apparent power multiplied by the power factor gives the effective power.

$$W_{eff} = W_{app} \times P.F.$$

Where: W_{eff} is the effective power in watts
W_{app} is the apparent power in watts
P.F. is the power factor expressed in a decimal

Substituting the known values in this equation, we have:

$$W_{eff} = 663 \times .6631$$
$$= 439.63 \text{ watts}$$

Hence, the circuit shown in Fig. 30 is capable of performing 439.63 watts of electrical work. Disregarding other resistance in the circuit, there will be 439.63 watts of heat produced in the 10-ohm resistor.

After completing these calculations on Fig. 30, it is apparent that if we had not taken the phase displacement and power factor into consideration, we would have arrived at the conclusion that the circuit contained 663 watts of power instead of 439.63 watts. This difference is entirely too great to be disregarded in practical work. In all AC circuits, therefore, the product of the meter readings (voltage and current) is by no means an indication of the true effective AC power in the circuit. The product of the meter readings is called the "apparent power" and it must be multiplied by the power factor before the effective power is to be known. The power factor in turn depends upon the inductive reactance, capacitive reactance and resistance in the circuit.

Now that we have learned the method of calculating the power factor, determining the effective power and finding the angle of phase displacement, let us continue with the solution of the problem in Fig. 24. For convenience, this same figure is reproduced

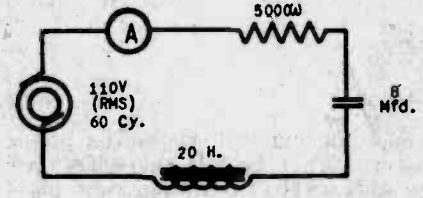


Fig. 31 AC circuit containing inductance, capacitance and resistance. (This is a reproduction of Fig. 24.)

as Fig. 31. The values calculated so far are:

$$X_L = 7{,}536 \text{ ohms}$$
$$X_C = 331.7 \text{ ohms}$$
$$X_N = 7{,}204.3 \text{ ohms}$$
$$Z = 8{,}769 \text{ ohms}$$
$$I = .0125 \text{ ampere}$$

Continuing with this circuit, it is next necessary to calculate the power factor. The impedance was found to be 8,769 ohms and the resistance was given as 5,000 ohms. Dividing the resistance by the impedance:

$$P.F. = \frac{5,000}{8,769}$$

$$= .5702 \text{ or } 57.02\%$$

The angle of phase displacement may be determined by referring to the Power Factor Table. In this table, locate the number nearest .5702. This is found to be .5736 and corresponds to a phase angle of 55 degrees. Since the table does not indicate whether the current is leading or lagging, it is necessary to refer back to the original values of the inductive and capacitive reactance. The inductive reactance was 7536 ohms whereas the capacity reactance was only 331.7 ohms, so the current is lagging behind the applied voltage 55 degrees. (Predominance of X_L causes current lag.)

To find the effective power in the circuit, first calculate the apparent power, then multiply by the power factor.

$$W_{app} = 110 \times .0125$$

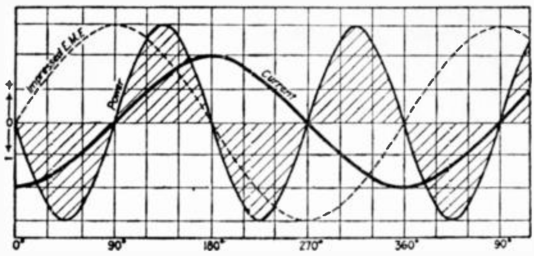
$$= 1.375 \text{ watts}$$

$$W_{eff} = 1.375 \times .5702$$

$$= .784 \text{ watt}$$

16. **WATTLESS CIRCUITS.** The student will sometimes hear a certain type of AC circuit spoken of as being "wattless".. This expression means that the power in the circuit is zero. This condition will exist when the power factor is zero and the angle of phase displacement is exactly 90 degrees. A circuit of this kind (wattless circuit) is only theoretical, because the resistance can never be completely reduced to zero. The resistance must be zero if the power factor is to be zero and the phase displacement, 90 degrees. In a theoretical "wattless" circuit, a voltmeter connected across the circuit will indicate voltage and an ammeter in series with the circuit will indicate current, but all of the power taken from the generator is delivered back to the generator. Fig. 32 illustrates the phase relation between the voltage and current and also shows

Fig.32 Illustrating the theoretical "wattless circuit".



the resulting power curve. Notice that the power curve is equal above and below the zero line, indicating that equal amounts of power are taken from and delivered back to the generator. The effective power in the circuit will be zero:

$$W_{eff} = \text{Power Factor} \times W_{app}$$

Since the Power Factor in a wattless circuit is zero:

$$W_{eff} = 0 \times W_{app}$$

$$= 0$$

Where: W_{app} and W_{eff} are the apparent power and effective power in any AC circuit when the power factor is zero.

Suggestion

Regardless of the simplicity of explanation, the study of AC circuits always appears difficult when it is first encountered by a student. The fundamental facts which have been introduced in this lesson are all essential in the formation of a secure knowledge of Radio and Television circuits. We have not discussed subjects which have no application to Radio and Television. Future lessons will frequently contain expressions and refer to formulas which are contained in this study. We realize that the enormous quantity of information which you have just completed in this lesson can not be thoroughly learned in a short length of time. Constant use and consistent application are the only methods of completely mastering this subject. Had space permitted, many more examples would have been included in this lesson; however, the study of future lessons will contain problems dealing specifically with the direct application of these various terms. When the student encounters these problems and they are not clear to him, he should immediately conduct himself through a review by returning to this lesson and repeating a study of the subject. Eventually, all of the herein contained information will be used sufficiently to establish a thorough working knowledge.

The study of AC theory is generally treated in a more mathematical manner than has been done in this lesson. We have avoided the use of this higher mathematics by giving more detailed word descriptions and approaching certain subjects from a practical side rather than purely theoretical. The elimination of higher mathematics has necessitated a more consistent use of elementary decimals and fractions with which the student is familiar. A few statements and laws have not been definitely proved simply because a proof entails the use of mathematics beyond the scope of this course.

In view of these facts, it is suggested that the student spend an average amount of time in studying this lesson, then proceed to the following lessons. REFER BACK TO THIS LESSON AT EVERY OPPORTUNITY until there is no doubt as to the comprehension of each subject discussed.

Notes

(These extra pages are provided for your use in taking special notes)

The text of this lesson was compiled and edited by the following members of the staff:

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UNIT NO. 1

RESONANT AND FILTER CIRCUITS

LESSON NO. 14

THOMAS ALVA EDISON (CONTINUED)

As you will recall, we told you in Lesson 12 that Thomas Edison had received forty thousand dollars for several of his inventions. With this capital, he opened a factory at Newark, New Jersey, and employed a force of some three hundred men.......a strong indication that he had faith in his own ability, as well as the future of electricity.

The next great achievement of Edison was the invention of his quadruplex system, which made it possible to send four telegraph messages over the same wire, two messages being sent in each direction. He received thirty thousand dollars from Western Union for this invention and immediately set forth to perfect a system that would make possible the transmission of six messages at the same time. It should be apparent to you that he was continually striving to improve upon his inventions..... always trying to make them better. This should serve as an inspiration for you to always strive to do your lessons and experiments more thoroughly, for upon the thoroughness of your training will hinge your future success.

No longer was Edison on his way to fame and fortune. He had arrived. But this did not dampen his ardor for more and more knowledge, for he continued to read and study far into the night. He loved his work and considered it as an important part of his life. If you will develop the same attitude towards your training, you will be surprised to discover that your progress will be speeded up greatly.

Electric lighting.......an achievement long sought after by eminent scientists.....was probably the one invention that brought Edison into the public eye more than any other. For months, he strived to find a filament that would not melt or break. He tried over two thousand different substances and sent one of his men more than two thousand miles up the Amazon River, while another travelled thirty thousand miles through India and China. Finally, a suitable bamboo fibre was found in Japan, but only after tireless effort and the expenditure of about one hundred thousand dollars. Again, Edison's tenacity and faith in an idea had emerged victorious......a triumph that virtually lifted the world out of darkness.

With the perfection of his carbon lamp, a factory was built to manufacture them. An electric generating station was built in New York so that the public could purchase electricity to be used for lighting, in much the same manner as they purchased gas. Today, electric utilities are a part of almost every American community; power lines cross the country in all directions, and when the sun dips under the western horizon, photoelectric cells turn on thousands of street lights and electric signs and banish grim shadows with brilliant light ....thanks to Thomas Alva Edison.

(We will tell you more about this great American in a future lesson.)

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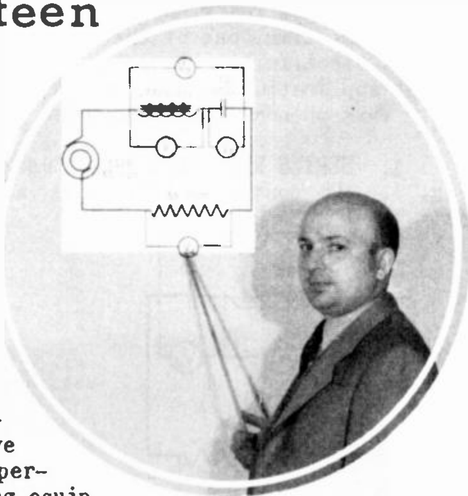
Lesson Fourteen

RESONANT and FILTER CIRCUITS



"Modern Radio and Television circuits could not function without *resonant circuits*, while if we did not have *filter circuits*, modern, AC operated receiving and transmitting equipment would be an impossibility. So even though the title of this lesson may not appear to be very impressive, I assure you that the subject covered is of great importance to the radio industry and to your future success.

"Therefore, I earnestly suggest that you seriously apply yourself to the study of this subject, now and in future lessons."

In Lesson 13, it was learned that the current flowing through a coil lags the applied voltage by 90 degrees if there is no resistance in the circuit, and that the current through a condenser leads the applied voltage by 90 degrees, also assuming that there is no resistance. Since inductive reactance and capacitive reactance have opposite effects upon the current (one tending to cause a lagging current and the other a leading current), it is possible for one type of reactance to neutralize the other type. For example, if there was 1,000 ohms of inductive reactance and 5,000 ohms of capacitive reactance in a circuit, the 1,000 ohms of inductive reactance would neutralize 1,000 ohms of capacitive reactance, leaving 4,000 ohms capacitive reactance as the net reactance of the circuit. The net reactance is the difference between the two reactances, and is found by this formula:

$$X_n = X_l - X_c \qquad (1)$$

or

$$X_n = X_c - X_l \qquad (2)$$

Where: X_n is the net reactance in ohms.
X_l is the inductive reactance in ohms.
X_c is the capacitive reactance in ohms.

Formula (1) is used when the inductive reactance is greater than the capacitive reactance and formula (2) is used when the capacitive reactance is greater than the inductive reactance.

We are now ready to consider one of the most important and, at the same time, one of the most interesting phases of alternating current electricity. It is especially interesting since it has a direct application to Radio and Television transmitters and receivers. This phenomenon is known as "resonance".

1. SERIES RESONANCE. Let us consider the circuit shown in Fig. 1. It consists of a coil, a condenser, and a resistor in

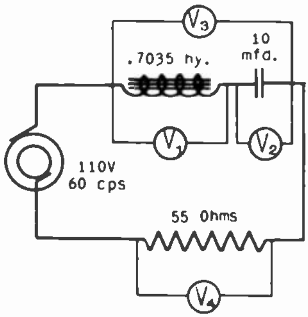


Fig. 1 Illustrating a series resonant circuit.

series with a 110-volt 60-cycle alternator. Suppose that the values of inductance and capacity have been so chosen that at a frequency of 60 cycles, the inductive reactance is exactly equal to the capacitive reactance. The impedance of a circuit, as we know, is the total opposition offered by the resistance and the net reactance of a circuit to the flow of alternating current, and is found by the formula:

$$Z = \sqrt{R^2 + X_n^2}$$

Where: Z is the impedance in ohms.
R is the resistance in ohms.
X_n is the net reactance in ohms.

Since the inductive and capacitive reactances are equal ($X_1 - X_c = 0$), there is no net reactance in this circuit. In this case, the formula for impedance becomes:

$$Z = \sqrt{R^2}, \text{ or } Z = R$$

There now exists this peculiar situation; the circuit contains a coil and a condenser, yet the only opposition to the flow of current is the ohmic resistance of the circuit. Let us assign some values to the circuit elements and calculate the amount of current that flows. The alternator has a voltage of 110 volts at a frequency of 60 cycles, and the resistor has a value of 55 ohms. The coil has an inductance of .7035 henry, and the condenser a capacity of 10 mfd. By computation, the inductive reactance of the coil and the capacitive reactance of the condenser are each found to be 265 ohms. The net reactance is:

$$X_n = 265 - 265 = 0 \text{ ohms.}$$

Substituting these quantities in the formula for impedance, we have:

$$Z = \sqrt{55^2 + 0^2}$$

$$= \sqrt{55^2}$$

$$= 55 \text{ ohms.}$$

Thus, the total impedance of this circuit is equal to its ohmic resistance. To find the amount of current flowing, use Ohm's Law.

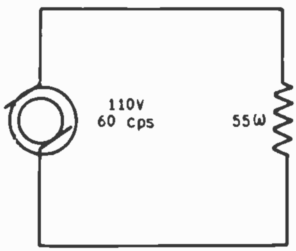
$$I = \frac{E}{R}$$

$$= \frac{110}{55}$$

$$= 2 \text{ amperes.}$$

The capacitive reactance has exactly balanced out or neutralized the inductive reactance of this circuit. If a wire were connected from the left end of the coil to the right end of the condenser, thus shorting them out, the same amount of current (2 amperes) would flow. The circuit would then be equivalent to Fig. 2. This condition is known as "series resonance".

Fig.2 This circuit is equivalent to that of Fig.1 under the resonant condition.



Since the same current flows whether the coil and condenser are in the circuit or not, why use them? The answer to this question may be found by a little thought. If the coil and condenser are shorted out, there will be 2 amperes of current flowing in this circuit as long as the applied voltage is 110 volts, regardless of its frequency. When the coil and condenser are in the circuit, however, a much different condition exists. Suppose that the frequency of the alternator is lowered to 50 cycles. With a lower frequency, the inductive reactance is smaller and the capacitive reactance greater. By calculation we find that the inductive reactance is 221 ohms and the capacitive reactance 318 ohms at 50 cycles. They are no longer equal and cannot exactly neutralize each other; so there must be some net reactance present in the circuit. This net reactance is:

$$X_n = 318 - 221$$
$$= 97 \text{ ohms}$$

Using the formula to calculate the impedance of the circuit, we have:

$$Z = \sqrt{55^2 + 97^2}$$
$$= \sqrt{12434}$$
$$= 111 \text{ ohms}$$

Then, using Ohm's Law to find the amount of current flowing, we have:

$$I = \frac{110}{111} = 1 \text{ ampere (approximately)}$$

If the frequency of the alternator is increased to 70 cycles, the inductive reactance is greater and the capacitive reactance less. By calculation it is found that the inductive reactance is 309 ohms and the capacitive reactance 228 ohms at 70 cycles. This gives a net reactance of:

$$X_n = 309 - 228$$
$$= 81 \text{ ohms}$$

This makes the impedance:

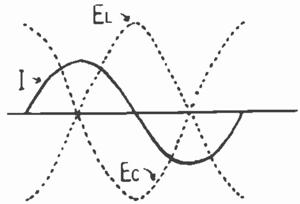
$$Z = \sqrt{55^2 + 81^2}$$
$$= \sqrt{9586}$$
$$= 98 \text{ ohms}$$

The amount of current that flows is:

$$I = \frac{110}{98}$$
$$= 1.12 \text{ amperes.}$$

From these calculations, it can be seen that 2 amperes flow when the frequency of the voltage source is 60 cycles, and approximately 1 ampere flows when the frequency is either 50 or 70 cycles; that is, the circuit offers less opposition to a current whose frequency is 60 cycles than it does to any other frequency, either higher or lower. This fact should be thoroughly understood. We can say that this circuit is selective; that is, it prefers the frequency of 60 cycles to all other frequencies. The frequency at which the inductive reactance is equal to the capacitive reactance is called the resonant frequency of the circuit. In this case it is 60 cycles. The inductive reactance tends to cause the current to lag the applied voltage, while the capacitive reactance tends to cause the current to lead the applied voltage. In this series resonant circuit, where the two reactances are equal, these tendencies neutralize each other and the current is in phase with the applied voltage. The self-induced voltage in the coil lags 90 degrees behind the current. Likewise, the counter-voltage built up across the condenser leads the current by 90 degrees. This condition is illustrated in Fig. 3, where E_L represents the self-induced

Fig.3 The phase relations between the current, I, the voltage across the coil, E_L, and the voltage across the condenser, E_C.



voltage in the coil, Ec, the counter-voltage across the condenser, and I, the current. Notice that both of these voltages are 90 degrees out of phase with the current, one leading and the other lagging it. Thus the two voltages are 180 degrees or exactly out of phase with each other. When one is maximum in a positive direction, the other is maximum in a negative direction.

The sum of two AC sine waves is called their "resultant", and this resultant is, itself, a sine wave. When the two AC waves are 180 degrees out of phase, the maximum value of the resultant wave is equal to the difference between the maximum values of the two AC waves. Using the two amperes calculated as the current flowing under the resonant condition , we shall find the reactive voltage across the coil and the counter voltage across the condenser as follows:

$$E_L = I \times X_L$$
$$= 2 \times 265$$
$$= 530 \text{ volts}$$

$$E_C = I \times X_C$$
$$= 2 \times 265$$
$$= 530 \text{ volts}$$

You will probably wonder how it is possible to have 530 volts across the coil and also across the condenser when the applied voltage is only 110 volts. As previously stated, the voltage across the coil is 180 degrees out of phase with the voltage across the condenser. The resultant of these two voltages, which is the voltage across both of them, is equal to their difference. In this case, the self-induced voltage in the coil is equal to 530 volts; also the counter voltage across the condenser is 530 volts. Therefore, their difference is zero. This means that the 110 volts of the alternator is opposed only by the 110 volts set up across the

55-ohm resistor, due to the 2 amperes flowing through it. The voltmeter V_1 in Fig. 1 reads 530 volts; voltmeter V_2 also reads 530 volts. Voltmeter V_3 reads 0 volts, while V_4 reads 110 volts. The fact that the inductive reactance of the coil balances out the capacitive reactance of the condenser allows a much larger current to flow, and this current, in flowing through the inductive reactance of the coil, creates a fairly high voltage across it. Likewise, this current, in flowing through the capacitive reactance of the condenser, sets up the same high voltage across it. It is hard to believe that by applying 110 volts to a circuit, we can set up 530 volts across the coil and across the condenser; yet, the fact that these two voltages neutralize each other so far as the alternator is concerned, allows the voltage of the source to force this relatively high current through the circuit, which, in turn, makes possible the production of these high voltages.

Just how this property of a series resonant circuit can be applied to radio will be discussed in detail in Lesson 22. Series resonance is sometimes called "voltage resonance", due to the rise in voltage across the coil and across the condenser above that of the applied voltage. The important points to remember about series resonance are:

First: A series resonant circuit offers minimum opposition to current of the resonant frequency. At resonance, the inductive reactance neutralizes the capacitive reactance and the only opposition to the flow of current is the ohmic resistance in the circuit.

Second: The voltage across either the coil or condenser may be many times the applied voltage.

Before leaving the subject of series resonance, we shall describe an experiment which clearly demonstrates the fact that an inductive reactance can neutralize an equal amount of capacitive reactance. The circuit diagram is shown in Fig. 4. The condenser

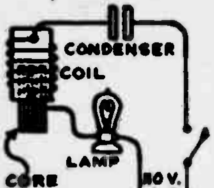


Fig. 4 An experiment to demonstrate series resonance.

should have a capacity of from 10 to 15 mfd., and may be constructed of several 1 or 2 mfd. condensers; however, they must be paper condensers, as an electrolytic condenser cannot be used with alternating current. The coil form is a cardboard tube 3 inches in diameter and 12 inches long. On it are wound from 800 to 1,000 turns of #18 double cotton covered wire. Since the condenser is fixed and cannot be varied, the coil must be so constructed that its inductance may be changed in order that its inductive reactance may be made equal to the capacitive reactance of the condenser. This is done by using a soft iron core which fits inside of the cardboard tube. When the iron core is out of the tube, the inductance of the coil is low. As the soft iron is inserted into the coil, its inductance increases since the reluctance of part of the magnetic circuit is decreased. By pushing the core partially into the coil, we can secure intermediate values of inductance. When the iron core is completely within the coil, the inductance is maximum.

With the coil, condenser and lamp in series with the 110-volt 60-cycle AC line, the switch is closed. If the iron core is out of the coil, the lamp glows dimly. This indicates that the inductance of the coil is not great enough to make its inductive reactance equal to the capacitive reactance of the condenser. A piece of wire is used to short out the condenser and coil, and the lamp bulb burns with full brilliancy, illustrating that the coil and the condenser were opposing the flow of current. The shorting wire is removed and the iron core is inserted into the coil form and moved back and forth. At one certain position, it is found that the lamp again glows brightly. At this point, the inductive reactance of the coil is equal to the capacitive reactance of the condenser; hence, they are neutralizing each other. In this case, the opposition to the flow of current is determined only by the resistance of the lamp, the coil and the connecting wire, which is ordinarily low. If the iron core is pushed farther into the coil form, the brilliance of the lamp decreases. This may be explained by the fact that the inductance of the coil is made so large that its inductive reactance is greater than the capacitive reactance of the condenser.

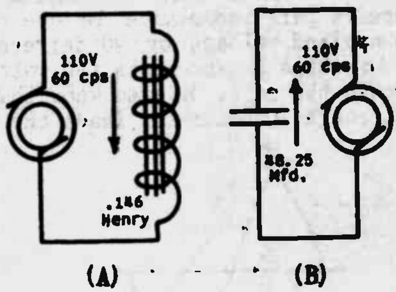


Fig.5 (A) A coil connected to an alternating voltage source.
(B) A condenser connected to an alternating voltage source.

2. **PARALLEL RESONANCE.** In Fig. 5 are shown two circuits. At A is illustrated an iron core coil connected in series with a 110-volt, 60-cycle alternator, and at B is shown a condenser connected to another alternator of the same voltage and frequency. For the present, it will be assumed that there is no resistance in either circuit; thus, the current flow in circuit A is opposed only by the inductive reactance of the coil and in circuit B, only by the capacitive reactance of the condenser. The coil has an inductance of .146 henry, and the condenser a capacity of 48.25 mfd. The inductive reactance of the coil and the capacitive reactance of the condenser are:

$$X_L = 6.28 \times 60 \times .146$$
$$= 55 \text{ ohms}$$

$$X_C = \frac{1}{6.28 \times 60 \times .00004825}$$
$$= 55 \text{ ohms}$$

Designating the current flowing through the coil by I_L and that through the condenser by I_C, we have:

$$I_L = \frac{E}{X_L}$$
$$= \frac{110}{55}$$
$$= 2 \text{ amperes}$$

$$I_C = \frac{E}{X_C}$$
$$= \frac{110}{55}$$
$$= 2 \text{ amperes}$$

We have learned that the current flowing through a pure inductance (a pure inductance is one that contains no resistance) lags the applied voltage by 90 degrees. This is illustrated in Fig. 6, in which E represents the voltage, and I_L the current flowing through the coil. We also know that the current flowing effectively through a condenser leads the applied voltage by 90 degrees if

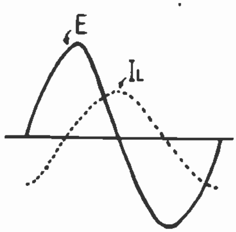


Fig.6 The phase relation between the current and voltage of the circuit shown in Fig. 5A.

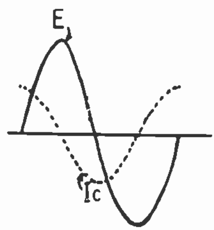


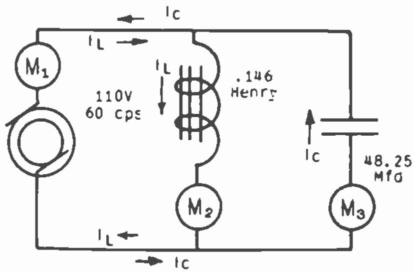
Fig.7 The phase relation between the current and voltage of the circuit shown in Fig. 5B.

there is no resistance in the circuit. This is illustrated in Fig. 7, where E is the applied voltage, and I_C the current flowing in the condenser's circuit. It is assumed that the two alternators are exactly in phase; that is, both reach a maximum positive voltage at the same instant, pass through zero at the same instant and reach a maximum negative voltage at the same instant.

Since the current through the coil lags the applied voltage by 90 degrees, and the current through the condenser leads the applied voltage by 90 degrees, then the two currents must be 180 degrees, or exactly out of phase. This can be seen by studying the two diagrams. When the coil current, I_L, is rising from zero to maximum in a positive direction, the condenser current rises from zero to its maximum in a negative direction. Or, it can be said that when current is flowing down through the coil, current will flow up through the condenser.

Now disconnect the condenser from the alternator and place it in parallel with the coil as shown in Fig. 8. Notice that a 110-

Fig.8 Illustrating a parallel resonant circuit.



volt, 60-cycle alternating voltage is still being applied to the coil and also to the condenser. The coil will, therefore, draw 2 amperes as before. Likewise, since we are using the same condenser, it will also draw 2 amperes from the alternator. It has been said that the coil current and condenser current are exactly out of phase; let us see how this affects the total current drawn from the alternator. At a given instant, there are 2 amperes flowing down through the coil from top to bottom; at the same time, 2 amperes are flowing up through the condenser from bottom to top. These are shown by the arrows drawn alongside the coil and the condenser. To clarify this, let us trace the flow of the current. During a certain instant of the cycle of alternating voltage, the 2 amperes of coil current flow out of the top terminal of the alternator to the top end of the coil, through the coil, and back to the bottom terminal of the alternator. At that same instant, the 2 amperes of condenser current flow from the bottom terminal of the alternator to the bottom of the condenser, through the condenser, and back to the top terminal of the alternator. The direction of current flow for this given instant is shown by the arrows in the diagram. Now how is it possible to have 2 amperes flowing in one direction, in the line, at the same instant that 2 amperes flow in the opposite direction? The answer to this question is that it is impossible. The 2 amperes flowing out of the top terminal of the alternator will be neutralized by the 2 amperes flowing out of the bottom terminal of the alternator and the net current flow in the line will be zero. Meter M_1 reads zero, while meters M_2 and M_3 each read 2 amperes.

Let us give this peculiar situation some thought. We have a coil and a condenser connected in parallel across a 110-volt, 60-cycle alternator. The coil draws 2 amperes; the condenser draws 2 amperes. Yet, there is no current being drawn from the alternator itself. The coil current exactly neutralizes the condenser current. In Fig. 9 are shown three sine waves. The applied voltage is represented by E, the coil current by I_L, and the condenser

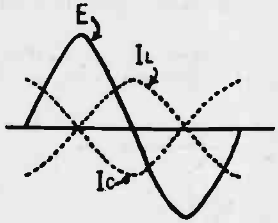


Fig.9 The phase relations of the currents and voltage of the circuit shown in Fig.8. The coil current I_L is 180° out of phase with the condenser current, I_C.

current by Ic. Notice that at every instant, the coil current and the condenser current are exactly equal, but opposite in direction or phase. The current drawn from the alternator is equal to the resultant of the coil and the condenser currents. Since I_L and Ic are exactly out of phase, their resultant is equal to the difference of their maximum values. Since they have the same maximum value, their difference is zero, which means that the current drawn from the alternator is zero. For all practical purposes, it can be stated that current surges back and forth between the coil and the condenser, charging the condenser first in one direction and then oppositely. For this condition to exist, the coil current must be exactly equal to the condenser current. Therefore, their reactances must be equal. The coil and condenser have been so chosen that the inductive reactance of one is exactly equal to the capacitive reactance of the other. Such a circuit is called a parallel resonant circuit, and the preceding phenomenon is known as parallel resonance.

The circuit just described is impossible from a practical viewpoint; that is, it was assumed there was absolutely no resistance in the circuit. The resistance of a circuit can be made very low, but it cannot be eliminated entirely. If it is considered that most of the resistance lies in the coil, as will be the case if resistance is not purposely included in the circuit, then the coil current will not lag a full 90 degrees behind the applied voltage, but by some lesser angle. This being the case, the coil current will not be exactly 180 degrees out of phase with the condenser current; therefore, the two currents cannot perfectly neutralize each other. Since complete cancellation of the two currents in the line is not possible with resistance in the circuit, there will be a small amount of current drawn from the alternator, when the resonant frequency is applied to this circuit.

As the resistance of the coil is increased, the coil current lags behind the applied voltage by a smaller phase angle. This makes the phase difference between the coil and condenser current less, and results in their cancellation being more imperfect. With a smaller degree of cancellation of these two currents, the current drawn from the alternator becomes correspondingly larger. The addition of resistance to the coil branch of the circuit increases the impedance of this branch, which results in the flow of a smaller coil current. However, even if the impedance of the coil branch were exactly equal to the impedance of the condenser branch (which would make both currents equal), yet these two currents could not perfectly neutralize each other, since they would not be exactly 180 degrees out of phase. In order to have perfect cancellation of these two currents, there would have to be absolutely no resistance in either branch of the circuit, since it is only by this means that the two currents can be made exactly out of phase. It can be said that the alternator supplies enough power to this circuit to compensate for the power dissipated by the current flowing through the resistance of the circuit.

The resonant frequency of this circuit is 60 cycles. If the frequency of the applied voltage is changed to 50 cycles, a different set of conditions will exist. The inductive reactance of the coil calculated for a frequency of 50 cycles is 45.8 ohms. The capacitive reactance of the condenser at this frequency is 66 ohms. The current flowing through the coil is:

$$I_L = 110 \div 45.8$$
$$= 2.4 \text{ amperes}$$

The condenser current is:

$$I_C = 110 \div 66$$
$$= 1.6 \text{ amperes}$$

Again assuming that the circuit contains no resistance, the coil current and the condenser current are exactly out of phase. There are, therefore, in the line leading from the alternator, two currents: one, 2.4 amperes, and the other, 1.6 amperes, and they are 180 degrees out of phase. At a given instant, there will be 2.4 amperes flowing out of the top terminal of the alternator at the same time that 1.6 amperes are flowing into the top terminal of the alternator. This results in a net current of .8 ampere (the difference between 2.4 amperes and 1.6 amperes), which flows out of the top of the alternator toward the parallel combination at the instant under consideration. Meter M_1 reads .8 amperes; meter M_2, 2.4 amperes; meter M_3, 1.6 amperes. This circuit illustrates the effect of applying to a parallel resonant circuit, a voltage whose frequency is less than the resonant frequency of the circuit. At a frequency lower than resonance, the inductive reactance of the coil is less than the capacitive reactance of the condenser. Therefore, the coil will draw more current than the condenser, and since the coil current and condenser current are not equal, they cannot exactly cancel each other, and there will be some current flowing in the line from the alternator. The addition of resistance to either the coil or condenser branch would make the cancellation of the two currents in the line even less complete and would result in a greater current being drawn from the alternator.

If a frequency higher than the resonant frequency of the circuit is applied to the parallel combination of the coil and the condenser, the inductive reactance of the coil is greater than the capacitive reactance of the condenser. The condenser, therefore, draws more current than the coil. Even though the two currents are exactly out of phase (assuming that no resistance is present), since they are unequal, complete cancellation is impossible. Let us apply a 70-cycle alternating voltage to this same circuit we have been using. By calculation, the inductive reactance of the coil is found to be 64.2 ohms and the capacitive reactance of the condenser 47.1 ohms. The coil current is:

$$I_L = 110 \div 64.2$$

$$= 1.7 \text{ amperes}$$

The condenser current is:

$$I_C = 110 \div 47.1$$

$$= 2.3 \text{ amperes}$$

The difference between the coil current and the condenser current is .6 ampere, which is the net current that must flow from the alternator to the parallel resonant circuit.

Let us consider what all this means. Assuming that the parallel resonant circuit has a very low resistance, the application of the 60-cycle alternating voltage to this circuit causes a very small line current flow. This line current would probably be on the order of .1 ampere. The 50-cycle alternating voltage produces a line current of .8 ampere, and the 70-cycle voltage, a current of .6 ampere. Thus, it can be seen that any frequency, either above or below the resonant frequency, allows more line current to flow than will flow at the resonant frequency of 60 cycles.

It has been stated that the 60-cycle alternating voltage caused a current of 100 ma. to flow out of the alternator. If 110 volts can force 100 ma. through the circuit, the effective resistance of the circuit is:

$$R = \frac{E}{I}$$

$$= \frac{110}{.1}$$

$$= 1100 \text{ ohms}$$

The parallel resonant circuit is offering a resistance of 1100 ohms to the alternator. Since the inductive reactance of the coil is equal to the capacitive reactance of the condenser, this circuit will cause neither a leading current nor a lagging current in the line from the alternator, but will act just the same as an 1100-ohm resistor in its place would act to the output of a 110-volt 60-cycle alternator. This 1100 ohms is known as the shunt impedance or the effective impedance of the parallel resonant circuit and it acts like a pure resistance, causing neither a lead nor lag of the current.

When the frequency of the applied voltage was 50 cycles, the current flowing through the alternator was .8 ampere. Let us calculate the effective impedance of the parallel circuit at this frequency. We have:

$$R = \frac{E}{I}$$

$$= \frac{110}{.8}$$

$$= 138 \text{ ohms.}$$

When a frequency of 70 cycles was applied to the circuit, the line current was .6 ampere. Therefore, the effective impedance of the parallel circuit at 70 cycles is:

$$R = \frac{E}{I}$$

$$= \frac{110}{.6}$$

$$= 183 \text{ ohms.}$$

Notice that the effective impedance of the parallel resonant circuit is greatest when the frequency of the applied voltage is the resonant frequency of the circuit. At other frequencies, either higher or lower, the effective impedance of the parallel resonant circuit is considerably less. Obviously, the more line current or current drawn from the alternator at a given frequency, the smaller is the effective impedance of the parallel circuit at that frequency.

Let us assume that there is available a voltage source whose frequency can be varied from zero frequency (corresponding to direct current) to an infinitely high frequency. This voltage source is connected to a parallel resonant circuit and included in the circuit are three meters to read the line current, the coil current, and the condenser current (see Fig. 10). When a pure direct voltage is applied to this circuit, the meter M_3 reads zero; that is, there is no condenser current flowing since the capacitive reactance of the condenser to pure direct current is infinitely high. Meter M_2 indicates a very high current. To pure direct current, the coil has a zero inductive reactance and the current through it is limited only by the resistance of the coil itself. Since any current that flows through the coil must also flow out of the alternator, the meter M_1 indicates the same amount of current as meter M_2. As the frequency of the applied voltage is increased, the inductive reactance of the coil increases and the meter M_2 indicates that less current is flowing through the coil. An increase in frequency causes a decrease in the capacitive reactance of the condenser and the meter M_3 indicates that a small current is flowing in the condenser branch. Since the coil current and the condenser current are 180 degrees out of phase, the line current, as read by meter M_1, is equal to their difference. When the frequency of the applied voltage is raised, the coil current is reduced and the

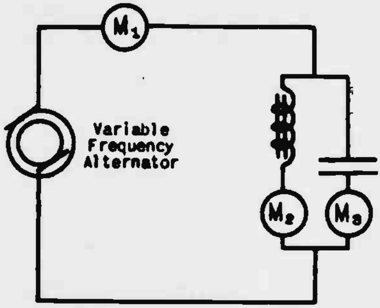


Fig.10 Circuit used to explain the effect of varying the frequency of the voltage applied to a parallel resonant circuit.

condenser current increased, which, thereby, decreases their difference and causes meter M_1 to indicate a smaller line current. The line current, therefore, steadily decreases as the frequency is raised. Finally, a point is reached where the coil current is equal to the condenser current. Since their difference is then zero, the line current as read by meter M_1 is zero and no current is being drawn from the alternator. Actually, however, we cannot obtain these theoretical results since it is impossible to have any circuit that does not contain some resistance. However, at the particular frequency at which the coil current is equal to the condenser current, the meter M_1 indicates that a minimum value of current is flowing in the line. If the circuit is so designed that its resistance is purposely kept as low as possible, the line current at this point, as read by M_1, is very small as compared to the current drawn by the coil and the condenser. This particular frequency is known as the resonant frequency of the parallel resonant circuit. A continued increase in the frequency of the applied voltage above the resonant frequency produces an increase in the inductive reactance of the coil, and a decrease in the capacitive reactance of the condenser. The coil current becomes smaller, and the condenser current larger; their difference increases and the line current becomes greater. The higher the frequency of the applied voltage is above the resonant frequency, the greater is the difference between I_L and I_C and, as a result, the greater the line current. If it were possible to increase the frequency of the applied voltage to an infinite value, the inductive reactance of the coil would be infinite, allowing no current to flow through the coil; the capacitive reactance of the condenser would be zero, allowing a very large current to flow through the condenser limited only by the resistance of the circuit. At this point, the meter M_1 would indicate the same amount of current as the meter M_3.

It should be evident that a parallel resonant circuit is just opposite in effect to that of a series resonant circuit. *The series resonant circuit allows a maximum current to flow at the resonant frequency and a smaller current at any other frequency. A parallel resonant circuit allows a minimum current to flow at the resonant frequency and a larger current at any other frequency.* Or, in other words, we can say that a series resonant circuit offers minimum opposition to current of the resonant frequency, while a parallel resonant circuit offers maximum opposition to current of the resonant frequency. Understand, that by current, we mean the current drawn from the alternator or voltage source. Parallel resonance is often called "current resonance", since the current flowing in the coil and condenser branches at the resonant frequency is many times greater than the line current at that frequency.

The addition of resistance to either the series or parallel resonant circuit causes the resonant effect to be less pronounced. When the resistance of a series resonant circuit is increased, the amount of current that can flow at the resonant frequency is decreased. When the resistance of a parallel resonant circuit is increased, the amount of line current that can flow at the resonant frequency is increased provided that the additional resistance is placed either in the coil or condenser branch of the circuit and not in the line. All resonant circuits with which we shall deal in our study of Radio and Television will be designed to have a minimum of resistance.

3. AC AND DC IN THE SAME CIRCUIT. Suppose that a circuit has a pure direct current of 100 ma. flowing through it. This current is represented by the diagram A in Fig. 11. In Lesson 6

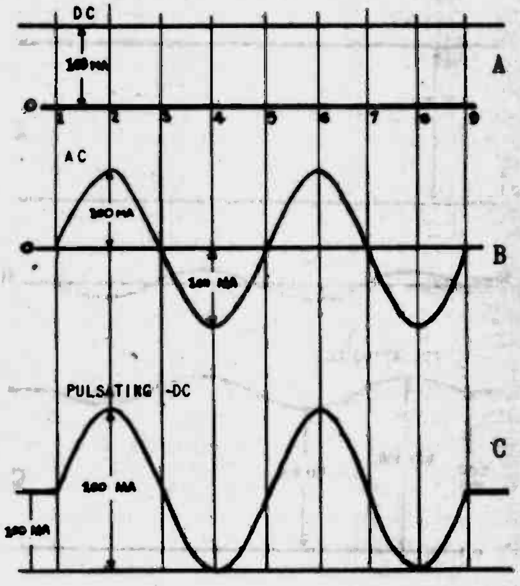


Fig.11 Illustrating how a pure direct current, A, and an alternating current, B, can be combined to form a pulsating direct current, C.

it was learned that a pure direct current could be represented by a line drawn parallel to the zero axis at a distance above the axis equal to the value of the current. In this same circuit, there is, in addition to this unvarying current, an alternating current whose peak value is 100 ma. Its wave form is shown at B in Fig. 11. This alternating current starts from zero, rises to a positive maximum value of 100 ma., falls to zero, rises to a negative maximum value of 100 ma., returns to zero, and then continues this periodic variation throughout succeeding cycles. A graphical method for adding two AC waves not in phase was given in Lesson 13. This same method may be used to find the sum or resultant of an alternating current and a direct current. To expedite this addition, the AC wave is placed directly below the diagram representing the DC, and vertical lines are drawn through various instants of the cycle. At the point marked 1, the DC has a value of 100 ma. and the AC a value of zero. Therefore, the resultant wave shown at C has a value at this point of 100 ma. At point 2, the DC has a value of 100 ma. and the AC a value of 100 ma. in the positive direction. Therefore, the resultant wave has a value of 200 ma. at this point. At point 3, the DC has a value of 100 ma. and the AC a value of zero. The resultant wave, therefore, has a value of 100 ma. at this point. At point 4, the DC is still 100 ma. and the AC is 100 ma. in the negative direction. Since the two currents are flowing in opposite directions, the net current or their resultant is found by subtracting one from the other. This makes the value of the resultant wave at point 4 equal to zero. Again, at point 5, the DC has a value of 100 ma., the AC a value of zero, and the resultant wave a value of 100 ma., and so on through-

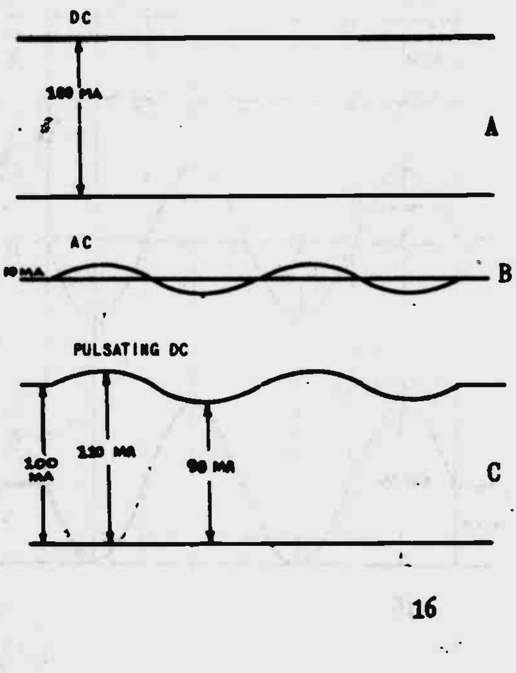


Fig. 12

(A) A pure direct current.

(B) An alternating current.

(C) Their sum, a pulsating direct current.

out the subsequent cycles of alternating current. From diagram C in the figure, it is noticed that the current starts from 100 ma., rises to a value of 200 ma., falls to a minimum of zero, rises to 200 ma., and so on throughout the succeeding cycles. It is a varying or pulsating wave, but it never crosses the zero axis. Therefore, it is not an alternating current, since it always flows in just one direction. A current which flows in just one direction is a DC current and, since this one is of varying value, it is called a pulsating direct current.

From the foregoing discussion, we may generalize and say that the addition of a pure direct current to an alternating current results in a pulsating direct current, provided that the peak value of the AC wave is not greater than the value of the pure direct current. Let us take another example. A pure direct current of 100 ma., and an alternating current of 10 ma. are flowing in the same circuit. The diagrams of the two currents are shown at A and B in Fig. 12. The resultant current is shown at C in the figure. It starts from 100 ma., rises to a maximum of 110 ma., falls to a minimum of 90 ma., and then repeats this cyclical variation. The resultant wave is a pulsating direct current as before.

It has been demonstrated that the sum of a pure direct current and an alternating current is a pulsating direct current. Since this is so, the converse should be true; that is, it should

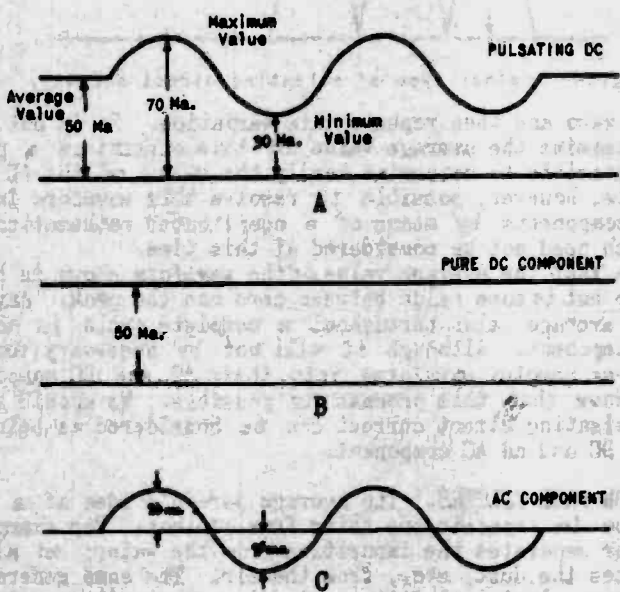


Fig. 13 Showing how a pulsating current, A, can be resolved into a pure direct current, B, and an alternating current, C.

be possible to break down any pulsating direct current wave into the pure direct current and the AC wave of which it is composed. For example: suppose that a pulsating direct current starts at a value of 50 ma., rises to a maximum of 70 ma., falls to a minimum value of 30 ma., and then repeats this variation. This wave form is shown at A in Fig. 13. It is possible to resolve this pulsating direct current into a pure direct current whose value is 50 ma., and an alternating current whose peak value is 20 ma. The pure direct current is shown at B, and the alternating current at C in Fig. 13. The pure direct current is called the DC component of the pulsating DC waveform, and the alternating current is known as the AC component of the waveform. Notice that the value of pure direct current at B is the average value of the pulsating direct current at A throughout a complete cycle. Likewise, the peak value of the alternating current at C is the amount of variation above or below this average value through which the pulsating direct current changes. By a similar method, any pulsating direct current whose waveform is the same as that of A in the diagram can be resolved into its DC and AC components.

Not all pulsating direct currents have a waveform like the one just discussed. Consider Fig. 14. Here is shown a pulsating direct current which changes from zero to a peak value of 100 ma.,

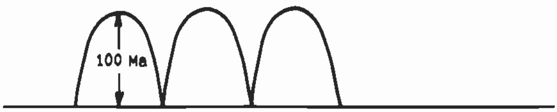


Fig.14 Another type of pulsating direct current.

returns to zero and then repeats this variation. It is not possible to determine the average value of this current at a glance. Nor is it possible to determine easily the value of the AC component. It is, however, possible to resolve this waveform into its AC and DC components by means of a complicated mathematical procedure which need not be considered at this time.

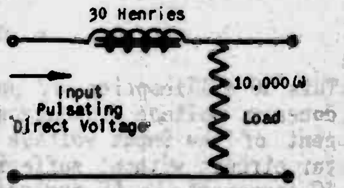
Notice that the average value of the waveform shown in Fig. 14 is not zero but is some value between zero and the peak. Any waveform whose average value throughout a complete cycle is not zero has a DC component. Although it will not be necessary for us to resolve these complex waveforms into their AC and DC components, we should know that this process is possible. We should realize that any pulsating direct current can be considered as being composed of a DC and an AC component.

4. LOW-PASS FILTERS. The average person's idea of a filter is a device to separate one thing from another. For example: a water filter separates the impurities from the water; an air filter separates the dust, etc., from the air. The same general idea applies to an electrical filter. An electrical filter of proper design may be used to separate widely different frequencies which exist in the same circuit. Another type of electric filter is em-

ployed to resolve a pulsating direct current into its two components, DC and AC. This is also a process of separation. It is this type of filter to which we shall first give attention.

A coil tends to pass currents of low frequency much more readily than those of high frequency, and the reverse is true of a condenser. Let us, therefore, consider the circuit shown in Fig. 15. A source of pulsating direct voltage, whose waveform is shown

Fig.15 A very simple low-pass filter.



at A in Fig. 16, is connected to the input of the filter. The filter, itself, consists of an iron core choke in series with the line and a resistor in parallel, which acts as the load. The pulsating DC source may be resolved into its DC component shown at B in Fig. 16, which has a value of 100 volts and its AC component

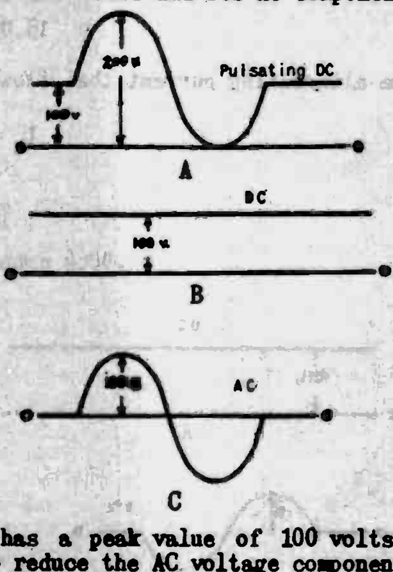


Fig.16 Waveform of the pulsating direct voltage, together with its DC and AC components, which is applied to the filter shown in Fig. 15.

shown at C in the figure, which has a peak value of 100 volts. It is the purpose of the filter to reduce the AC voltage component as much as possible without affecting the DC voltage component any more than is absolutely necessary. If the filter were perfect in its action, there would be no AC voltage across the load resistor, while the DC voltage across this resistor would be equal to the DC voltage component across the input of the filter. In determining the voltage set up across the load resistor, each of these components will be considered separately. The inductance of the choke is 30 henries and the value of the resistor is 10,000 ohms. For simplicity, it is assumed that the iron core choke has negligible resistance. The direct current which flows in the load resistor due to the DC voltage component is:

$$I = \frac{E}{R}$$

$$= \frac{100}{10{,}000}$$

$$= .01 \text{ ampere, or } 10 \text{ ma.}$$

This 10 milliamperes of pure DC flowing through 10,000 ohms produces a voltage drop across the load of 100 volts. The DC component of the input voltage has, therefore, passed through the filter circuit without suffering any loss. If the frequency of the AC component is 60 cycles, the inductive reactance of the choke is 11,304 ohms. This 11,304 ohms of inductive reactance is in series with the 10,000-ohm resistor, and the impedance of the combination is:

$$Z = \sqrt{10{,}000^2 + 11{,}304^2}$$

$$= 15{,}093 \text{ ohms}$$

The alternating current that flows through the filter circuit is:

$$I = \frac{E}{Z}$$

$$= \frac{100}{15{,}093}$$

$$= .0066 \text{ ampere, or } 6.6 \text{ ma.}$$

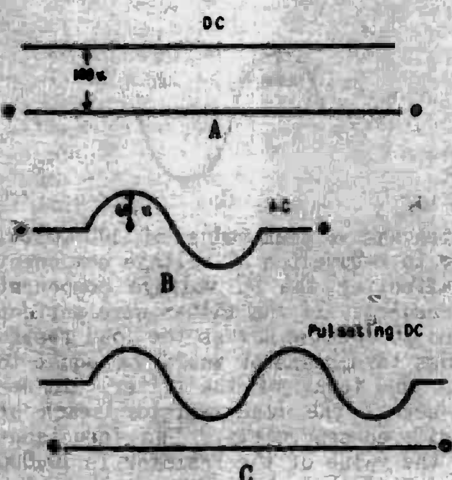


Fig.17 Waveform of the pulsating direct voltage, and its DC and AC components which appear across the output of the filter of Fig. 15.

The 6.6 ma. of AC flowing through the 10,000 ohm load resistor produces a voltage drop of:

$$E = I \times R$$

$$= .0066 \times 10{,}000$$

$$= 66 \text{ volts.}$$

Remember that we are using peak values in this calculation and not R.M.S. values. In Fig. 17 are shown three diagrams. A represents the DC voltage component across the load; it is 100 volts. B represents the AC voltage component across the load; it has a peak value of 66 volts. C, their sum, is the pulsating direct voltage across the load; its average value is 100 volts. Notice that this pulsating direct voltage varies through a smaller amplitude than the pulsating direct input voltage. The filter, therefore, has served to reduce the value of the AC component. Such a filter is, itself, impractical, since the filtering action is very inefficient.

A slightly more complicated and a considerably more efficient low-pass filter is shown in Fig. 18. This circuit, except for the

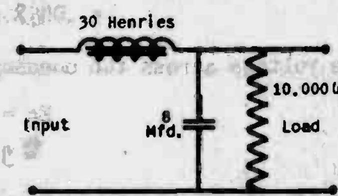


Fig. 18 A single section low-pass filter.

addition of the 8 mfd. condenser, is the same as the one previously used. To the input of this filter, there is connected the same pulsating direct voltage used in the foregoing example. Again, assuming that the iron core choke has negligible resistance, the DC component of the input voltage suffers no loss in passing through the filter, and produces 100 volts pure direct voltage across the load resistor. To find the amount of AC voltage produced across the load due to the AC component of the input voltage, the impedance of the circuit at a frequency of 60 cycles must next be calculated. The 30-henry choke has an inductive reactance of 11,304 ohms and the 8 mfd. condenser a capacitive reactance of 332 ohms. In parallel with the 332 ohms of capacitive reactance are 10,000 ohms of

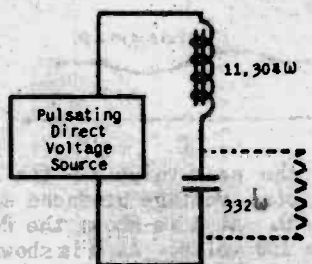


Fig. 19 The circuit of Fig. 18, redrawn to show the relation of the circuit elements to each other.

resistance. Since 10,000 ohms is so much larger than 332 ohms, the shunting effect of the resistor will be negligible, and it can be assumed that the effective impedance of this parallel circuit is approximately 332 ohms. This circuit has been redrawn in Fig. 19. The figure shows that the coil and condenser are in series insofar as the voltage source is concerned. The load resistor is drawn in dotted lines, since at present it is being ignored. There are 11,304 ohms of inductive reactance in series with 332 ohms of capacitive reactance. The net reactance of the circuit is:

$$11{,}304 - 332 = 10{,}972 \text{ ohms}$$

This net reactance is also the impedance of the circuit. The alternating current that flows is:

$$I = \frac{E}{Z}$$

$$= \frac{100}{10{,}972}$$

$$= .0092 \text{ ampere, or } 9.2 \text{ ma.}$$

The voltage across the condenser is:

$$E_c = .0092 \times 332$$

$$= 3.0544 \text{ volts}$$

This is the peak value of the AC voltage across the condenser and since the load resistor is in parallel with the condenser, this is

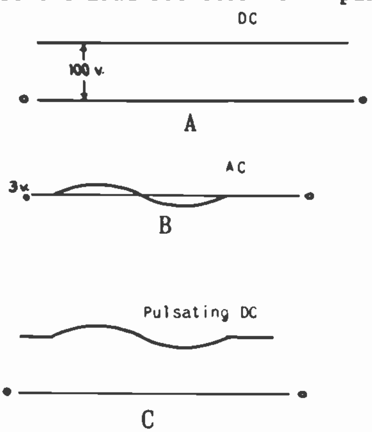


Fig.20 Waveform of the pulsating direct voltage, and its DC and AC components which appear across the output of the filter of Fig. 18.

also the peak value of the AC voltage across the load resistor. The total voltage produced across the load resistor is shown in Fig. 20. At A is shown the DC voltage component across the load; it is 100 volts. At B is shown the AC voltage component across the load; it is approximately 3 volts, peak value. At C is shown the result of the addition of these two; it is a pulsating direct voltage having an average value of 100 volts, and it varies three volts above and below this average value. The total variation of the pulsating direct voltage across the load is considerably less than the total variation of the pulsating direct input voltage. The filter has served to reduce the AC component to a very small value.

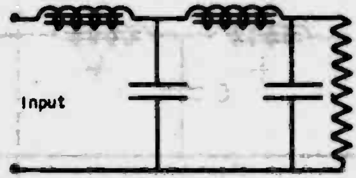


Fig.21 A two-section low-pass filter.

The circuit just considered is called a one section low-pass filter. It reduced the AC component of the input voltage 97%. By using two such sections as shown in Fig. 21, and connecting the output of the first section to the input of the second, a total reduction of 99.91% is obtained. The first section reduces the AC component 97%, and the second section reduces the output of the first section by 97%. The voltage across the load resistor is, for all practical purposes, a pure direct voltage. Its AC component has a peak value of approximately .09 volts. This very small AC component is often called the "ripple voltage". A two-section low-pass filter of this type is very efficient in separating the DC component from the AC component of a pulsating direct voltage. It is called a low-pass filter, since low-frequency current, in this case direct current or zero frequency, can pass through it easily, while higher frequency currents pass through it with difficulty. In an actual filter, the pure DC output voltage will not be quite equal to the DC component of the input voltage, since the chokes do have some resistance which causes a voltage loss.

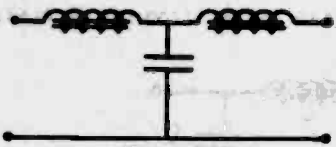


Fig.22 One "T" section of a low-pass filter.

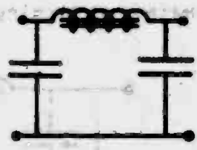


Fig.23 One pi section of a low-pass filter.

The coils offer a high opposition to the alternating component and a very low opposition to the DC component. The condensers offer a low opposition shorting path for the AC component and practically an infinite opposition to the DC component. Therefore, the coils serve to choke back the AC component and the condensers serve to short it from one side of the line to the other.

Filter sections are assembled in two different fashions. In Fig. 22 is illustrated a "T" section of a low-pass filter, so-called because of its general resemblance to the letter "T". In Fig. 23 is illustrated a "pi" section of a low-pass filter, which, in appearance, resembles the Greek letter π. Fig. 24 shows the output of one "T" connected to the input of another. Notice that the two coils between the two condensers are in series. When inductors are connected in series, the effective inductance is equal to the sum of the separate inductances. Therefore, these two coils may be replaced by one whose inductance is equal to their sum, as shown

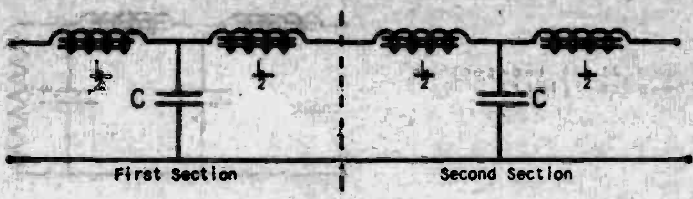


Fig.24 Method of forming a T type low-pass filter from two sections.

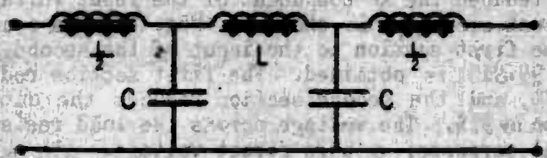


Fig.25 A two-section T type low-pass filter.

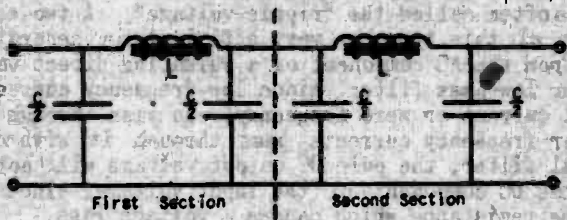


Fig.26 Method of forming a pi type low-pass filter from two sections.

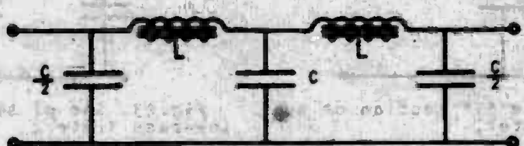


Fig.27 A two-section pi type low-pass filter.

in Fig. 25. In this figure, the middle coil has an inductance equal to twice the inductance of either the input or output coil; thus it is a part of the first and also the second section. When the output of one pi section filter is connected to the input of a second pi section filter, a circuit like that of Fig. 26 is obtained. The two inner condensers are in parallel; therefore, they may be replaced by one condenser which has twice the capacity of either. The circuit then looks like Fig. 27. In this case the middle condenser is in both the first and second sections.

It is possible to design low-pass filters which have the property of allowing all frequencies below a given frequency to pass through them easily, while all frequencies above the given frequency pass through them only with great difficulty; that is, they are considerably reduced in value. This given frequency is called the cut-off frequency. The characteristic of such a filter is shown in Fig. 28. In this figure, the current has been plotted against the frequency.

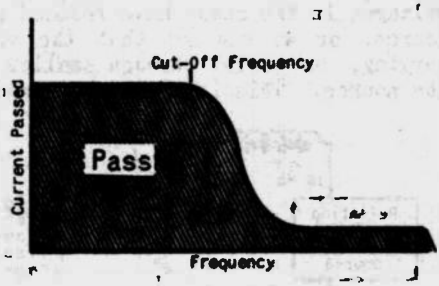


Fig.28 Graph showing the filter action of a low-pass filter. All currents of frequencies lower than the cut-off frequency are passed.

Let us now consider the action of a simple low-pass filter from the electron viewpoint. In Fig. 29 is illustrated a pulsating direct current voltage source connected to an iron core choke and a load resistor in series. It is assumed that the voltage output of the source has a waveform as shown in Fig. 30. The voltage starts from a value of 100 volts and rises to a maximum of 200 volts. As it is rising from 100 to 200 volts, it attempts to force more current through the circuit. As the current rises, it creates

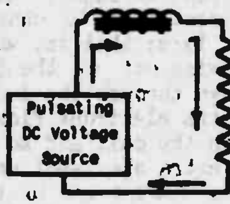


Fig.29 Circuit used to explain the action of a low-pass filter from the electron viewpoint.

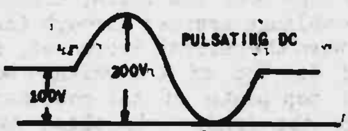


Fig.30 Waveform of pulsating voltage applied to inputs of the filters of Figs. 29 and 31.

an expanding magnetic field about the choke which cuts through the turns of the choke, producing therein a counter voltage which opposes this rise in current. Therefore, the current does not rise to as high a maximum as it would if the choke were not in the circuit. Since the current flowing through the circuit does not reach as high a value, the voltage produced across the load does not rise to 200 volts, but to some lesser value.

The voltage of the source now falls to zero, tending to cause the current to drop to zero. As the current decreases through the circuit, the magnetic field about the iron core choke collapses, and in collapsing, it induces in the turns of the choke a voltage which tends to keep the current flowing. The counter voltage induced in the choke keeps the current from falling to zero. It does not, however, prevent it from varying at all. This minimum current in flowing through the load resistor produces a voltage drop across it which is somewhat greater than zero. Let us say, for example, that the voltage produced across the load varies from a maximum of 150 volts to a minimum of 50 volts. The self-induced voltages in the choke have reduced the AC component of the voltage source, or we can say that the voltage across the load is less varying, or varies through smaller amplitudes than the voltage of the source. This is a somewhat imperfect low-pass filter.

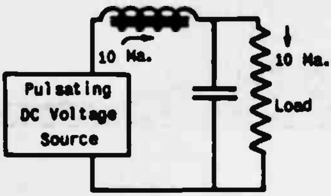


Fig.31 Illustrating the currents which flow in the various parts of a low-pass filter when the applied pulsating DC voltage is at its average value.

Now let us add a condenser to the filter as shown in Fig. 31. First, assume that the voltage of the source is 100 volts, and that this voltage forces a current of 10 ma. through the load. The voltage of the source begins to increase to 200 volts. As previously explained, the choke produces a self-induced voltage which tends to prevent the current from increasing. The action of the choke is not perfect, however, so the current through it does increase somewhat. Most of the increased current goes to charge the condenser and does not flow through the load; that is, when the voltage was 100 volts, electrons were flowing out of the top of the voltage source, through the coil and down through the load. Then, when the current increased, most of the extra electrons flowed out of the top of the voltage source, through the coil and so on to the top plate of the condenser; very few extra ones went down through the load. As these extra electrons flowed on to the top plate of the condenser, they repelled an equal number of electrons from the bottom plate. These electrons that were on the bottom of the plate now flow back to the positive terminal of the voltage source. Let us say that the current through the circuit tends to rise from 10 to 20 ma. as the voltage of the source rises from 100 to 200 volts. Since the choke tends to prevent a rise in current, let us assume that the maximum increase in current through the choke is from 10 to 15 ma. If the condenser were not in the circuit, a maximum of 15 ma. would flow through the load. With the condenser in the circuit, 4 ma. of this 15 ma. will flow into the condenser, the other 11 ma. going through the load. Likewise, 4 ma. will flow out of the bottom of the condenser, joining the 11 ma. which come from the bottom of the load, and the combined 15 ma. will then flow back to the positive terminal of the voltage source. Even though the current has changed from 10 to 15 ma., the current through the load resistor only changes from 10 to 11 ma. The values of the currents flowing through the various parts of the circuit, when the applied voltage is at its maximum value of 200 volts, are shown in Fig. 32.

The voltage of the source now falls to zero, tending to cause the current flowing through the circuit to drop to zero. The self-induced voltage of the choke, however, prevents the current from falling below 5 ma. This 5 ma. flows through the load resistor and, in addition to this, the condenser discharges 4 ma., which

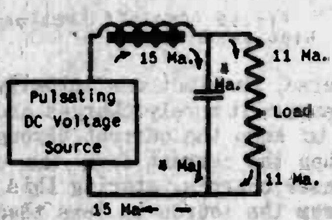


Fig.32 Illustrating the current flow when the applied voltage is at its maximum value.

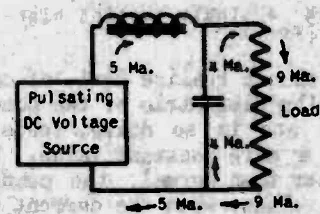


Fig.33 Illustrating the current flow when the applied voltage is zero.

also flows through the load. The total current flowing through the load is, therefore, 9 ma. From the bottom of the load, this 9 ma. divide, 4 ma. flowing into the condenser and 5 ma. flowing back to the voltage source. This condition is illustrated in Fig. 33. If the load resistor is 10,000 ohms, the voltage across it when the voltage of the source is 100 volts, is.

$$E = I \times R$$
$$= .01 \times 10{,}000$$
$$= 100 \text{ volts.}$$

Then when the voltage across the source rises to 200 volts, the current through the load rises to 11 ma., producing a voltage across the load of:

$$E = I \times R$$
$$= .011 \times 10{,}000$$
$$= 110 \text{ volts}$$

When the source of voltage falls to zero, the current through the load drops to 9 ma., producing a voltage across the load of:

$$E = I \times R$$
$$= .009 \times 10{,}000$$
$$= 90 \text{ volts}$$

Thus the total variation of the input voltage is 200 volts (from 0 to 200), while the total variation of the load voltage is only 20 volts (from 90 to 110). The filter has reduced the variation 90%.

Fig.34 A single section high-pass filter.

Fig.35 One "T" section of a high-pass filter.

We should realize that, of course, no electrons actually flow through the dielectric of the condenser; it merely charges and discharges, and in so doing, tends to keep the current through the load at a more constant value. When the current from the source is greater than normal, the condenser charges, storing this extra current. Then, when the current from the source is less than normal or average, the condenser discharges through the load, releasing the stored current and keeping the current through the load at a more constant value. This by-passing action of the condenser will not be effective unless the condenser's capacitive reactance is considerably less than the resistance of the load. Also, the inductive reactance of the choke should be considerably greater than the resistance of the load, if the filter is to be effective. In Lesson 16 we shall have occasion to use low-pass filters.

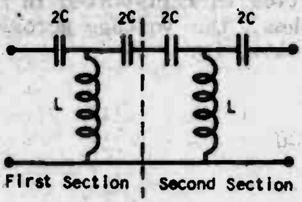


Fig.36 Method of forming a T type high-pass filter from two sections.

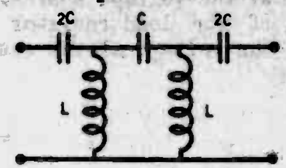


Fig.37 A two-section T type high-pass filter.

5. **HIGH-PASS FILTERS.** Obviously, a high-pass filter is one which will pass currents of all frequencies above the cut-off frequency and reject all lower frequencies. A single section high-pass filter is illustrated in Fig. 34. It consists of a condenser connected in series with the line and choke connected in parallel with the line. The condenser allows the easy passage of high-frequency currents and tends to oppose low-frequency currents. The choke shorts the low-frequency currents from one side of the line to the other, but has practically no effect upon high-frequency currents. A "T" section of a high-pass filter is illustrated in Fig. 35. Fig. 36 shows the output of one "T" section high-pass filter connected to the input of a second section. The two condensers between the chokes are in series; they may, therefore, be replaced

by one condenser, whose capacity is half that of either of them. This is shown in Fig. 37. The two end condensers have twice the capacity of the center condenser. Fig. 38 shows a pi section of a high-pass filter, and Fig. 39 illustrates two pi sections connected together. The two inner chokes are in parallel and may

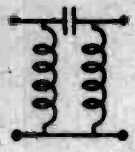


Fig.38 One pi section of a high-pass filter.

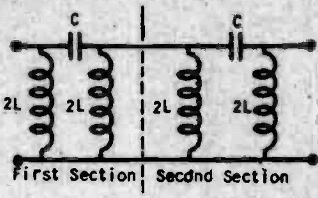
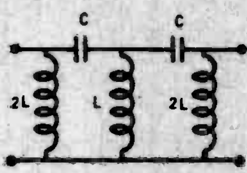


Fig.39 Method of forming a pi type high-pass filter from two sections.

be replaced by a single choke equal to their effective inductance. The reconstructed circuit is shown in Fig. 40; the two end chokes have twice the inductance of the middle choke. High-pass filters are sometimes used in dynamic speaker circuits to reject all frequencies of 120 cycles or lower, and to pass all higher frequencies. Their major application, however, is to pass a band of high frequencies, when used in conjunction with low-pass filters.

Fig.40 A two-section pi type high-pass filter.



Other applications of resonant circuits and filter circuits will be introduced in future lessons when they are needed for various phases of Radio and Television. Methods of calculating the exact values for definite characteristics in these types of circuits will be given.

Notes

(These extra pages are provided for your use in taking special notes)

GREEK ALPHABET

Greek letter	Greek name	English equivalent		Greek letter	Greek name	English equivalent
α	Alpha	a		ν	Nu	n
β	Beta	b		ξ	Xi	x
γ	Gamma	g		ο	Omicron	o
δ	Delta	d		π	Pi	p
ε	Epsilon	e		ρ	Rho	r
ζ	Zeta	z		σ	Sigma	s
η	Eta	e		τ	Tau	t
θ	Theta	th		υ	Upsilon	u
ι	Iota	i		φ	Phi	ph
κ	Kappa	k		χ	Chi	ch
λ	Lambda	l		ψ	Psi	ps
μ	Mu	m		ω	Omega	o

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UNIT NO. 1

CONSTRUCTION OF BATTERIES

LESSON NO. 15

THE "IFFER"

.....a little word with a tragic meaning.

The little word "if" is probably used to a greater extent by "men that might have been a success" than any other group of individuals. They use it to explain why they are up against it or to tell their listeners how close they were to success. For example, there are many men today who will tell you what a wonderful opportunity they had to make a lot of money when radio broadcasting became a reality "IF" they had only done this or that. But the strange thing about such men is that radio has been chuck full of money-making opportunities ever since its advent, yet they have failed to take advantage of them. It is unfortunate to know that professional "iffers" will always lay their failures at the door of "if", for they must have some excuse. Of course, not all men who are failures can be placed in the "iffer" classification. Some are just plain unfortunate.

Probably you have experienced an occasion or two when you could have made more money "if" you had done something different. But regardless of whether you have or not, make a resolution right now that you are NOT going to be an "iffer" failure.....cast the word "if" out of your vocabulary!

Marvelous new discoveries are continually opening up fresh opportunities in the radio field. What the future will bring is beyond the realm of our most vivid imagination. Right now, you are taking a thorough course of instruction that will prepare you for a better job in radio. Furthermore, you are securing training which will make it possible for you to take advantage of future money-making opportunities created by new radio discoveries. Stick to your studies and we are sure there will be no need for you to use the word "if" in the future. Every lesson that you complete, every examination paper that you send us, removes you farther and farther from the "iffer" group of men that "might have been".

You are on the track that leads to success in life. Stay on that track, for it leads to the realization of your hopes and ambitions!

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Lesson Fifteen

CONSTRUCTION of BATTERIES

"Batteries are used extensively on all types of radio receivers that cannot be operated from an AC supply line. About 50% of all radio stations use batteries for some purpose or another, and every ship radio installation has battery supply.

"No Radio-Television training would be complete without a thorough understanding of the theory of operation of all types of batteries. Therefore, in this lesson, I am going to cover the construction and principle of operation of both dry and wet cells."

1. THE IMPORTANCE OF BATTERIES. *A battery is a device capable of converting chemical energy into electrical energy.* Batteries have been used for many years as the source of electrical power for the grid, filament, and plate circuits of a vacuum tube. Prior to 1927, the vacuum tubes available on the commercial market were designed in such a manner that satisfactory operation could be secured only when a DC voltage was applied to the filament. The battery was the source of DC voltage commonly used. The advent of vacuum tubes designed to operate from an AC filament supply and the perfection of commercial vacuum tube rectifier circuits have eliminated the use of batteries as power supply wherever an AC source of voltage is available. It is still necessary, however, for those residing in rural communities to depend entirely upon batteries as the power source for radio receiver operation. Farm receivers are far more numerous than realized by the average person who lives in a locality served by an AC power supply. Constant association with modern conveniences, made possible by public power distribution, has caused those service-men and residents of metropolitan areas to disregard the importance of any but the all-electric radio receivers. However, the rural service-man is well acquainted with the fact that more than 2,800,000 battery receivers are now in operation. These receivers must be properly serviced the same as all-electric sets, and their maintenance requires a thorough knowledge of modern, highly efficient batteries.

In addition to the use of batteries for receiver operation, they are also employed in several other branches of the Radio and Television industry. A few examples are: electrical measuring instruments; portable receiving and transmitting equipment; marine radio; police radio; and aeronautical radio.

For these reasons, a fundamental knowledge of the construction and characteristics of batteries is of extreme importance to a modern radio technician. The theoretical chemical reactions involved in the operation of batteries is of little consequence in the study of Radio and Television except in those instances where the operating characteristics of the battery are affected. To properly maintain and care for batteries, a general knowledge of their construction is essential. In this lesson, the construction and operating characteristics of the more popular types of batteries will be given. The chemicals used in the various batteries will be named, but the theoretical chemical reactions are reviewed only when it is necessary from the standpoint of maintenance procedure. Students whose knowledge of chemistry permits may reinforce the herein contained information for their own personal satisfaction; however, such study is not necessary for future work in Radio and Television.

2. PRIMARY AND SECONDARY CELLS. All batteries[1] may be subdivided into two general classifications. These are: (1) Primary batteries. (2) Secondary batteries.

A primary cell is defined as one in which the chemical reaction is not reversible. This means that after the chemical reaction has gone to completion, it is necessary to discard the cell and replace with a new one.

A secondary cell is defined as a cell in which the chemical reaction may be reversed. This means that the chemical energy originally possessed by the battery can be replaced after it has been consumed.

All types of cells, such as flashlight batteries, Radio B and C batteries, Air Cells, etc., are included under the classification of primary cells, whereas the so-called "storage batteries", such as automobile batteries, radio A batteries, and Edison batteries are classified as secondary cells.

Primary and secondary batteries are of equal importance in the study of Radio and Television. The construction of the dry cell is the simpler of the two, so we shall begin our study of batteries with this type.

3. DRY CELLS. The dry cell is not "dry" in the true technical sense of the word, because it contains a moist chemical solution which is extremely important in the operation of the cell. The word "dry" has come into common usage for describing this type of cell because the moist solution is in the form of a paste rather than a free-flowing liquid.

[1] The words "battery" and "cell" are consistently interchanged because a battery is nothing more than several individual cells connected in series. Any definition or explanation pertaining to a cell likewise applies to a battery, and vice-versa.

In order to construct any electrical cell, it is necessary to provide two electrodes, one of which is at a higher potential than the other. In other words, an accumulation of electrons must occur on one of the electrodes and a deficiency of electrons must be effected on the other. As a result of this electron difference, these two electrodes are negative and positive, respectively, and are capable of forcing a current through an external circuit connected across them.

Many years ago, it was discovered that if two dissimilar substances were held apart in a certain chemical solution, electrons would be transferred from one substance to the other. Of course, it is true that not all different kinds of substances immersed in any kind of liquid solution are capable of producing this effect. Certain combinations which have been found particularly effective are copper and zinc immersed in a solution of sulphuric acid and water; carbon and zinc in ammonium chloride; lead and lead peroxide in sulphuric acid and water; iron and nickel oxide in potassium hydroxide and water; etc. The extent of the electrical voltage produced across the two electrodes of the cell depends entirely upon the kind of electrodes used and the type of solution in which the electrodes are immersed. The actual physical size of the cell has no effect on the initial voltage produced.

Of the voltage producing chemical combinations just mentioned, the dry cell consists of zinc and carbon electrodes immersed in a solution of ammonium chloride. This ammonium chloride is commercially known as sal-ammoniac, and the chemical formula for it is NH_4Cl. This particular combination of chemicals was discovered by Leclanche. The commercial dry cell at the present time is merely a modification of the original cell invented by Leclanche. The voltage produced across the electrodes in a cell of this type is about 1.5 volts when all of the constituent chemicals are in good condition. As the cell is used to produce electrical power, some of the chemicals are consumed or "eaten away", resulting in a lower voltage. This consumption of the chemicals represents the normal deterioration which is to be expected as the cell delivers electrical power. When the cell's voltage drops below a useful value, it must be discarded and replaced.

A cross-sectional view showing the internal construction of a typical dry cell is shown in Fig. 1. The cell fundamentally consists of a zinc cup that has been lined with an absorbent layer of blotting paper[1]. The absorbent blotting paper is saturated with a solution of sal-ammoniac and zinc chloride. As mentioned previously, the sal-ammoniac is essential for the chemical operation of the cell; however, the zinc chloride does not enter into this reaction. Its purpose is to counteract any deteriorating effect which may occur during the shelf life[2] of the cell. A large

[1] This absorbent blotting paper is labeled "paste coated pulpboard separator" in Fig. 1.

[2] The shelf life of a cell is the length of time after manufacture that the cell still possesses a useful voltage, assuming it has not yet been placed in operation.

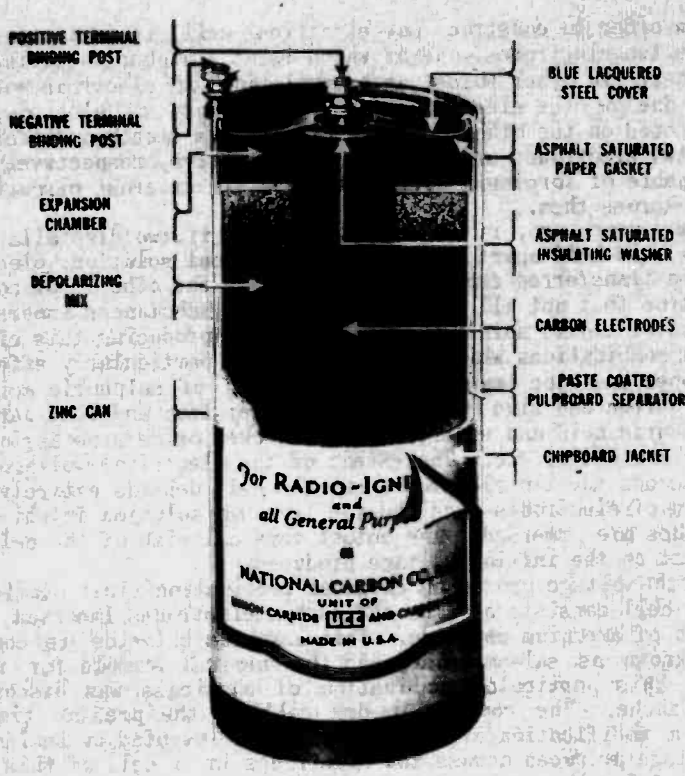


Fig.1 Illustrating the internal composition of a dry cell.

Courtesy National Carbon Co.

carbon rod extends down through the center of the zinc cup. The rod is not of sufficient length to touch the bottom of the cup. The space between the carbon rod and the saturated blotting paper is filled with a paste consisting of a mixture of granulated carbon, manganese dioxide, sal-ammoniac, and zinc chloride. This pasty solution serves to maintain a supply of the sal-ammoniac and zinc chloride to be absorbed by the blotting paper. The manganese dioxide and granulated carbon in the mixture do not enter chemically into the operation of the cell, except that the manganese dioxide acts as a depolarizer[1] for the hydrogen bubbles formed around the surface of the carbon rod. A thin layer of sand is placed over the top of the manganese dioxide mixture in some dry cells. Other manufacturers merely leave a small space to serve as an expansion chamber. A waterproof sealing cement or a tight paper

[1] Depolarizers must be used in all types of primary and secondary cells to prevent a high internal resistance of the cell. This subject will be discussed fully in a subsequent paragraph of this lesson.

gasket covers the top of the cell. Perfect sealing of the cell is very essential, for if air is allowed to enter, the active chemical constituents become dried out, resulting in ruination of the cell. The binding posts for connection to the external circuit are connected to the zinc cup and carbon rod. The chemical action occurring within the cell causes the zinc cup to become negatively charged and the carbon rod to become positively charged. When the external circuit is completed, the electrical voltage produced across the positive and negative terminals of the cell is capable of forcing a DC current through the circuit from the negative to the positive terminal.

When current is drawn from the cell, the zinc electrode is affected by the electrolyte solution, causing it to be eaten away. As the pure zinc is eaten away, a crystalline formation of solid zinc chloride appears over its surface. This solid zinc chloride is white, and no doubt you have noticed it many times on flashlight batteries after they have been used to depletion.

Theoretically, the life of a dry cell should continue until the zinc cup is entirely eaten away; however, this is not true in a practical sense, because an increase of resistance within the cell will cause its useful life to end when some of the zinc still remains in its original condition. Those dry cells which are small in physical size will not provide as long a useful life as the larger cells, considering that each of them is subjected to the same drain, simply because the larger cell has a greater amount of zinc originally available for deterioration. The positive carbon terminal of the cell is not affected by the chemical action; however, it must expose a reasonable amount of surface area in order to provide an efficient life. The life of the cell also depends upon the quantity of depolarizing manganese dioxide which can be used in the cell. For these reasons, the size of the carbon rod and the quantity of depolarizer (manganese dioxide) must be selected with a reasonable degree of compromise consistent with the permissible physical dimensions of the cell.

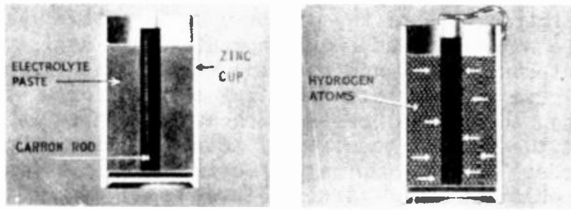
4. ELECTROLYTES. *An electrolyte is a moist or liquid solution which is capable of conducting an electric current.* The conductance of an electrolytic solution depends upon several chemical factors which we shall not discuss for obvious reasons. Insofar as the construction of any battery is concerned, the electrolyte solution must be such that its conductance is very high, or, stated in other words, its resistance must be extremely low. The electrolyte solution in the dry cell consists of ammonium chloride (sal-ammoniac). Ammonium chloride has a high electrical conductivity, which makes it satisfactory for the electrolyte solution in a dry cell. Other electrolytes which we shall encounter in the study of other types of batteries are: sodium hydroxide, potassium hydroxide, and sulphuric acid. All of these chemical solutions possess the property of offering low resistance to the passage of an electric current. High-resistance electrolytes are entirely unsuitable for use in the construction of any type of battery.

5. LOCAL ACTION. Local action is an internal chemical action which generally occurs at the negative terminal of a battery and causes the useful life to decrease. Local action is in no way effective in supplying electrical energy to a circuit connected across the terminals of the battery. The common cause for local action is impurities in the chemical constituents of the cell. For example, in the dry cell, the zinc which is used for the negative terminal may contain certain impurities, such as carbon, iron, etc. These impurities are possibly imbedded within the zinc to the extent that they cannot be removed economically by the ordinary commercial methods of preparing the zinc container. After the assembly of the cell, these impurities come into contact with the electrolyte solution and set up a minute active cell, thus causing an internal discharge of the chemical energy. If these minute, internal discharging cells are sufficient in number, the result is a complete deterioration of the active chemicals within a short length of time. Manufacturers attempt to maintain the original purity of the zinc to as high a degree as possible in order to prevent local action.

Local action occurs not only in dry cells, but also in all other types of batteries, both primary and secondary. Its cause in each case is fundamentally the impurity of the active substances involved.

6. POLARIZATION AND DEPOLARIZATION. During the chemical action which occurs in nearly all types of primary cells, hydrogen gas is formed over the surface of the positive terminal. The positive terminal of a primary cell generally consists of copper or carbon, and hydrogen gas will not combine with the carbon or copper electrode. Instead, the hydrogen gas clings, in the form of bubbles, until its lightness causes it to rise to the top of the cell and escape into the air. In the case of the dry cell, the top of the cell is sealed, so there is no possible chance for the hydrogen gas to escape into the air; hence, it is necessary to use some other method of preventing it from collecting. If not prevented, this layer of gas tends to set up a voltage in a direction opposite to that of the cell and thus decreases the voltage output of the cell. It also reduces the conducting area of the plates and so increases the internal resistance of the cell. *The formation of a hydrogen gas on the surface of the positive electrode is called "polarization".*

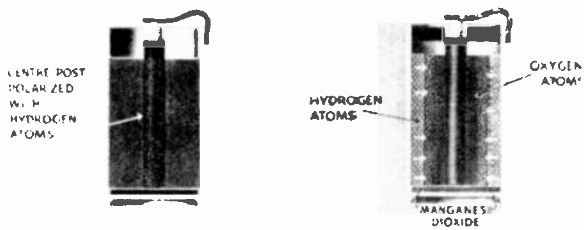
In a dry cell, manganese dioxide is introduced into the cell to serve as a means of preventing polarization. *Any substance which is employed in this respect is known as a "depolarizer" because of the counteracting effect it has on polarization.* When manganese dioxide is used as a depolarizer, part of the oxygen which it contains will combine with the hydrogen gas to form water. As long as the hydrogen gas is not produced too rapidly and as long as the manganese dioxide is in good condition, all of the hydrogen gas formed over the surface of the positive terminal will be depolarized, and the internal resistance of the cell will remain at a low value. Fig. 2 shows this action diagramatically.



(A) Essential constituents of a dry cell. (B) Direction of hydrogen atoms.

Fig. 2

Courtesy National Carbon Co.



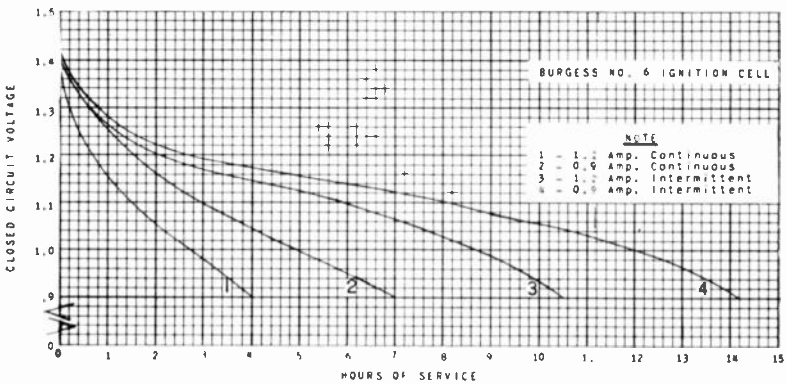
(C) Showing how the carbon pole is polarized. (D) Combination of the oxygen from manganese dioxide with the hydrogen forms water and the cell is depolarized.

Other types of primary cells may secure depolarization by the use of a different chemical, or by employing an electrode which is capable of extracting oxygen from the air. As other types of primary cells are discussed, the depolarizing agent will be mentioned in each case.

7. INTERNAL RESISTANCE OF A CELL. One of the main factors affecting the internal resistance of a cell is the extent of the polarization. The depolarizing agent should be sufficiently effective to remove all traces of the polarizing gas as soon as it is formed. If not, the internal resistance of the cell rises rapidly. Other factors affecting the internal resistance of a cell are: The area of the plates exposed to the electrolyte, the distance between plates, the temperature, and the strength of the electrolyte solution. Even though the modern commercial methods of manufacturing primary cells have been perfected to a high degree of efficiency, all cells will have some internal resistance. The actual calculation of this internal resistance in the cell is very difficult because of the many factors which affect its value. As a general rule, it may be stated that the internal resistance of a cell in good condition is exceedingly low (less than an ohm), but as the cell becomes "worn out" due to usage, the resistance may increase to several ohms. Obviously, if a cell is to have a long, useful life, it should be constructed so as to maintain a low internal

resistance as long as possible. A large plate surface area, a small separation between the positive and negative plates, a strong electrolyte solution, and a low temperature all assist in maintaining the internal resistance to a low value. The large, 6-inch dry cell will give satisfactory operating service for a longer period of time than the smaller cells (such as those used in flashlights) because of the greater quantity of active chemicals contained.

In order to care for a dry cell properly, two precautions should be observed. The first of these is the temperature at which cell is operated. Ordinary temperatures will have little effect upon the voltage output of a cell when current is not being drawn from it. When the temperature of operation is exceedingly low, both the voltage output and life of the cell will be decreased. High temperatures generally cause an increase of local action within the cell, thereby reducing the life of the cell. When dry cells are to be kept in storage, they should be kept as cool and as dry as possible.



Courtesy Burgess Battery Co.

Fig.3 Characteristic curves for a standard 6-inch dry cell. Dimensions are 6 x 2½ inches.

The other important precaution to be observed when using a dry cell is the amount of current continuously drawn from it. If a drain is placed on a cell intermittently (at short intervals), the life of the cell will be extended beyond the normal life which it possesses when it is subjected to a continuous drain. The graph shown in Fig. 3 will serve to illustrate the effect of intermittent and continuous drains on a typical 6-inch dry cell. The cell used for the collection of this data was a No. 6 Burgess ignition cell. It will be noticed that the curves are not shown below .9 of a volt because when the cell output voltage has decreased to this value, its useful life is generally considered at an end. Whether or not the life of the dry cell actually ends at this voltage depends to a large extent upon the service in which it is engaged. If satisfactory operation is possible beyond .9 of a volt, it is permissible to continue the service.

By carefully studying the graph in Fig. 3, which illustrates the characteristics of a standard 6-inch cell, it can be seen that when a high, continuous current drain is placed on the cell, its life is very short compared to the life resulting from a slow intermittent drain.

Whereas, the graph in Fig. 3 shows the characteristics of a typical 6 × 2½-inch cell, it should be understood that dry cells of smaller physical size will not give as many hours of satisfactory service when the same current is drawn from them. Similar characteristic curves for smaller cells will be given later in this discussion.

8. **DRY CELLS IN SERIES.** A single dry cell produces an output voltage of only 1.5 volts. When a higher potential than this is desired, it may be secured by connecting several small cells in series. The total voltage output produced by the series connection will be equal to the sum of the individual voltages. The current which is drawn from the entire battery will place an equal drain on each of the smaller series cells. That is, if 25 milliamperes is being drawn from a 45-volt B battery, there will be 25 milliamperes drawn from each of the 30 small cells which have been connected in series to secure the 45 volts. Series connection does not increase the current-delivering capacity of a battery even though a higher output voltage is secured. Since each of the individual cells in a series combination will have a current drawn from it that is equal to the total current drawn from the entire battery, the characteristics of the small cells themselves must be taken in-

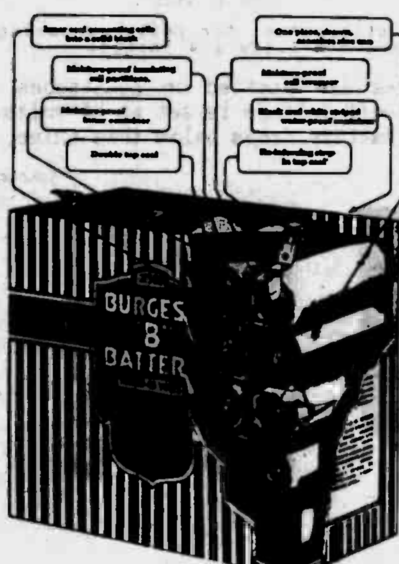


Fig.4 Cut-away view of a 45-volt B battery.

Courtesy Burgess Battery Co.

to consideration when determining the maximum permissible current drain. This fact is pointed out because there is a tendency to assume that a high current drain is permissible from a battery consisting of several cells in series. After having seen that the total current drain from the battery is also placed on each individual cell, it can be concluded that this assumption is incorrect.

A cut-away view showing the internal construction of a typical heavy-duty B battery is shown in Fig. 4. Notice that the small cells are separated into individual compartments, and are connected in series so as to secure the 45-volt output. There are 30 cells contained within this type of battery, and the size of each cell is 1.276 inches × 4 inches. Since the cells are smaller in physical size than the 6-inch ignition cell, not as much current can normally be drawn from them. The characteristic curves for the cells composing the battery shown in Fig. 4 are shown by the graph in

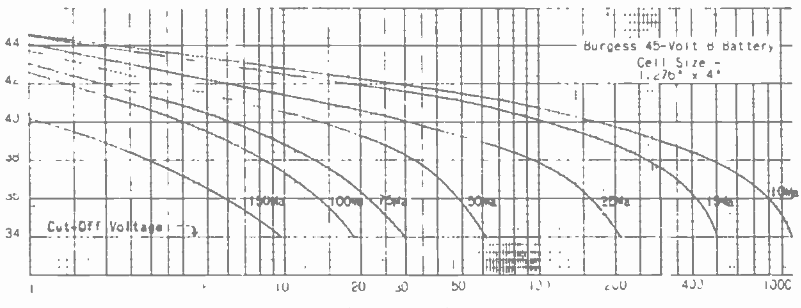
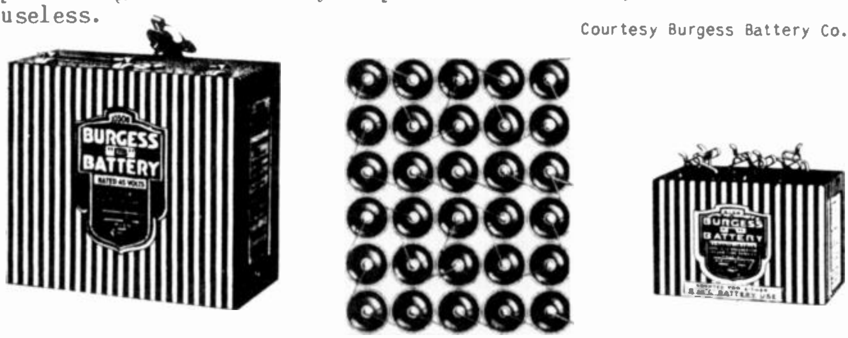


Fig.5 Characteristic curves for cells composing battery shown in Fig.4. Dimensions are 1.276 x 4 inches.

Fig. 5. These curves are plotted on continuous current drains. Notice that the cut-off voltage is set at 34 volts. When the output voltage of the battery drops below this value, it is considered useless.

Courtesy Burgess Battery Co.



(A) (B) (C)

Fig.6 (A) Common type Radio B battery.
(B) Illustrating the series connection of the 30 small cells.
(C) Typical 22½-volt C battery.

One of the smaller, commonly used Radio "B" batteries is shown in Fig. 6A. This cell also contains 30 small cells (see Fig. 6B) connected in series to secure the output voltage of 45 volts. A tap is brought out from the 15th cell to obtain the 22½-volt terminal. The only difference between this battery and the battery shown in Fig. 4 is that the cells are smaller in size. These cells measure 1.253 × 3.67 inches. The smaller physical size of the cell results in a lower permissible current drain for an average life. The characteristic curves for this battery are plotted in Fig. 7. The C batteries used for grid bias supply in radio receivers

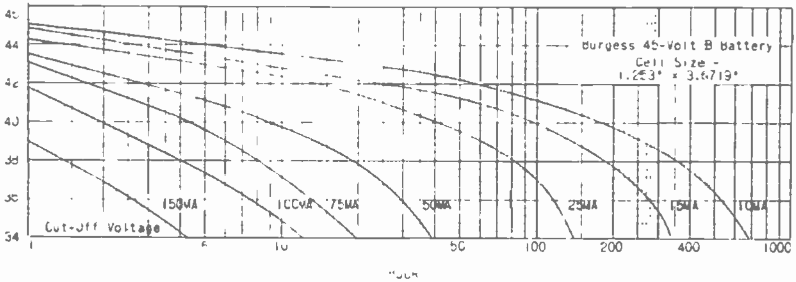
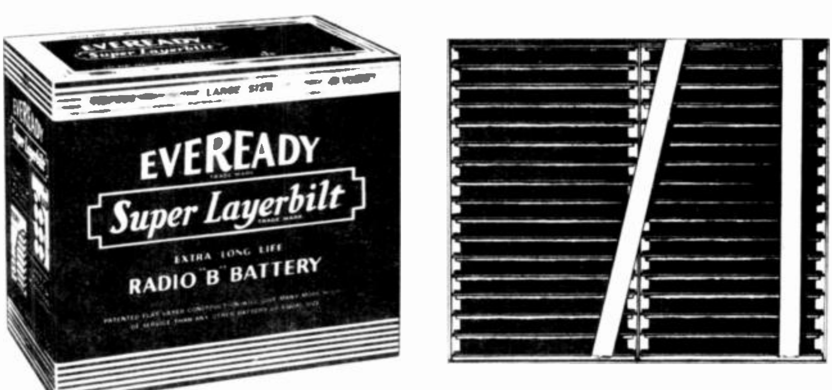


Fig.7 Characteristic curves for cells composing battery shown in Fig.6A. Dimensions are 1.253 x 3.67 inches.

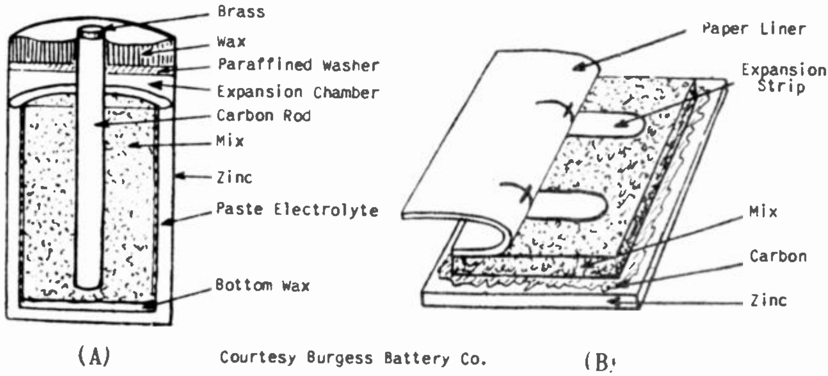
and transmitters are fundamentally of the same construction as the B batteries. Most C batteries, however, contain a fewer number of cells and the cells are smaller in physical size. C batteries are not designed to have any current drawn from them. In all cases, they should be used only to produce a potential difference and not to supply electrical power. The typical 22½-volt C battery is shown at C in Fig. 6.



(A) Courtesy National Carbon Co. (B)

Fig.8 (A) Exterior view of a Layerbilt battery.
(B) Internal view of a Layerbilt battery.

9. LAYERBILT CELLS. All of the cells used in the B and C batteries so far discussed were shown to be of the cylindrical type; that is, each cell consisted of the active chemical constituents contained in a cylindrical zinc cup. An inspection of the cut-away photograph shown in Fig. 4 will reveal that considerable unoccupied space exists between the cylindrical cells as they are arranged within the battery. To reduce this waste space, a battery known as the "Layerbilt" type has been developed by the National Carbon Company, Inc. An internal and an external view of a typical Layerbilt battery are shown in Fig. 8. In the construction of the Layerbilt battery, the cells are arranged in tiers forming two cubes. These two cubes are connected in series internally by a copper band as shown across the center of the internal view in Fig. 8. The active chemical constituents of the Layerbilt cell are ex-



Courtesy Burgess Battery Co.

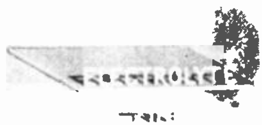
Fig. 9 Drawings to show a comparison between the construction of the cylindrical cell (A), and the Layerbilt cell (B).

actly the same as those used in the cylindrical type. A drawing illustrating the internal construction of a single cell from a Layerbilt battery is shown at B in Fig. 9. The carbon (positive terminal of the cell) is pasted directly on the zinc plate. This eliminates the necessity of connecting these cells in series by short pieces of wire. The paper liner which serves to absorb the moist electrolyte solution, the manganese dioxide, granulated carbon mixture, and the expansion space are shown as they exist in the Layerbilt cell in comparison to the same materials used in the construction of the cylindrical cells.

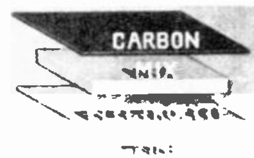
Fig. 10 illustrates the steps in manufacturing a Layerbilt battery.

Upon comparing the construction of a round cell battery with a Layerbilt battery, one difference in particular will be noted. The round cell battery uses one element, the zinc, as the can or container, and as soon as the zinc is eaten through by the chemical action during discharge, the small hole appearing in the can allows the electrolyte to dry out rather rapidly. The result is a rapid decrease of output voltage. In the Layerbilt construction, the zinc is not a part of the electrolyte container; hence, when small holes appear in the zinc electrode, the sal ammoniac (electrolyte) is not exposed. For this reason, the useful life of the battery may be extended until nearly the entire zinc plate is destroyed, with the electrolyte still remaining moist. The discharge curve of the Layerbilt battery does not show a rapid decline in voltage, but rather falls in a nearly "straight line" manner.

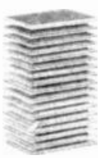
(A) Commercially pure zinc plate.



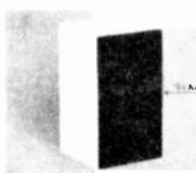
(B) Flat, electrolyte-saturated pad applied to one side of the zinc plate.



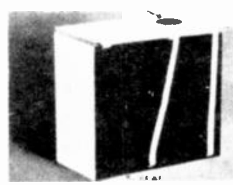
(C) Manganese dioxide mix cake and carbon are next in assembly.



(D) Stack or tier of 15 elements as shown in (C).



(E) Stack is dipped in special compound to seal tightly.



(F) Two tiers placed side by side and connected in series.

Courtesy National Carbon Co.

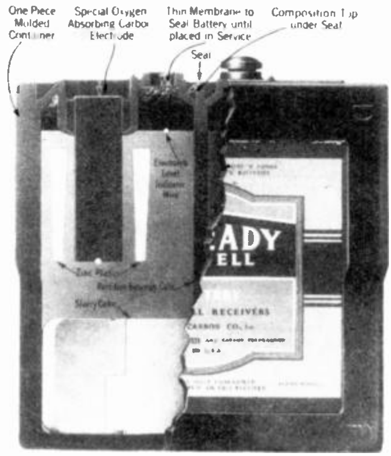
Fig. 10

10. AIR CELLS. The Air cell is the only other type of primary battery which is used to any great extent for Radio purposes. This cell has been developed by the National Carbon Company, Inc., for the purpose of supplying a constant voltage to the filament of the two-volt type tubes used in battery operated receivers.

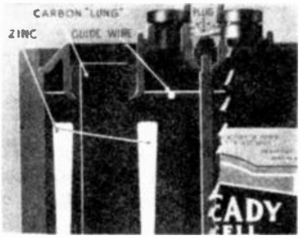
A cross-sectional view showing the internal construction of an Air cell is shown in Fig. 11A. The battery consists of two cells permanently connected in series internally. Zinc and carbon electrodes are used for the negative and positive terminals respectively the same as in a dry cell. The electrolyte solution employed in the Air cell is considerably different, however, consisting of a solution of sodium hydroxide (caustic soda). During the discharge of the cell, the negative zinc electrode is dissolved in the electrolyte solution, and a waste product known as sodium zincate is formed. The formation of this waste product would cause the electrolyte solution to become quickly weakened were it not for the calcium hydroxide introduced in the cell to act as a rejuvenator. The calcium hydroxide unites with the sodium zincate to reform the electrolyte solution. As this rejuvenation of the electrolyte solution occurs, a plentiful supply of the electrolyte (sodium hydroxide) is maintained.

Fig. 11 Courtesy National Carbon Co.

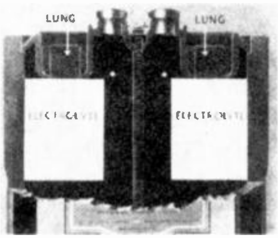
(A-1) External appearance of an Air cell.



(A-2) Cut-away view revealing the internal construction of an Air cell.

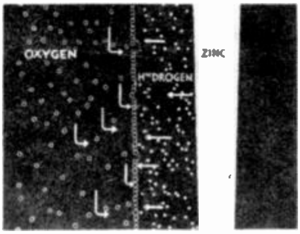


(B-1) Showing carbon and zinc elements of the Air cell.



(B-2) Cut-away to show space occupied by electrolyte.

(B-3) Oxygen is absorbed by the carbon "breather".



(B-4) Absorbed oxygen combines with hydrogen to form water and the cell is depolarized.

During the discharge, the chemical action causes hydrogen gas to be formed over the surface of the carbon electrode the same as in the dry cell. In a dry cell, manganese dioxide acts as the depolarizer to prevent the consistent presence of hydrogen around the carbon electrode. In the Air cell, the electrolyte solution contains no depolarizer, but the special "oxygen-absorbing" carbon electrode possesses the property of extracting oxygen directly from the air to combine with the hydrogen gas which tends to form. The water produced by this combination enters the electrolyte solution. As long as a sufficient supply of oxygen is available at the top surface of the special carbon electrode, the accumulation of the undesirable hydrogen is negligible; consequently, the internal resistance of the cell and the normal voltage output remains practically constant throughout the useful life of the battery. Fig. 11B illustrates this method of depolarization.

To prevent a "shelf life" deterioration of the active chemicals in an Air cell, they are inserted in solid cake form at the time of manufacturing. The battery is sealed by placing thin rubber membranes over the filler holes, and by placing a transparent piece of cellophane over the top of the oxygen-absorbing carbon electrode. Due to this efficient sealing, the active constituents of the battery are as fresh when it is placed in use as they were at the time of manufacture. When the battery is to be placed in service, it is only necessary to break the thin rubber membranes covering the filler holes and remove the cellophane from the oxygen-absorbing carbon electrode. Cold drinking water is then poured into the filler holes until the level of the water coincides with the indicator on the side of the battery. The water dissolves the "cake like" sodium hydroxide to form the electrolyte solution.

In the operation of this type of cell, one important precaution must be observed very closely. *It is absolutely essential that the discharge rate does not exceed approximately .75 amperes.* This limit on the discharge rate is fixed by the speed at which the oxygen-absorbing carbon electrode is capable of extracting oxygen from the surrounding air to prevent polarization at the positive terminal. If an attempt is made to compel the special electrode to absorb oxygen too rapidly, the open pores of the carbon become clogged, resulting in a complete ruination of the battery. After an Air cell has once been seriously overloaded, it is impossible to secure future satisfactory service from it. Whereas an ordinary dry cell can be instantaneously overloaded without any serious effect, this is not true of the Air cell; hence, the discharge rate must be watched very carefully.

The Air cell is capable of supplying about 250 milliamperes for 2400 hours, 500 milliamperes for 1200 hours, etc. It will be noticed that this current-delivering capacity is much higher and the length of useful service is much longer than for any type of dry cell available. Another advantage of the Air cell is that the output voltage remains practically constant throughout its entire life. This is desirable from the standpoint of maintaining a constant filament voltage on the 2-volt battery-operated tubes. Accurate tests which have been made on Air cell batteries show that the output voltage of the cell does not decrease more than .5 of a volt over a period of 1000 hours service under normal load conditions.

This is an outstanding advantage insofar as satisfactory receiver performance is concerned, because unless full electron emission is maintained from the filaments of the tubes in the set, the original capabilities of the receiver cannot be expected. The "constant voltage" output of the Air cell battery is largely responsible for the fact that it is rapidly gaining popularity as a satisfactory filament supply for battery-operated receivers.

The disadvantages of the Air cell are its high initial cost and the fact that it is a primary battery. The initial cost of an Air cell is several times that of a dry cell. This is off-set by the fact that the Air cell will give a longer period of satisfactory service. Since an Air cell is a primary battery, when its discharge has been completed, it must be replaced with a new battery. The cell cannot be recharged.

In view of the many problems involved in the design and servicing of modern battery-operated receivers, no attempt will be made in this lesson to discuss them in detail. Special circuits and operating characteristics pertaining to battery receivers will be explained in detail during Unit 2, which is devoted entirely to servicing information.

11. SECONDARY BATTERIES. As previously defined, a secondary battery is one whose chemical action is reversible. When a secondary cell is discharged, it can be returned to its original charged condition by the application of electrical energy. The electrical energy supplied to the discharged cell is used to convert the depleted chemicals to their original state.

The two types of common secondary cells popular in Radio work are: (1) The lead-acid cell. (2) The nickel-iron-alkaline or Edison cell. Of these two, the lead-acid cell will be discussed first.

12. LEAD-ACID CELLS. The lead-acid cell and the Edison cell are both called "storage batteries". Storage batteries produce a voltage across their positive and negative terminals as a result of chemical action only after they have been subjected to an initial charge. During the initial charging process, a chemical reaction takes place between the active plate materials and the electrolyte to cause the storage of chemical energy.

In a lead-acid cell, the active material in the positive plate consists of lead peroxide[1] (PbO_2), and the active material in the negative plate is pure sponge lead (Pb). Normally, the lead peroxide on the positive plate is chocolate-brown in color, and the sponge lead on the negative plate is pearl-gray. The electrolyte consists of a 25% solution of sulphuric acid in distilled water.

In the construction of a typical lead-acid battery, such as used in automobiles, the positive and negative plates are made by

[1] The chemical name for PbO_2 is either "lead peroxide" or "lead dioxide".

applying a lead oxide (PbO) paste to frameworks or "grids" of lead and antimony alloy. A framework partially filled with paste is shown in Fig. 12. The plate framework provides mechanical strength and is not attacked by the sulphuric acid electrolyte. Several methods are used commercially to apply the lead oxide paste to the

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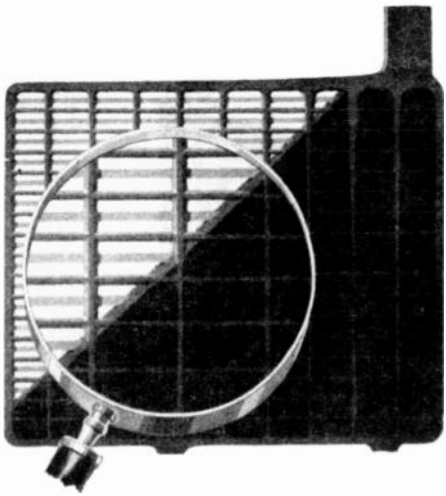
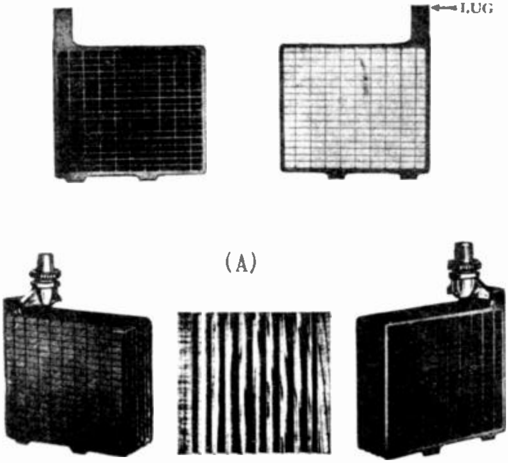


Fig.12 Framework (grid) partly filled with active material.

plates. One of these methods is to paste both plates (positive and negative) with a stiff mixture of lead oxide and water, then immerse them in a dilute sulphuric acid solution. The resultant sulphation (formation of lead sulphate) hardens the paste, causing it to adhere to the antimony framework. Another method is to mix the lead oxide with dilute sulphuric acid or a solution of ammonium sulphate and stir to a uniform thick paste, then apply it quickly to the grid framework before it becomes hardened.

After the plates have been pasted with lead oxide and dried, they are then immersed in a dilute sulphuric acid solution to become "formed". "Forming" consists of passing an electric current from one plate to the other through the electrolyte. The electric current converts one plate into pure spongy lead (the negative plate) and the other plate into lead peroxide (the positive plate).

A group of positive and negative plates which have been formed and are ready for assembly are shown in A, Fig. 13. The two plate groups are intermeshed and wooden separators are inserted between each pair of plates to prevent a short circuit. The group of plates thus assembled form a cell. The cell is placed in a hard rubber or glass container, a cover is placed over the top, and the cell is tightly sealed. B, in Fig. 13, illustrates the method of sealing.



(A)

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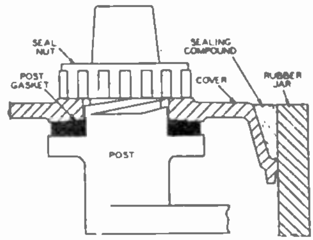

(B)

Fig.13 (A) Positive and negative plates for a lead-acid battery. A wooden separator is shown in the lower center.
(B) Drawing to illustrate the cover seal.

The cell cover has a tapped hole in the center to permit inspection of the electrolyte solution. A vent plug is inserted in the filler hole to prevent spillage. The vent plug has a small hole in the center, which must be kept open to permit gases to escape. A complete lead-acid cell is shown in Fig. 14.

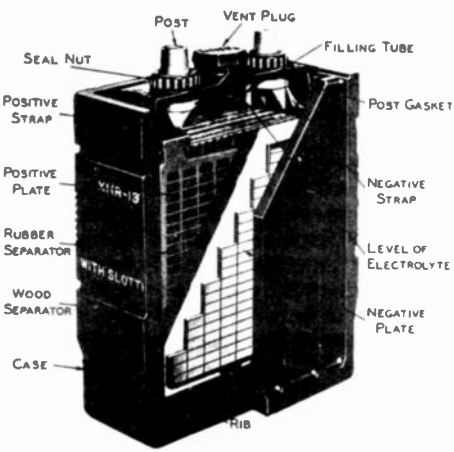

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Fig.14 Complete lead-acid cell cut away to show details of construction.

13. THE ELECTROLYTE. The electrolyte of a lead-acid battery consists of sulphuric acid (H_2SO_4) and distilled water (H_2O). The specific gravity of the solution is generally about 1.275[1] Lead-acid batteries which are to be used for stationary purposes generally have a lower specific gravity electrolyte than those which are to be used for portable purposes. For a specific gravity of 1.275, commercial sulphuric acid is mixed with water in the ratio of 1 to 3 by volume. This means that for each volume of sulphuric acid, there must be three volumes of distilled water. The percentage of the solution is approximately 25%.

When mixing the electrolyte solution, it is very essential that commercially pure (93.5%) sulphuric acid and pure distilled water be used. Sulphuric acid in this concentrated form is rather dangerous if not handled properly, so extreme care must be taken to avoid personal injury. If the occasion arises to mix an electrolyte solution, *EXTREME CAUTION MUST BE OBSERVED!*

Fig.15 Top: Section of a Manchester positive plate. Note how the buttons are securely locked in place by the "hour-glass" shape of openings in the grid.
Bottom: Manchester button, showing how it is rolled into a spiral before inserting in grid of the positive plate.

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14. LEAD-ACID CELLS WITH MANCHESTER POSITIVE PLATES. A more modern type of plate construction in the lead-acid battery consists of the use of Manchester positive plates and Box Negative plates. This plate construction is essentially different than the pasted plate method such as used in the construction of automobile batteries. The grid or framework of the Manchester positive plate is a cast lead-antimony alloy which is able to resist the forming action of the electric current during charge and discharge, thereby retaining its strength, shape, and dimensions. This grid is provided with circular openings, slightly tapered toward the center, into which are forced by hydraulic pressure the rosettes or buttons of soft lead which constitute the active portion of the positive plate. These buttons are made of strips of pure lead, corrugated crosswise and rolled into a spiral. This is shown in Fig. 15. After being forced into place in the grid, they are subjected to the forming process, whereby the active material or lead peroxide is developed electro-chemically on the surfaces. The expansive action of this forming process, combined with the double-taper shape of the opening, securely locks the buttons in place.

The fact that there is always available a supply of solid lead in the rosettes or buttons that can be converted into active material (lead peroxide) as it is needed accounts for the extreme ruggedness and long life of this type of positive plate. A group of Manchester positive plates is shown at C in Fig. 16.

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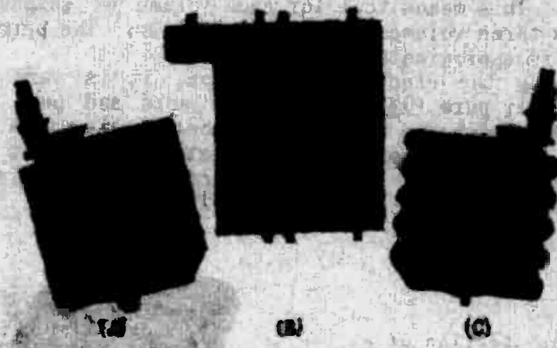

Fig. 16 (A) Group of Box Negative plates.
(B) Board and Rubber dowel separator.
(C) Group of Manchester Positive plates.

The grid of the Box Negative plate, which is also of lead-antimony alloy, is formed of horizontal and vertical ribs, spaced about one inch apart, forming pockets which are closed on both sides with perforated sheet lead. In these pockets, the active material

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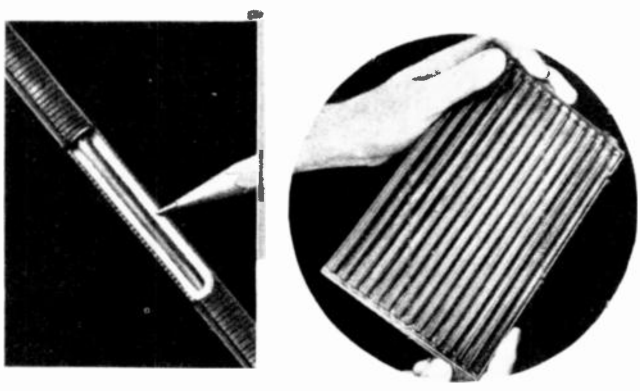
Fig. 17 Single cell lead-acid battery illustrating Manchester and Box plates.

is permanently held in place. The grid must be rigid and inactive, whereas the active material must be exceedingly porous and finely divided in order to obtain a maximum of capacity. By confining this active material within the pockets, as described above, these results are attained and a permanent negative plate is secured. A group of Box Negative plates is shown at A in Fig. 16.

The Manchester positive plates and Box Negative plates are insulated from each other by board and rubber dowel separators. The separator is shown at B in Fig. 16. A cross-sectional view of a typical stationary battery employing the Manchester and Box plates is shown in Fig. 17. Lead-acid storage batteries which are to be used for light commercial service are generally of this construction.

15. THE EXIDE IRONCLAD PLATE CONSTRUCTION. In the Exide ironclad lead-acid battery, the positive plate is of unique construction. This plate consists of a series of vertical tubes of finely slotted rubber within which the active material is contained. The slots in the tube are so fine that, while they permit ready access of the electrolyte to the active material within, they prevent the active material from readily washing out and dropping to the bottom of the jar. The method of retaining the active material may be compared to a tea ball in brewing a cup of tea. The boiling water in the tea cup penetrates the small openings in the ball and easily reaches the leaves, but the latter cannot escape through the small openings.



(A) Courtesy Electric Storage Battery Co. (B)

Fig. 18 (A) Section of a tube from an Exide Ironclad positive plate.
(B) Assembled Exide Ironclad positive plate.

The negative plate is also designed to give a long life.

A section of a single tube from an ironclad positive plate is shown at A in Fig. 18. Notice the metal core surrounded by active material held in place by the finely slotted rubber tube. An assembled ironclad positive plate is shown at B in Fig. 18. Each of the pencil-like ribs is a slotted rubber tube like the one illustrated at A.

The separators used in this type of lead-acid battery are known as the "Exide-Mipor" separators. This separator material satisfies all the requirements demanded of the ideal separator. It is a permanent electrical insulator, but permits free and continuous diffusion of the electrolyte. The mipor is unaffected by either sulphuric acid or excessive battery temperatures. The material is of

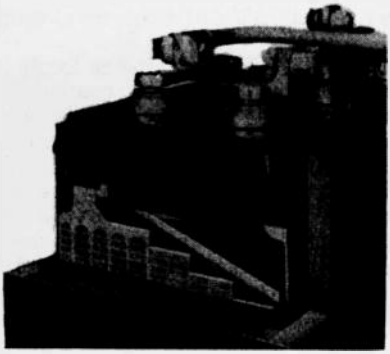


Fig.19 Cut-away section of a typical ironclad battery cell.

Courtesy Electric Storage Battery Co.

uniform structure and strength, with the necessary mechanical qualities to withstand severe vibration and the rough conditions often encountered in everyday use. It will not crack, crumble, or break down even after years of hard service.

The manner of assembling the negative and positive plates with the separators between them is illustrated in the cut-away view of the typical Exide ironclad battery cell as shown in Fig. 19.

Fig.20 Battery container on a railroad car.

Courtesy Electric Storage Battery Co.

These ironclad lead-acid batteries are generally used where tremendous power and extreme ruggedness are the essential characteristics. Industrial trucks and tractors, railroad car lighting, railway signaling, Diesel and gas engine starting are a few of the common commercial uses for this type of cell. Fig. 20 shows the battery container on the side of a railroad car. Railroad cars are lighted and air conditioned by batteries. A generator on the car charges these batteries when the car is in motion.

A multi-cell, ironclad battery such as generally used in industrial trucks and tractors is shown in Fig. 21.

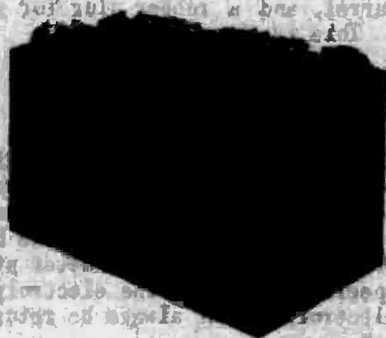


Fig.21 Ironclad battery assembled for industrial truck service.

Courtesy Electric Storage Battery Co.

16. SPECIFIC GRAVITY. *The specific gravity of an electrolyte solution is defined as the weight of the electrolyte solution compared to the weight of an equal volume of water.* This is expressed as follows:

$$\text{Specific Gravity} = \frac{\text{Weight of electrolyte solution}}{\text{Weight of equal volume of water}}$$

The numerical value secured from this ratio means that the electrolyte solution is that many times heavier than an equal volume of pure distilled water. For example, if 1 pint of benzene weighs .9219 pounds and 1 pint of water weighs 1.05 pounds, the specific gravity of the benzene is:

$$\text{S.G.} = \frac{.9219}{1.05} = .878$$

As another example, by measurement, a quart of water is found to weigh 2.1 pounds, and a quart of glycerine weighs 2.646 pounds. The specific gravity of the glycerine is:

$$\text{S.G.} = \frac{2.646}{2.1} = 1.26$$

As stated previously, the specific gravity of the electrolyte solution to be used in a stationary battery is approximately 1.275!

It is possible to measure the specific gravity of any liquid solution by use of a hydrometer syringe. The hydrometer portion of the syringe consists of a glass tube about 3 to 5 inches long, having an elongated bulb on one end and partially filled with lead shot or mercury so that it will float in an upright position when placed in the electrolyte. The upright end of the hydrometer tube is calibrated to show the specific gravity of the solution drawn into the syringe.

The complete syringe consists of a glass barrel, a hydrometer which fits inside the glass barrel, a short rubber tube for reaching into the electrolyte, a rubber bulb which fits on one end of the barrel, and a rubber plug for joining the glass barrel to the tube. This is shown in Fig. 22.

Fig.22 A complete hydrometer syringe.

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To take a specific gravity reading with the hydrometer syringe, place the rubber tube into the electrolyte solution, then squeeze the bulb and slowly release it, drawing enough of the electrolyte into the barrel to freely float the hydrometer. The reading on the calibrated stem of the hydrometer at the surface of the liquid is the specific gravity of the electrolyte. After taking the reading, the electrolyte must always be returned to the cell from which it was taken.

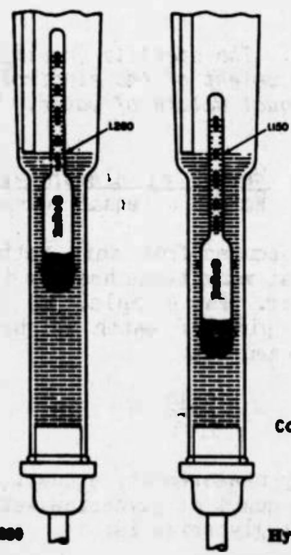

Fig.23 Illustrating specific gravity readings on a hydrometer scale.

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Hydrometer Reading 1.200

Hydrometer Reading 1.150

Two drawings illustrating different readings on the hydrometer scale are shown in Fig. 23.

The specific gravity of any electrolyte solution is affected by the temperature; hence, a temperature correction factor must be applied to the specific gravity after it is read on the hydrometer. Most hydrometers are calibrated to read the specific gravity at 80° F. At temperatures above 80° F, the electrolyte solution expands; hence, the specific gravity reading on the hydrometer will be lower than the actual specific gravity of the solution. *For each 3 degrees above 80° F, one point (.001) should be added to the specific gravity reading.* Similarly, if the temperature is less than 80° F, the electrolyte solution contracts, and the specific gravity reading obtained on the hydrometer will be greater than the actual specific gravity of the solution. *For each 3 degrees less than 80° F, one point (.001) should be subtracted from the hydrometer reading.*

Example 1: If the hydrometer reading is 1.260 at a temperature of 95° F, what is the actual specific gravity of the electrolyte?

SOLUTION: 95° is 15° higher than the standard 80° temperature. Dividing 15° by 3, we obtain 5; so 5 points must be added to the hydrometer reading, thus making the actual specific gravity of the solution 1.265!

Example 2: If the hydrometer reading is 1.175 at a temperature of 50° F, what is the actual specific gravity of the electrolyte solution?

SOLUTION: The temperature of 50° is 30° below the standard temperature of 80°. Dividing 30° by 3 we obtain 10. Subtracting 10 from the hydrometer reading, we obtain an actual specific gravity of 1.165!

The freezing point of the battery depends upon its specific gravity, the following table showing how this varies:

Specific Gravity	Freezing Point
1.275	-85° F
1.250	-62° F
1.225	-35° F
1.200	-16° F
1.175	- 4° F
1.150	+ 5° F
1.125	+13° F
1.100	+19° F

If water is added to a battery in freezing temperatures and the battery is let stand in the cold and not charged to mix the water with the electrolyte, the water will remain on top and freeze.

This complete discussion on the hydrometer and methods of taking specific gravity readings has been given because a specific gravity test of the electrolyte solution in a lead-acid cell is a very common procedure. The state of charge of a lead-acid battery can be determined to a high degree of accuracy by observance of the specific gravity reading.

17. CHEMICAL ACTION IN A LEAD-ACID CELL. The chemical reaction in a lead-acid cell is particularly important, because without it, it would be impossible to satisfactorily maintain and preserve continuous normal operation. When a lead-acid cell is being discharged, the sulphuric acid in the electrolyte is being decompos-

ed, a portion of it combining with the active material on both plates. The composition of each plate gradually changes to lead sulphate. This conversion of the active plate material will continue until nearly all of the acid has been removed from the electrolyte solution. From the discussion on specific gravity, we know that as sulphuric acid is removed from the electrolyte, the specific gravity of the solution decreases. By making a specific gravity test, and correcting the reading for temperature, it is possible to determine the extent of the electrolyte decomposition and thus determine the state of charge of the cell. When the specific gravity reaches a value as low as 1.150, the positive and negative plates of the cell are nearly similar in composition and the useful output voltage of the cell has decreased considerably. A continued discharge of the cell beyond this point is not advisable because it will be difficult to recharge the cell. When measured with a low-resistance voltmeter, the discharged voltage of a lead-acid battery is approximately 1.75 volts. The fully charged voltage is 2.1 volts.

Charging a secondary cell consists fundamentally of returning the electrical energy which was taken from the cell on discharge. A DC voltage of the proper potential and capable of delivering the required current is connected across the cell. The charging current is forced through the electrolyte solution in the opposite direction to the flow of current from the cell when it was discharging. This causes the lead sulphate formed on both plates during discharge to be converted back to lead-peroxide on the positive plates and pure sponge lead on the negative plates. The decomposition of the lead sulphate is accompanied by a return of the sulphuric acid to the electrolyte solution. As the concentration of the sulphuric acid increases, the specific gravity of the electrolyte solution rises. As soon as the electrolyte solution is restored to normal specific gravity (1.275), the cell is fully charged and is again capable of delivering electric power.

The four changes through which a lead-acid cell passes during the discharging and charging process are shown at A, B, C, and D in Fig. 24. A careful study of these four drawings will serve to substantiate the foregoing information. Stated in chemical terms, the reaction which occurs during discharge and charge is:

On Discharge: $\underset{\text{Negative Plate}}{Pb} + \underset{\text{Positive Plate}}{PbO_2} + \underset{\text{Electrolyte}}{2H_2SO_4} \longrightarrow \underset{\text{Both Plates}}{2PbSO_4} + \underset{\text{water}}{2H_2O}$

Pure Lead + Lead Peroxide + Sulphuric Acid   Lead Sulphate + Water

On Charge: $\underset{\text{Both Plates}}{2PbSO_4} + \underset{\text{Water}}{2H_2O} \longrightarrow \underset{\text{Negative Plate}}{Pb} + \underset{\text{Positive Plate}}{PbO_2} + \underset{\text{Electrolyte}}{2H_2SO_4}$

Lead Sulphate + Water   Pure Lead + Lead Peroxide + Electrolyte

As can be seen, these two reactions are exactly opposite, which indicates that the lead-acid cell undergoes exactly opposite changes on charge and discharge.

18. CHARGING RATES. *The charging rate of a battery refers to the amount of current in amperes which is passed through the cell during the charging process.* The charging voltage must be a DC

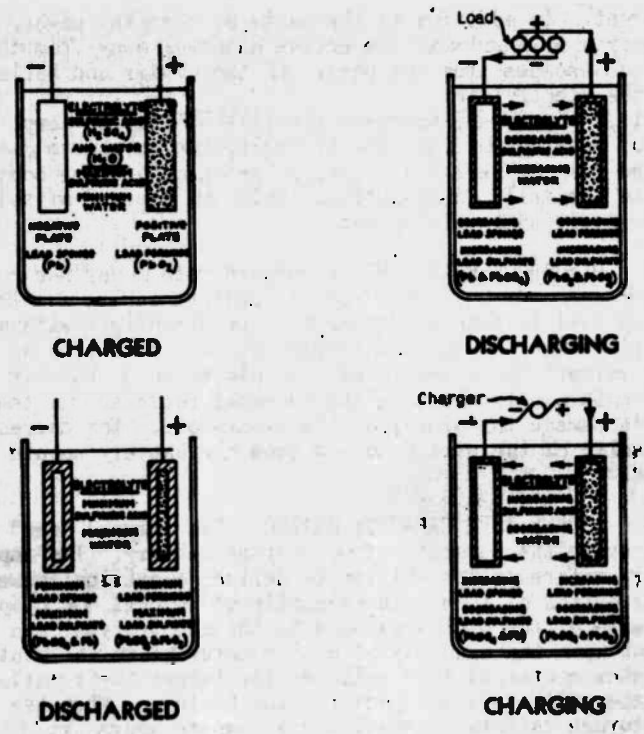

Fig.24 Diagrams showing the essential chemical actions in a storage battery.

Courtesy Electric Storage Battery Co.

voltage and its value must exceed the voltage of the cell in order to force current through it. If the charging rate is excessively high (too much current), considerable damage to the battery may result. When a battery is being charged, the amount of sulphate in its plates decreases and the ability of the plates to give up acid becomes reduced. During the earlier part of the charge, the plates can give out the acid at a rapid rate because there is a large amount of sulphate available. Therefore, a battery which has been discharged to a low specific gravity can be charged with a high rate at the start, but as the charge approaches completion, the charging rate must be reduced because there is not sufficient sulphate in the plates to be rapidly driven out. If the high charging rate is maintained, only a portion of the charging current is used to drive out the acid from the plates, the balance of it acting to decompose the water in the electrolyte into oxygen and hydrogen, which are given off in the form of gas. Gassing of the battery, therefore, at any time, shows whether or not the charging rate is too high; consequently, when it is found that the cells are gassing, the rate of charge should be reduced so as not to waste the charging current. In addition to the waste of charging power, there is a tendency to wash and wear the active material away from the plates as the gas escapes from the pores of the plates and boils to the top of the electrolyte.

This, of course, shortens the life of the battery. A small amount of gassing is not objectionable, but excessive gassing, if continued for any period of time, is certain to cause considerable damage to the cell. A comparison table at the end of this lesson supplies additional information.

19. DISCHARGE RATE. *The discharge rate is defined as the rate at which current is drawn from a battery during discharge.* Any lead-acid cell in good condition may be discharged without injury to the plates at any rate of current it will deliver. An extremely high current drain should not be placed on a battery for any great length of time because the internal increase in temperature is apt to damage the plates or the separators. The current-carrying capacity of the wiring to and from the battery should never be exceeded.

20. AMPERE-HOUR CAPACITY RATING. The "ampere-hour" is a unit for measuring the capacity of a storage battery. The **capacity** of a battery refers to its ability to deliver electrical power over a definite period of time. The capacity of a cell is proportional to the area of the plates exposed to the electrolyte, and is also dependent upon the quantity of active material in the plates. The more plates contained in a cell and the larger their surface area, the greater will be the capacity of the battery. When the capacity of a storage battery is specified in ampere-hours, it is usually based on a normal eight-hour rate of discharge. This means that if a battery has a rating of 100 ampere-hours capacity, it will deliver a continuous current (without injury) of 12.5 amperes for 8 hours. Also, if a battery has an ampere-hour capacity rating of 80, it is capable of delivering a continuous current of 10 amperes for 8 hours. Use of the 8-hour period as the basis for the ampere-hour rating has been adopted by general agreement among the storage battery manufacturers. If the discharge rate is higher (more current) than that specified by the normal ampere-hour capacity rating, the total capacity of the battery will be less than the manufacturer's specifications. Similarly, if the rate of discharge is lower (less current) than the standard 8-hour rate of discharge, a greater capacity will be obtained from the battery than that specified by the manufacturer. The greatest amount of electrical power will be secured from a storage battery when it is discharged at a low, intermittent rate.

21. DISCHARGE LIMIT. In an emergency, little if any, permanent harm will result if the battery is discharged to the full amount that it will give, provided that it is promptly recharged. It has already been pointed out that the specific gravity of the electrolyte should not be permitted to fall below a certain value.

The danger of harm from "over-discharge" may be illustrated by a comparison between the active material of the plates and the action which goes on when some of the electrolyte is allowed to act on the copper wiring terminals of a battery. It is noticeable that a comparatively large amount of copper sulphate is formed when only a small quantity of the metal is eaten away by the acid. In the same manner, when the acid combines with the lead in the active material, the resulting lead sulphate occupies more space than the active material from which it is formed. The active material of all battery plates is porous, and this expansion of the sulphated material is accommodated by reducing the size of pores in the active material. All battery plates are designed to accommodate a certain amount of this expansion of the active material during sulphation, and in batteries of the type under consideration, this is limited to the amount represented by a certain specific gravity reading.

Further discharge, even if it can be obtained at a satisfactory voltage, results in an excessive expansion which so closes the pores in the active materials that it becomes increasingly difficult to recharge the battery properly after an excessive discharge, and unless a proper reoharge is given, the battery is likely to deteriorate.

Additional information will be given on the maintenance and charging methods for lead-acid and nickel-iron cells in a future lesson.

22. THE NICKEL-IRON-ALKALINE CELL. The Edison nickel-iron-alkaline storage cell is the only alkaline cell produced in the United States and is manufactured by the Edison Storage Battery Division, Thomas A. Edison, Inc. It is more commonly known as the Edison cell. The Edison cell differs from the lead-acid cell in many respects. The electrolyte solution, the mechanical construction, the electrical characteristics and the cell assembly are vitally different from the lead-acid storage cell just discussed.

The positive plate of the Edison cell consists of a nickeled-steel grid holding nickeled-steel tubes which contain the positive active material. When inserted in the tubes, the active material is in the form of nickel hydrate, but this changes to an oxide of nickel after the formation treatment (to be described later). In order to give the electrolyte free access to the active material, the tubes are perforated. To obtain maximum utilization of the positive active material, it is alternated with layers of nickel-flake at the time it is tamped into the tubes. The tubes are reinforced with eight encircling seamless steel rings, equally spaced. The tubes are mounted in the grid and forced into permanent position under forty tons of pressure.

Fig. 25 shows the entire positive plate assembly and also a cross-sectional view revealing the internal construction of a single tube. In the cross-sectional view, notice the alternate layers of nickel-hydrate and nickel-flake which have been tightly packed into the tube.

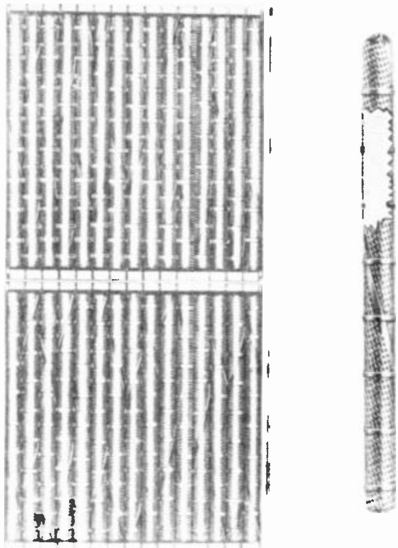

Fig.25 (Left) Assembled positive plate of an Edison cell.
(Right) Single tube cut away to reveal internal construction.

Courtesy Edison Storage Batteries

The negative plate is generally similar in construction to the positive, except that a finely divided oxide of iron is used as active material and is contained in rectangular perforated steel pockets instead of tubes. The pockets are forced into place under 120 tons pressure. The grid and the pockets, like the positive grid and tubes, are of nickeled-steel. A side view of an assembled cell showing the appearance of the negative plate is shown in Fig. 26.

By passing a connecting rod through holes at the top of the plates, the positive and negative plates are assembled into positive and negative groups. Steel spacing washers between adjacent plates and the connecting rod insure proper plate spacing. The base of the pole piece is the middle spacer and being thus secured to the connecting rod, insures unfailing electrical contact between pole, connecting rod, and all plates. A lock washer and nut are drawn up tight at each end of the connecting rod, binding the plate group firmly together. All washers, nuts, connecting rods, and terminal posts, like the plates, are of nickeled-steel.

The positive and negative plate groups are intermeshed to form complete elements. The negative group always contains one more plate than the positive, so that both outside plates are always negative. Insulation between the alternate positive and negative plates is accomplished by vertical, hard rubber pins running their entire length. Rubber sheets insulate the outside negative plates from the sides of the container, while the edges of the plates are insulated from the bottom and the other sides of the container by hard rubber frames. These frames also serve the purpose of separating the plates and holding them in correct alignment. They are so designed as to permit free circulation of the electrolyte.

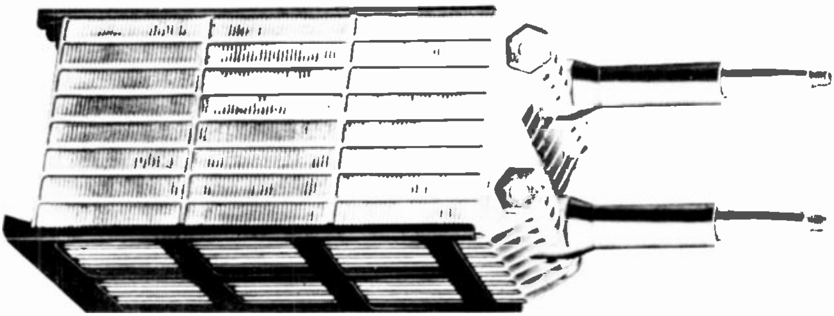

Fig.26 Side view of assembled Edison cell showing the construction of the negative plate.

Courtesy Edison Storage Batteries

The electrolyte consists of a 21% solution of potassium hydroxide in distilled water, to which has been added a small percentage of lithium hydrate. The electrolyte has a specific gravity of about 1.2 at 60° F, and does not vary appreciably in specific gravity during charge and discharge. The electrolyte (potassium hydroxide) does not attack steel and advantage is taken of this fact in the nickel-iron-alkaline cell in order to obtain the strength and durability of steel in the container as well as in the elements. The container is made of nickeled-steel and all joints welded. For the larger sizes, the containers are corrugated to increase strength and to facilitate the radiation of heat.

The cell cover is made of nickeled-steel and is welded in place. Soft rubber bushings, expanded by steel rings and hard rubber, threaded gland caps, insulate the pole pieces where they project through the cell cover and at the same time provide an air and liquid-tight packing around the poles.

Projecting from the cell cover is the filling aperture on which is mounted a hinged filler cap. The filler cap is held either open or closed by a steel clip spring. Suspended from the filler cap is a hard rubber valve which seats by gravity when the cap is closed, thus excluding external air and reducing evaporation, but permitting the escape of gas.

The electrolyte is at a level varying from ½ inch to 3 inches above the plate tops, depending on the type of cell. The small quantity of lithium hydrate which is added to the electrolyte solution tends to increase the capacity and cell life.

23. FORMATION OF THE CELL. After the assembly of the cell is completed, it is given several cycles of charge and discharge. This is known as "forming" and is for the purpose of stabilizing the electro-chemical characteristics. It is continued until factory tests show normal operation and an ability to deliver an excess over the rated capacity.

All cells are coated with a heavy insulating paint, after which a protective film of rosin petroleum jelly is applied to the cell tops.

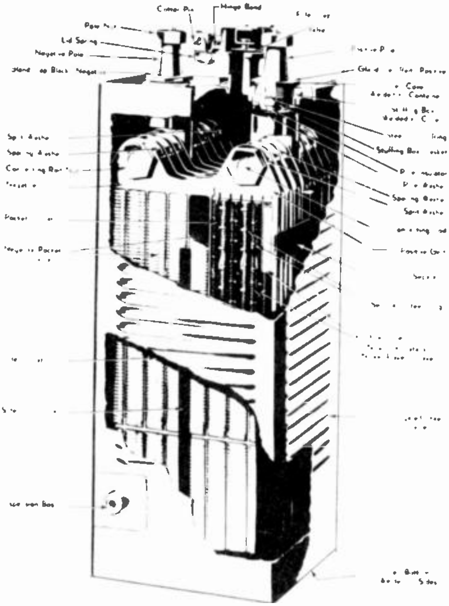

Fig. 27 Cut-away view of Edison cell to show constructional detail.

Courtesy Edison Storage Batteries

The internal construction and assembly of the Edison nickel-iron-alkaline cell is clearly shown in Fig. 27.

24. BATTERY ASSEMBLY. The nickel-iron-alkaline cells are assembled into batteries in hardwood trays. Steel suspension bosses previously spot welded to the sides of the cell containers fit into hard rubber buttons recessed in the tray slats. This assembly supports each cell in place and insulates it from the tray and from adjacent cells, and at the same time permits free circulation of air around each cell. The typical battery assembly is shown in Fig. 28.

25. CHARACTERISTICS OF THE EDISON CELL. Edison storage cells possess several important characteristics which make them ideally suited to different services to which they are applied. These advantages and characteristics are directly attributable to the materials used, method of construction and to the fundamental electrical and chemical principles of operation of cells of this type.

For example, the containers of Edison cells are made of steel instead of rubber, the plates are also made of steel instead of lead and the electrolyte is an alkaline solution instead of an acid. The use of steel for all metal parts permits precision manufacturing and produces a cell physically strong and capable of withstanding successfully the wear and tear incident to service. The use of steel for the positive and negative plates makes possible a sturdy plate structure securely holding the active materials and not subject to buckling and warping as a result of internal stresses and strains. The alkaline electrolyte is a preservative of steel and its use makes possible a cell free from acid fumes and spray.

In a subsequent lesson, additional information will be given on the care and maintenance of an Edison cell.

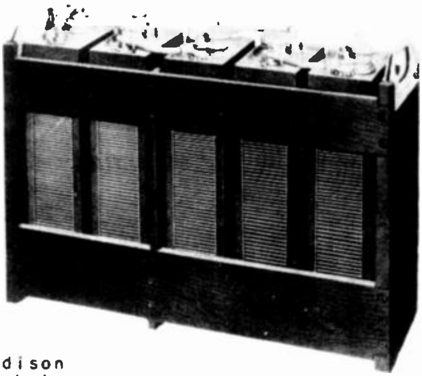

Fig.28 Five Edison cells in a typical battery assembly.

Courtesy Edison Storage Batteries

26. ELECTRICAL CHARACTERISTICS OF THE EDISON CELL. Like other storage cells, direct current must be used to charge the Edison cell. If only an alternating current supply is available, suitable rectifying equipment must be provided to convert to direct current. The voltage to be used for charging varies with the method of charging and time available. The simplest method, that of "Constant Current Charging", requires a voltage of at least 1.85 volts per cell with the rate held approximately normal by means of variable series resistance. Higher rates of charge can be used providing the temperature of the solution in the cells nearest the center of the warmest part of the battery does not exceed 115° F. The battery is fully charged when, with constant current flowing, a maximum voltage has been reached and maintained for at least 30 minutes. The initial voltage of an Edison cell, when placed on discharge at normal rate after having been fully charged, will be approximately 1.37 volts. The average discharge voltage under the same conditions is 1.2 volts per cell.

The state of charge cannot be determined by a hydrometer reading since the specific gravity of an Edison cell does not change to any marked extent during the charge or discharge cycle. The only time it is necessary to take specific gravity readings is to determine when a change of electrolyte would be advantageous. The potash electrolyte in Edison cells has a normal specific gravity of approximately 1.200 at 60° F, when at the normal level above the plates and thoroughly mixed by charging and when sample is taken at least one-half hour after charge to allow for dissipation of gas.

The most accurate method of determining the state of charge is by means of a key voltage reading taken from a pilot cell of the battery with a calibrated resistance applied across the poles of the cell. Suitable charts will then give the state of charge and the amount of charge necessary to restore the battery to a fully charged condition. Such an instrument is known as the Edison Charge Test Fork.

While charging storage batteries, a certain amount of water is always dissociated and an explosive mixture of hydrogen and oxygen given off so sufficient ventilation must be provided for Edison, as well as lead cells to permit rapid dissipation of gas.

Because of their extreme sturdiness of construction and their fundamental electro-chemical principle of operation, Edison cells last for a long period of time, depending on the type of service. Many Edison users have received fifteen and more years of useful life and it is not at all unusual for these batteries to remain in consistent service for even a longer period of time.

27. **CHEMICAL ACTION OF THE EDISON CELL.** One of the generally accepted chemical formulas for describing the actions and reactions during the charge and discharge of an Edison cell may be expressed as follows:

KOH	+	$6NiO_2$	+	$3Fe$		Fe_3O_4	+	$2Ni_3O_4$	+	KOH
Electrolyte		Positive Plate		Negative Plate	$\longrightarrow$	Negative Plate		Positive Plate		Electrolyte
Potassium Hydroxide	+	Nickel Dioxide	+	Iron	becomes	Magnetic Iron Oxide	+	Nickel Oxide	+	Potassium Hydroxide

The chemically active material in the positive plate of an Edison cell is nickel-dioxide and the active chemical constituent of the negative plate is the pure metallic iron. The electrolyte solution is potassium hydroxide and, as can be seen from the above reaction, it is not changed during the chemical reaction. When on discharge, the pure metallic iron is oxidized and converted to magnetic iron oxide (Fe_3O_4). The nickel-dioxide on the positive plate is converted during the discharge into a lower oxide of nickel (Ni_3O_4).

As the cell is charged, the reverse of the above reaction takes place; that is, the low oxide of nickel (Ni_3O_4) is raised to the higher nickel-dioxide (NiO_2), and the magnetic iron oxide (Fe_3O_4) is reduced to pure iron (Fe). This transfer of oxygen which takes place from the positive to the negative plates on discharge produces electrical energy. Since the potassium hydroxide electrolyte of the Edison cell does not enter into the chemical reaction, its specific gravity does not change appreciably during charge and discharge.

28. SUMMARY OF DATA ON LEAD-ACID AND EDISON CELLS.

	EDISON CELL	LEAD CELL
Voltage, charged	1.37	2.1
Voltage, discharged	1.	1.75
Specific Gravity, charged	1.2 app.	1.275
Specific Gravity, dischargec	1.2 app.	1.150
Charging Voltage per Cell	1.85	2.3 to 2.65
Ampere-Hour Efficiency (%)	80 to 82	85 to 95

Notes

(These extra pages are provided for your use in taking special notes)

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INC.

POWER & LIGHT BUILDING KANSAS CITY, MISSOURI

UNIT NO. 1

POWER SUPPLY
RECTIFIER CIRCUITS

LESSON NO. 16

THOMAS ALVA EDISON

.......(CONCLUDED)

On February 19, 1873, a patent was secured by Edison on one of the most marvelous inventions which his ingenious mind ever conceived.....an invention which revolutionized the business world and added another enjoyment to life's pleasures.....the phonograph. It was while singing into the mouthpiece of a telephone that the idea of the 'talking machine' was conceived by him. The vibrations of the fine steel point of the mouthpiece on his fingers lead him to believe that they could be recorded on a strip of material which, when again run under the needle, would give back the same sound which was impressed. He tried the experiment first on a strip of telegraph paper, shouting the words 'Hello! Hello!' into the mouthpiece. Then, when this paper was run again under the steel point, a faint 'hello! hello!' was heard. Although the idea of his invention was laughed and scoffed at, Edison was not discouraged in the least. He continued on until his crude model had taken on the refinements which made the 'talking machine' the marvelous instrument that entertained millions previous to radio's advent, and whose use in the Radio field is tremendous.

Ever searching for something new in the realm of science, and never discouraged, he next conceived doing for the eye what he had just accomplished for the ear; that is, preserving a moving picture for the eye the same as he had made possible the preserving of voice and sound for the ear. Although he had but little knowledge of cameras, and had never taken a snapshot or developed a plate, he plunged into the study of photography with a zeal which knows nothing but success. After mastering the study of photography, he reasoned that to secure natural, life-like movement to the eye, it would be necessary to take separate pictures at a high rate of speed--forty to sixty per second--and then project them on a screen at this same speed. By so doing, the eye would not be able to differentiate between them and they would appear as a moving picture. Although such a machine promised to be very interesting and presented wonderful possibilities, there was also present the fact that there was no film capable of taking pictures at such a rapid rate of speed. However, with his usual quality of not 'giving up' in the face of difficulties, he added a photographic laboratory to his establishment and immediately set to work to find the kind of film he desired. As usual, his efforts were rewarded with the evolving of a film which suited his purposes, together with the 'kinetoscope', the machine to be used for the portrayal of the pictures.

The actual demonstration of the machine now began, with the boys in the laboratory turning somersaults, standing on their heads, playing leap-frog, and doing everything imaginable for the film camera. Edison then turned his attention to the talking motion picture, and from his idea has sprung today's modern motion picture, one of the nation's largest industries, which provides entertainment for millions of people the world over.

Although what we have told you of the life of Edison has covered only a very small portion of his many inventions and achievements, it should give you an idea of his remarkable foresight, his firm belief in his ideas, and his unfailing determination to carry them out. You should, indeed, profit much by his wonderful example, and by his motto: 'Genius is 2% inspiration and 98% perspiration'. Let this be your motto. You have the foresight, for you are preparing yourself for a future in the promising field of Radio and Television; so apply your determination and carry it out with '98% perspiration'. STICK TO YOUR STUDIES AND WIN!

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Lesson Sixteen

POWER SUPPLY RECTIFIER CIRCUITS

"Vacuum Tube Rectifiers with their associated Filter Circuit and Transformer constitute the Power Supply System for practically all modern Radio and Television Receiving and Transmitting equipment.

"Since you are going to use Power Supplies in every phase of your future work, I suggest you study this lesson thoroughly and carefully so that you will have no trouble in associating this equipment with the other apparatus you will study. One of your first experiments will be the construction and testing of a complete Power Supply System."

The use of batteries for power supply to the filament, grid and plate circuits of vacuum tubes has several disadvantages. First, batteries have a relatively short life, and the output voltage of a battery depends upon its age. With reduced voltages, the operation of a receiver is far from efficient. Battery power is also more expensive than the power taken from AC supply lines. Then, too, batteries are inconvenient. If a storage battery is used for the filament voltage supply, it requires regular attention. It must be charged and filled with distilled water at frequent intervals. It must be placed where there is no possibility of the acid bubbling out and spilling upon the furniture, rugs, or floor, where it will cause great damage. The use of an Air-cell for filament supply eliminates the difficulties associated with acid electrolytes; however, the Air-cell is a primary battery. Dry cell B batteries are expensive and inconvenient. After a B battery has been in use for some time, the output voltage does not remain steady, but fluctuates, causing the set to become noisy.

For these reasons, batteries have, wherever possible, been discarded and the radio set designed to operate from the AC line supply voltage. In many instances, battery power is the only type of power available. This is especially true of farm receivers, automobile receivers and aircraft receivers. A number of farms, at present, have 32-volt lighting systems and all-electric receivers have been designed for this voltage. Many automobiles now use small generators which supply a 110-volt alternating current. These generators are driven by the gasoline motor.

About 1924, the B eliminator was introduced. This device, as its name implies, converts the lighting supply voltage into voltages suitable for the plates of the vacuum tubes, thereby eliminating the B battery. This was a forward step toward the all-electric receiver. In a short time, the A eliminator appeared; a device which converted the alternating supply voltage into a low DC voltage for filament supply. These two devices were decided improvements, yet they left much to be desired. They were cumbersome and required a certain amount of attention.

In 1927, the first AC operated vacuum tubes were introduced. They were designed so as to have their filaments operated by an alternating voltage. Three tubes, the type 26, type 27, and type 71-A were brought out at this time and they made possible a completely AC-operated radio receiver.

1. **FILAMENT SUPPLY.** In all of the vacuum tube circuits given in previous lessons, batteries have been used for filament voltage. Fig. 1 illustrates a single type 01-A tube with its filament voltage supplied by a 6-volt storage battery. Since the type 01-A re-

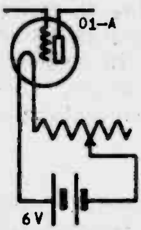
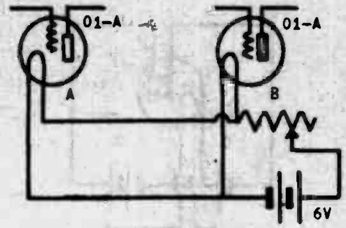


Fig. 1 An 01-A tube receiving its filament voltage from a 6-volt storage battery.

quires 5 volts on its filament, it is necessary to include a rheostat in the filament circuit to reduce the 6 volts of the storage battery to 5 volts for correct operation of the filament. The rheostat, which is a variable resistor, allows us to set the filament voltage at the correct value. A variable resistor must be used because the output voltage of the storage battery will fall as it discharges. By referring to a tube manual, it is found that the type 01-A requires a .25-ampere filament current.

If the 6-volt storage battery is used to heat the filaments of the two tubes, they are connected in parallel as shown in Fig. 2. It would be possible, of course, to insert a separate rheostat in each filament circuit; however, since both tubes require 5 volts for correct operation, only one need be used. It is connected so that the filament current of both tubes flows through it. The filament of tube A draws .25 ampere from the battery and the filament of tube B draws an equal amount. Therefore, the total current flowing through the battery and through the rheostat is .5 ampere. Since the rheostat has twice as much current flowing through it,

Fig. 2 Two 01-A tubes connected to the same battery. One rheostat serves to control both tubes.



its resistance should be half as great in order to produce the voltage drop from 6 volts to 5 volts. In Fig. 3 are shown three type 01-A tubes securing their filament voltage from the same 6-volt storage battery. Each of the tubes draws .25 ampere; therefore, since the tubes are connected in parallel, the total current flowing through the battery and the rheostat is .75 ampere and the

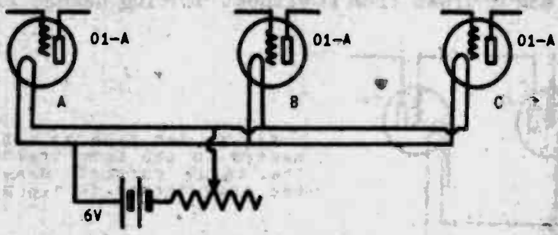


Fig. 3 Three 01-A tubes connected to the same battery. The total current drawn from the battery is .75 ampere.

value of the rheostat in ohms must be such that it will correctly drop the voltage of the 6-volt storage battery to 5 volts. Since the three tubes are connected in parallel, the voltage across each filament is 5 volts.

In a previous lesson, the construction of the cathode type tube was studied. This tube consists of a heater, the purpose of which is to heat the cathode, a metal sleeve in close proximity to, but not in electrical contact with, the heater. The cathode is coated with a material which emits electrons at relatively low temperatures. The cathode itself is the emitter; and it is the cathode (not the heater) to which the plate and grid circuits must be returned to make them complete. Fig. 4 shows a tube of this type using a filament transformer to supply the heater voltage. This is a type 27 tube which requires 2.5 volts heater voltage and draws 1.75 amperes heater current. This 2.5 volts is supplied by the stepdown transformer. The primary is connected to a 110-volt, 60-cycle alternating current source and the transformer is designed to produce 2.5 volts across the secondary. Fig. 5 shows two tubes connected to the same transformer. The two heaters are connected in parallel; therefore, the voltage across each is 2.5 volts. Each heater draws 1.75 amperes; therefore, the total current drawn from the secondary of the transformer is 3.5 amperes and the transformer must be so designed that its secondary is capable of passing this much current without overheating. The rating of a transformer wind-

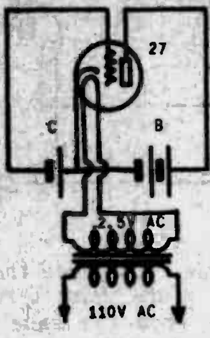


Fig.4 A type 27 tube connected to a filament transformer.

ing includes the voltage which is produced across it and the maximum current that can be drawn from it without causing damage from excessive heat.

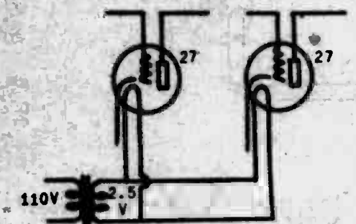


Fig.5 Two type 27 tubes connected to the same transformer. The total current drawn from the transformer is 3.5 amperes.

The directly heated cathode or filament type tube has also been designed to be used with AC on its filament. A typical example is the type 45. When an AC voltage is applied to the filament of a directly heated cathode type tube, a difficulty arises. This can best be explained as follows: Fig. 6 shows the various circuits of a tube using batteries for power supply. The A battery is 5 volts,

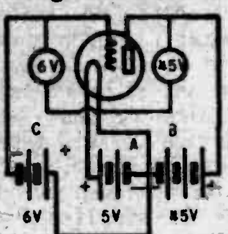


Fig.6 Illustrating the plate and grid voltages when these circuits are returned to the negative side of the filament.

the B battery, 45 volts and the C battery, 6 volts. We have learned that all voltages are measured from the elements of the tube to the negative side of the filament. For instance, the plate voltage is measured from the plate of the tube to the negative side of the filament and the grid voltage is measured from the grid of the tube to the negative side of the filament. In this case, then, the plate voltage is 45 volts and the grid voltage is 6 volts. Now, consider Fig. 7. Suppose the grid and plate circuits are returned to the

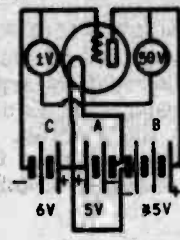


Fig.7 Illustrating the plate and grid voltages when these elements are connected to the positive side of the filament.

positive side of the filament. The B battery has the same voltage as before; however, the plate voltage, as measured from the plate of the tube to the negative side of the filament, is now equal to 50 volts, or the voltage of the B battery plus the voltage of the A battery since these two batteries are connected in series. Also, the grid voltage as measured from the grid of the tube to the negative side of the filament is now found to be 1 volt, or the difference between the C battery and the A battery. These two batteries are also connected in series, but they are connected in such a manner that the voltage of one opposes the voltage of the other; that is, the grid is 6 volts negative with respect to the positive side of the filament, but is only 1 volt negative with respect to the negative side of the filament.

Suppose that an alternating voltage is applied to the filament of this tube as shown in Fig. 8. The plate and grid circuits are

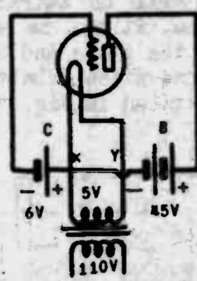


Fig.8 Returning the grid and plate circuits to one side of the secondary of the filament transformer.

returned to point X. Let us see how this affects the operation of the tube. The voltage between X and Y, or across the secondary of the filament transformer, is 5 volts; however, it is an alternating voltage. During one alternation, point X is 5 volts positive with respect to point Y. During the succeeding alternation, point X is 5 volts negative with respect to point Y. When point X is positive, the plate voltage (voltage between the plate and the negative side of the filament) is 45 + 5 or 50 volts. The grid voltage (grid to negative filament) is 6 - 5 or 1 volt. During the next alternation when X is negative, the plate voltage is 45 volts and the grid voltage is 6 volts. Thus, when the plate and grid circuits are returned to point X, it is found that the plate and grid voltages vary 5 volts, as the current through the filament circuit alternates. This is very objectionable. We know that if the plate and grid voltages are changed, the plate current of the tube changes. The plate and grid voltages are changed at a 60-cycle rate. This causes the plate current to vary at a 60-cycle rate and this variation of the plate current is amplified through succeeding stages and appears in the loudspeaker as a very loud, objectionable hum, practically over-riding the program.

Let us further investigate this problem. Considering just the plate voltage, examine Fig. 9. The difference in voltage between

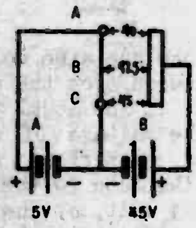


Fig.9 The voltages between the plate and various parts of the filament when the plate circuit is returned to the negative terminal of the A battery.

the plate and the positive end of the filament is 40 volts and between the plate and negative end of the filament is 45 volts. Likewise, the plate is 42.5 volts positive with respect to the center point of the filament. The number of electrons which the plate draws from any part of the filament depends upon the difference in potential between the plate and that point. Therefore, more electrons will be attracted from point C than from point A. From the diagram, it can be seen that the average potential difference between the plate and the whole filament is 42.5 volts. If the connections of the A battery are reversed, the potentials will be those illustrated in Fig. 10. The voltage between the plate and point A

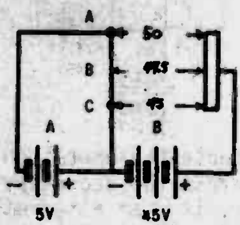


Fig.10 The voltages between the plate and various parts of the filament when the plate is returned to the positive terminal of the A battery.

is 50 volts; between the plate and point C is 45 volts; between the plate and point B, the center of the filament, is 47.5 volts. The average potential difference between the plate and the filament as a whole is 47.5 volts. If the A battery is replaced by an alternating voltage source of 5 volts, Fig. 11 at A would illustrate the potentials during one alternation and Fig. 11 at B, those during the succeeding alternation. It should be noticed that the average potential difference between the plate and the filament changes 5 volts (42.5 to 47.5) from one alternation to the next. This, of course, causes a 60-cycle variation of the plate current.

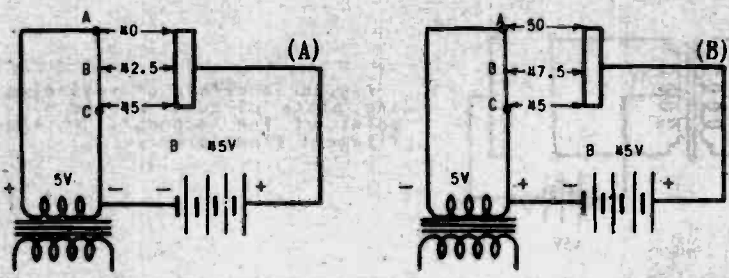


Fig.11 (A) The voltage difference between the plate and various parts of the filament during one alternation of the filament voltage. The plate is returned to one side of the secondary of the transformer. (B) The voltage difference during the next alternation.

If it were possible to connect B minus to the exact center of the filament, the potential diagrams would be those shown in Figs. 12 and 13. In Fig. 12, point A is 5 volts positive with respect to point C; in Fig. 13, point A is 5 volts negative with respect to point C. These two diagrams correspond to the conditions which exist during the positive and negative filament voltage alternations. Notice that during each alternation, the average potential difference between the plate and the whole filament is 45 volts. Such a connection is ideal; there is no change in the average potential difference between the plate and the filament and, therefore, no variation in plate current.

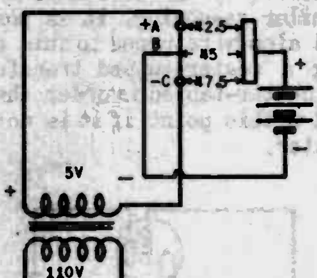


Fig.12 Illustrating the effect of returning the plate circuit to the mid-point of the filament.

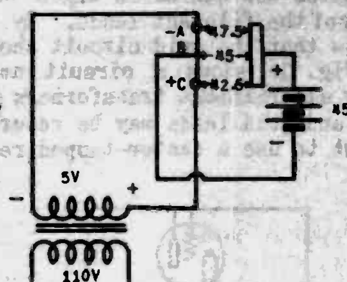


Fig.13 The voltage difference between the plate and various parts of the filament during the alternation following that shown in Fig.12.

It is impractical to center-tap the filament; however, if B minus is connected to a point which has the same potential as the center of the filament, then equally good results could be expected. This may be accomplished by connecting B minus to the electrical center of the filament secondary winding, which is tapped as shown in Fig. 14. It is obvious that this point will have the same potential as the midpoint of the filament if it is located at the exact center of the transformer winding and if the two leads from the transformer terminals to the filament ends are exactly the same length. The transformer is usually located some distance from the

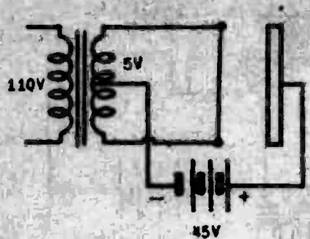


Fig.14 A method of returning the plate circuit to the midpoint of the secondary of the filament transformer.

filament prongs of the tube which necessitates long leads. Since it is quite possible that these leads would not be of exactly the same length, better results can be obtained by returning B minus to the midpoint of a center-tapped resistor, connected directly across the filament prongs of the tube as shown in Fig. 15. This

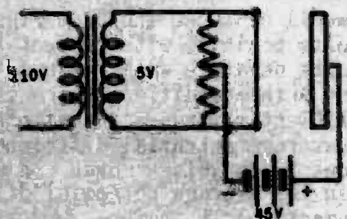


Fig.15 A circuit in which the plate circuit is returned to the center tap of a resistor.

eliminates the hum which might be caused by an unbalance in the length of the filament leads. By similar reasoning, it is possible to show that the grid circuit should also be returned to this point.

Fig. 16 shows a circuit using a center-tapped transformer. Nearly all filament transformers are center-tapped in order that the plate and grid leads may be returned to this point if it is not convenient to use a center-tapped resistor.

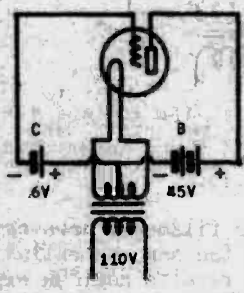


Fig.16 A circuit using a center-tapped transformer.

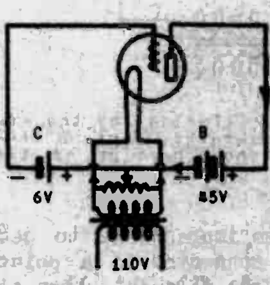


Fig.17 A circuit using a center-tapped resistor.

A circuit using a center-tapped resistor is shown in Fig. 17. The electrons, collected by the plate, flow down through the B battery to the center tap of this resistor. At this point, they divide, part going to one end of the resistor and the rest to the opposite end. They then flow up through each side of the filament to be emitted again. Since this center-tapped resistor is in parallel with the secondary winding of the filament transformer, there will be an alternating current flowing through it at all times. Therefore, this resistor should not have so low a value as to cause too large a current to be drawn from the filament winding, thereby

Fig. 18 Two center-tapped resistors for use in filament circuits.

overheating it. Fig. 18 shows two types of center-tapped resistors. The following table gives the size of center-tapped resistors to be used with different filament voltages.

FILAMENT VOLTAGE	TOTAL RESISTANCE OF CENTER-TAPPED RESISTOR
1.5 volts	10 ohms
2.5 "	20 "
5 "	50 "
6.3 "	50 or 75 "
7.5 "	75 or 100 "

A low-resistance potentiometer is sometimes used in place of the center-tapped resistance. The sliding arm of the potentiometer is to be adjusted until a minimum amount of hum appears in the output of the receiver. This device is called a "hum adjuster"

The use of the indirectly heated cathode type tube eliminates all of these difficulties. For that reason, most modern tubes are of this type.

2. **REQUIREMENTS OF THE POWER SUPPLY.** The plate voltage of a vacuum tube should be as pure a DC as it is economically possible to obtain. If an alternating voltage were applied to the plate of a tube, plate current would flow only during those times when the plate was positive with respect to the filament. The plate current would consist of a series of pulses having a frequency of 60 cycles per second. These pulses would produce a very loud annoying hum in the output of the receiver. This hum would be so loud that it would be almost impossible to receive any program with the receiver. If a pulsating DC voltage were applied to the plate of a vacuum tube, the plate current would rise and fall in direct accordance with the variations of the pulsating direct voltage. This would also produce hum in the output.

The problem confronting us is as follows: The 110-volt, 60-cycle alternating supply voltage must be raised to 300 volts or more. This alternating voltage must be converted into a pulsating direct voltage and then the DC component of this pulsating direct voltage must be separated from the AC component by means of a low-pass filter. This DC component, which is a pure DC, is then used to supply the plate voltages of the tubes. A block diagram of a power supply unit appears in Fig. 19. The power transformer steps

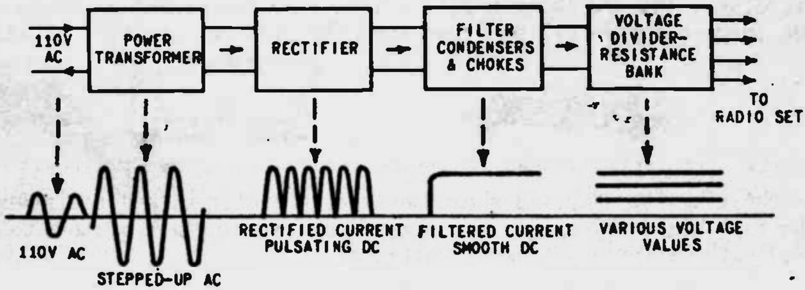


Fig.19 A block diagram of a power supply.

up the 110 volts AC to 350 volts AC or higher in some cases; the rectifier then changes this alternating current into a pulsating direct current. The filter circuit smooths out the pulsations of the pulsating direct current, making the output of the filter a pure DC. The voltage divider then provides a means of securing various voltages up to the maximum for the correct operation of the set.

3. POWER TRANSFORMERS. A power transformer consists of one primary and several secondary windings. Most primary windings are constructed to be used with 110 volts AC; however, it is possible to buy power transformers which use 220 volts AC for their primary windings. The 220-volt type is for receivers to be used in the few communities which are supplied with this voltage.

Most of the power plants in this country supply an alternating voltage with a frequency of 60 cycles. A few plants, however, especially the smaller ones, supply a 25-cycle alternating current. If the power transformer in your radio receiver was designed for 60-cycle alternating current, it most positively will not work on a 25-cycle current. Let us see why this is so. The primary of the power transformer to be used on 60-cycle alternating current was designed to have sufficient inductance to make its inductive reactance at 60 cycles great enough to safely limit the primary current to a value which does not cause overheating of the transformer. The inductive reactance of a coil becomes less as the frequency is lowered. Therefore, if this same transformer is now connected to a 25-cycle alternating current line, its inductive reactance at 25 cycles is less than half as much as it was at 60 cycles. This causes the primary current to be more than twice as great as normal. The excessive primary current produces more heat than the transformer can safely dissipate and its continued flow will burn out the primary winding in a very few minutes. A transformer constructed to be used with a 25-cycle alternating current must have a primary winding which has a much greater value of inductance than the 60-cycle transformer. This large inductance is obtained by using a much larger iron core for the power transformer. A 25-cycle transformer is about twice as large as a 60-cycle transformer, due to this greater amount of iron in its core. If the 25-cycle transformer were used with 60-cycle alternating current, no particular damage would be done, although the transformer would not work as efficiently as one designed particularly for 60 cycles.

One of the secondary windings has more turns than the primary. It is called the "high voltage winding", and the high voltage to be applied to the rectifier is taken from it. Another secondary winding has fewer turns than the primary winding. It is a low-voltage, high-current winding used to supply filament voltage to the rectifier tube. These are the only windings needed for the B power supply; however, since the filaments of the other tubes in the set require a high current at a low voltage, the power transformer usually possesses two or more filament windings. You must be careful not to use a filament winding on the power transformer to supply more tubes than the number for which it was intended. Otherwise, the winding will be overloaded; excessive current will flow through it; and it is liable to burn out. The amount of current that may be drawn from each winding is given with the manufacturer's specifications. All power transformers will have at least two filament windings, since the winding used to supply filament voltage for the rectifier tube cannot be used for any of the other tubes. Fig. 20 illustrates several types of power transformers. Most alternating

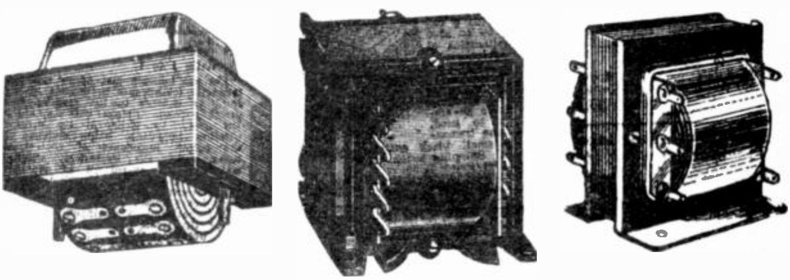


Fig. 20 Various types of power transformers.

lighting supply lines are rated at 110 volts. The actual voltage at the outlets in your home depends upon how distant you are from the lighting supply transformer and upon how many homes this transformer is supplying. If you are close to the lighting supply transformer, the voltage in your home may be as high as 120 volts, or if you are far from this transformer, you may find that the voltage is as low as 100 volts. To overcome this difficulty, some manufacturers have designed transformers with tapped primary windings, as illustrated in Fig. 21. This figure shows a power transformer whose primary has three taps.

If the voltage at the outlet is 120 volts, the AC line is connected across the entire primary winding; while if the voltage is only 105 volts, the AC line is connected between the 105-volt tap and the bottom end of the transformer. In the latter case, fewer primary turns are in use. Decreasing the primary turns increases the turns ratio between the secondaries and the primary, therefore producing the same secondary voltages as those created by the 120-volt line.

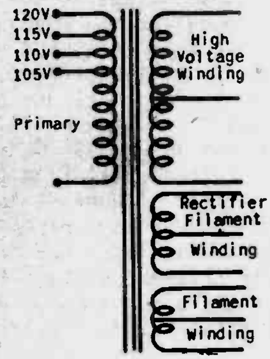


Fig.21 Symbol of a power transformer which has a tapped primary.

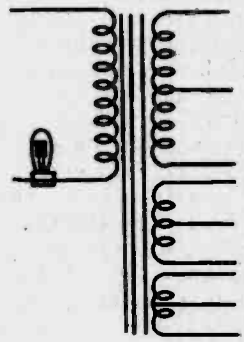


Fig.22 A ballast tube connected in series with the primary of a power transformer.

There is usually a variation in the lighting supply voltage from one part of the day to another. This variation may amount to 15 or 20 volts. Naturally, when the voltage is high or above normal, all of the voltages in the receiver are high. Likewise, when the voltage falls below normal, the receiver voltages are low and maximum efficiency cannot be expected. A few manufacturers have taken means to obviate this difficulty by using what is known as a ballast tube, or voltage regulator tube. Ballast tubes are constructed in many different forms; one type has a filament made of iron wire. It is enclosed in an evacuated bulb into which has been introduced a small quantity of hydrogen. The ballast tube is connected in series with the primary of the power transformer as shown in Fig. 22. It is nothing more than a resistor which is capable of changing its resistance as its temperature is changed. The normal voltage drop across the tube is 50 volts. If the lighting supply voltage is 110 volts, this leaves 60 volts applied across the primary of the power transformer. Therefore, the ballast tube must be used with a power transformer designed to deliver the correct secondary voltages when the primary voltage is 60 volts. An increase in the lighting supply voltage from 110 to 120 volts tends to send more current through the primary and the ballast tube. The increased current flowing through the iron wire of the ballast tube raises its temperature and, in direct consequence thereof, its resistance. The voltage drop across the tube increases to 60 volts and since the line voltage is 120 volts, this leaves 60 volts applied across the primary of the power transformer, or the same as before. If the line voltage falls to 100 volts, a smaller current flows through the circuit. This allows the filament of the tube to cool somewhat and in turn decreases its resistance. The voltage drop across the tube decreases to 40 volts which leaves 60 volts applied across the primary winding as before. From the foregoing, it can be seen that when the lighting supply voltage changes from 100 to 120 volts, the actual voltage applied to the primary winding of the power transformer remains at 60 volts. Therefore, the secondary voltages are constant and unaffected by the line voltage variations. The ballast tube is, by no means, a perfect arrangement, but it does help to keep the set voltages at a more constant value.

4. TUBE RECTIFIERS. It is the rectifier's job to convert the alternating voltage, which appears across the high-voltage winding of the power transformer, into a pulsating, direct voltage. When an alternating voltage is applied across a resistor, current flows through the resistor first in one direction and then in the opposite direction. If we had a resistor which would allow the passage of current in one direction but would not allow any current flow in the opposite direction, then we would have a rectifier. If you consider a moment, you will realize that we have already studied such a device. It is the vacuum tube. A vacuum tube allows current to flow from the heated filament to the positive plate, but does not allow the flow of any current in the opposite direction. Many different types of rectifiers have been constructed, but the vacuum tube rectifier has so many advantages that it is used almost exclusively. Rectifier tubes are constructed in two forms, the half-wave and the full-wave type. Why these names were chosen for the two tubes will become apparent as we continue the study of the rectifier. The half-wave rectifier tube is a high-vacuum tube containing a filament and a plate; it has just the two elements. The filament is of the oxide-coated type and is made of thick, ribbon-like wire. It must be constructed in such a manner as to enable it to emit a liberal supply of electrons. This is especially true since the amount of current that can be drawn from the power supply depends upon the emitting ability of the filament of the rectifier tube.

Now we shall see how it is possible to use one of these half-wave rectifier tubes in a circuit. A half-wave rectifier tube, a load resistor and the high-voltage winding of the transformer all connected in series are illustrated in Fig. 23. The filament winding is used only to heat the filament to a temperature sufficient to cause it to emit a liberal supply of electrons. It is designed to supply the correct filament voltage for the type of tube with which it is used and is wound with wire large enough so that the

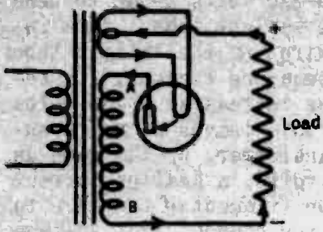


Fig.23 A half-wave rectifier circuit.

proper current may be drawn from it without overheating. Since it has no bearing on the actual process of rectification, it will not be given further consideration. The voltage between A and B is an alternating voltage. During one alternation, point A is positive with respect to point B. This causes the plate of the rectifier tube to be positive with respect to its filament. It, therefore, attracts electrons from the space charge surrounding the filament and current flows from the plate of the tube through the high-voltage winding from A to B to the bottom of the load resistor, through the load resistor to the center tap of the filament winding and then through both sides of the filament winding back to the filament. Since the current flows from the bottom of the resistor to the top, the bottom end is negative with respect to the top end. This load resistor is used merely to explain the process of rectification. In actual application, a filter circuit must be connected between the output of the rectifier and the load. During the next alternation, point B is positive with respect to point A. This makes the plate negative with respect to its filament and it, therefore, cannot attract any electrons. There is no current flow through the circuit during this alternation. The current flowing through the load resistance consists of a series of pulses, all in the same direction. The waveform of the voltage between the points A and B is shown at A in Fig. 24. The current, which flows through

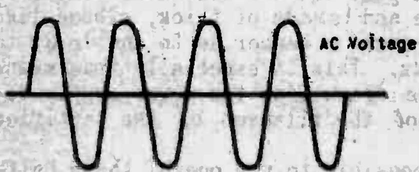


Fig.24A Waveform of the AC voltage produced across the high-voltage secondary of the circuit of Fig.23.

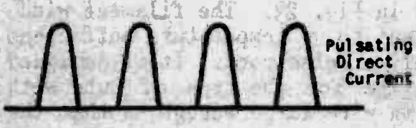


Fig.24B Waveform of the current flowing through the load resistor of a half-wave rectifier.

the resistor and the remainder of the circuit as a result of this voltage, is shown at B in this same figure. There are 60 pulses of current passing through the load resistor each second; therefore, the frequency of this pulsating direct current is 60 cycles. Notice that advantage is taken of only the positive alternation of the alternating current. During the negative alternation, the circuit and tube are idle. Since only half of the AC wave is useful, this circuit is known as a half-wave rectifier and the tube as a half-wave rectifier tube. A typical half-wave rectifier tube is the 81 an illustration of which is shown in Fig. 25.

It is possible to use two half-wave rectifier tubes connected as shown in Figs. 26 and 27. The alternating voltage is produced between points A and C. The filaments of both tubes are connected through the load resistor to the center tap of the high-voltage secondary (point B). When point A is positive with respect to point

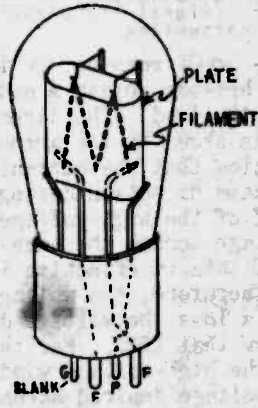
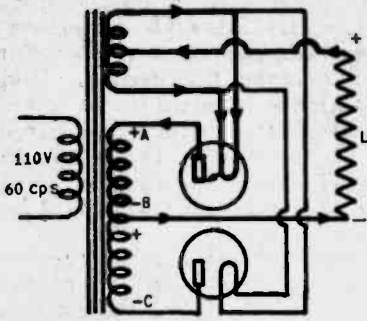


Fig. 25 Phantom view of a half-wave rectifier tube.

C, it is also positive with respect to this center tap, which causes the plate of the top tube to be positive with respect to its filament. Thus, the top tube operates; current flows from the plate to point B, through the load resistor to the center tap of the filament winding and back to the filament of the top tube. Now consider the bottom tube. During this time, point C is negative with respect to the center tap, which causes the plate of this tube to be negative with respect to its filament. Unable to pass current, this tube idles during this alternation and that voltage present between points B and C is ineffective in producing a current flow through the load. The direction of current flow is shown by the arrows in Fig. 26.

As the AC voltage begins its negative alternation, the polarity of the voltage across the high-voltage secondary is reversed. Point C becomes positive with respect to point A, thereby making point C positive with respect to the center tap and the plate of the bottom tube positive with respect to its filament. The bottom tube passes current, which flows from its plate to point B, through the load to the filament winding center tap and back to the filament of the bottom tube. As this current is flowing, point A is negative with respect to the center tap and the plate of the top tube is



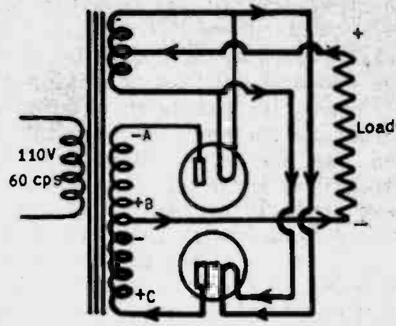


Fig.26 (Left) A full-wave rectifier circuit using two half-wave tubes. The heavy lines show the direction of current flow when the top tube is conducting.
Fig.27 (Right) The direction of current flow when the bottom tube is conducting.

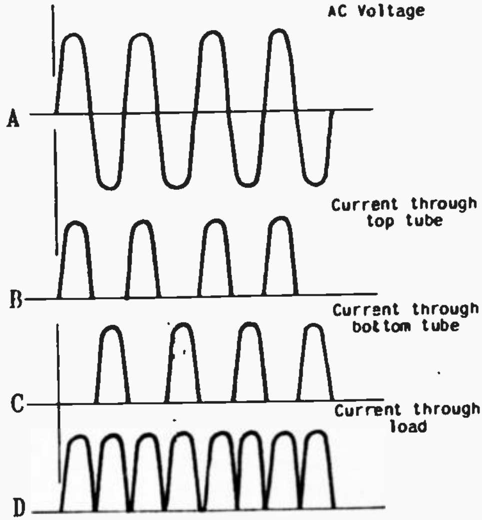
negative with respect to its filament. This tube idles and the voltage between points A and B is unable to produce a current flow through the load. The direction of current flow during this alternation is shown by the arrows in Fig. 27.

Notice that the current flowing through the load resistor is in the same direction during each alternation. Only one tube and one-half of the high-voltage secondary function at any instant. If the voltage across the high-voltage winding is 700 volts, only 350 volts of this is effective in producing a current flow through the load. Therefore, the voltage created across the load resistor is 350 volts less the voltage drop across the tube which is passing current at that time. For this reason, the total voltage developed across the high-voltage winding must be more than twice as large as the voltage desired across the load.

Fig. 28 at A shows the waveform of the AC voltage which is produced across the high-voltage secondary. Fig. 28 at B is the current which flows through the top tube and Fig. 28 at C shows the current which flows through the bottom tube. The combined current of the two tubes or the current which flows through the load resistor is shown at D in the figure. Each tube supplies 60 pulses of current to the load every second, which causes 120 pulses of current to flow through the load in a second of time. The frequency of the pulsating direct current flowing through the load is, therefore, 120 cycles. Since this circuit takes advantage of both alternations of the AC voltage, it is called a full-wave rectifier circuit and it requires two half-wave rectifier tubes. It should be evident that it is much easier to filter the output of a full-wave rectifier than that of a half-wave rectifier; the chokes used in the filter system need not have as large inductances, nor the condensers as large capacities. For these reasons, full-wave rectification is practically always used.

In both the half-wave and full-wave type rectifier circuits, the filament of the rectifier tube is the most positive point of the circuit. It is common practice to ground the B minus of a power supply to the chassis; therefore, you should remember never to

Fig. 28



(A) Waveform of the AC voltage across the high-voltage secondary.

(B) Waveform of current flow through top tube of Fig.26.

(C) Waveform of current flow through bottom tube.

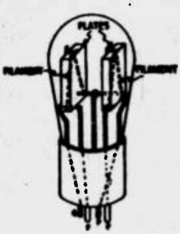
(D) Waveform of current flow through load circuit.

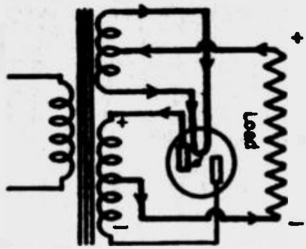
touch any part of the filament circuit of a rectifier tube and at the same time touch the chassis or ground. The voltage between the filament and the chassis is usually as high as 300 volts. It is for this reason that the rectifier filament winding cannot be used to supply filament voltage to any of the other tubes since this would be the same as supplying a high positive voltage to these filaments. The rectifier filament winding must be thoroughly insulted from the core of the power transformer as well as from the other windings. This, of course, also applies to the high-voltage winding.

The first full-wave rectifier circuits employed two half-wave rectifier tubes, but it was not long until the tube manufacturers designed and constructed a full-wave rectifier tube. This tube consists of two separate plates and has two filaments internally connected in series. Each plate surrounds one of the filaments as revealed in the phantom drawing of Fig. 29. Four prongs are provided, two for the composite filament and one for each of the plates. The type 80 is the most common example of a full-wave rectifier tube.

One type 80 tube may be used in a full-wave rectifier circuit in place of two of the type 81's. Such a circuit is illustrated in Fig. 30. This figure shows the direction of current flow when the left plate is conducting, while Fig. 31 illustrates the path followed by the current when the right plate conducts.

In all of the rectifier circuits thus far illustrated, the positive output terminal has been connected to the center tap of the rectifier filament winding. In many rectifier circuits, the positive terminal is connected to one side or the other of the filament. No noticeable difference results from either type of connection, because the slight voltage variation resulting from a con-





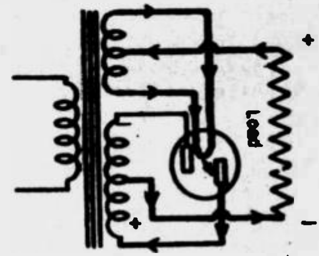


Fig.29 (Left) Phantom view of full-wave rectifier tube.
Fig.30 (Center) A full-wave rectifier circuit using one full-wave tube. The direction of current flow when the left plate conducts is shown in the figure.
Fig.31 (Right) The direction of current flow when the right plate conducts.

nection to either side of the filament is inconsequential, compared to the pulsating DC output voltage produced and both are smoothed out by the action of the filter.

The amount of current that can flow through the load circuit depends primarily upon the emission capability of the rectifier filament. The filament is capable of such great emission that should a short circuit occur between the filament and ground, a very large current would flow from the filament to the plates, through the high-voltage secondary to B minus which is grounded and then through the short circuit which exists between ground and the filament. The excessive current flowing through the transformer winding produces more heat than the winding can dissipate. It is more probable, however, that before the winding is seriously impaired, the tube itself will suffer irreparable damage. The filament literally destroys itself in its attempt to supply this abnormal current. The large mass of electrons accelerated at tremendous velocities impinge upon the plates with considerable force. These impacts convert the kinetic energy acquired by the electrons into heat energy, which raises the temperature of the plates to a red heat. Thus, the presence of a short circuit in the power supply is readily determined by observing the color of the plates.

The high-vacuum rectifier tubes which have been discussed are called *thermionic rectifiers*. They are manufactured in a variety of sizes, ranging from the smaller type 80 up to very large water-cooled tubes capable of rectifying alternating voltages of 50,000 volts.

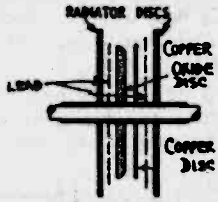
In addition to the thermionic type rectifier, there is another kind of rectifier tube, known as the mercury vapor type. This tube is rarely used in receiver power supplies, but finds wide application in the design of power supplies to be used with transmitters. Its complete study will be taken up in a later lesson.

5. CONTACT RECTIFIERS. A type of rectifier which has a limited application and yet possesses advantages peculiar to itself is the contact rectifier. Its principal elements are a metal in contact with a crystal or metallic salt. A very common example is the copper-oxide rectifier which consists of a disc of copper in contact with copper-oxide. Copper-oxide is a black substance which

forms a thin film on the surface of copper in much the same way that rust forms on iron.

The device depends for its operation on the fact that electrons can easily flow from the copper to the copper-oxide, but only with great difficulty in the opposite direction. Thus, this combination produces rectification since it offers a low resistance to current flowing in one direction and a high resistance to current flowing in the opposite direction. Fig. 32 illustrates a single copper-

Fig.32 The constituents of a copper-oxide rectifier element.



oxide rectifying element. Discs of lead are provided to conduct the current from one element to another. All but the very smallest of these rectifiers are equipped with flanges or radiator discs to allow the rapid radiation of heat which is developed by the current flowing through the resistance of the rectifying element. The symbol for a copper-oxide or other contact rectifying element is shown in Fig. 33. The arrow indicates the direction in which current will flow.

Fig.33 Symbol for a contact rectifying element. The arrow shows the direction in which current will flow.

The amount of voltage that may be safely placed across a typical small rectifying element is only 11 volts AC. If this type of rectifier is to be used with moderate or high voltage, several of the elements must be connected in series. In this manner, the voltage drop across each element is kept within safe limits.

The characteristics of a contact rectifier vary with the pressure between the contact surfaces. This pressure determines the resistance of the element. The whole assembly of rectifying elements is bolted together under very high pressure. Never take the bolt out or loosen the pressure, for it is impossible to again secure the same pressure as the device originally had and its characteristics would, therefore, be changed.

The maximum current that can safely pass through an element is about 500 ma. per square inch of contact surface. If either the maximum voltage or maximum current is exceeded for one of these rectifying elements, it breaks down and current flows through it easily in both directions. Its operation as a rectifier is then valueless.

No contact rectifier is perfect in its process of rectification; that is, all of them will allow some reverse current to flow through them. This reverse current is known as leakage current and its amount increases rapidly with temperature. It is for this reason that cooling flanges have been provided to keep the temperature within safe limits, thereby reducing the leakage current. The temperature of a rectifying element should not exceed 160 degrees F. for efficient operation.

Due to the fact that there is a leakage current, a certain minimum current must be maintained through the rectifier at all times for efficient operation. This minimum current should not be less than 50 ma. per square inch of contact surface. The copper-oxide rectifier is said to have a rectifying ratio of 10,000 to 1. This means that its resistance in the direction in which it will pass current easily is only .0001 as much as its resistance in the opposite direction. Instead of using a separate disc of copper oxide, this material is sometimes formed directly on the surface of the copper disc.

A single copper-oxide rectifying element is a half-wave rectifier and can be used in a half-wave rectifying circuit as shown in Fig. 34. The voltage produced across the secondary of the transfor-

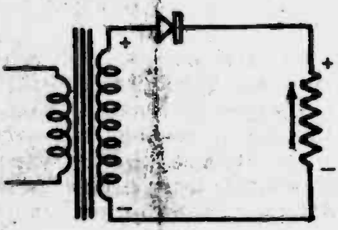


Fig.34 A half-wave rectifier circuit using a copper-oxide rectifier.

mer is an alternating voltage. Due to the presence of the rectifying element in the circuit, current will flow only from the bottom of the resistor to the top. There will be no current flow when the polarity across the transformer winding reverses. The pulsating direct current which flows through the load will have a frequency of 60 cycles.

Two rectifying elements may be connected in a full-wave rectifier circuit as shown in Fig. 35. When the top end of the secondary is positive, current will flow out of the center tap, upward

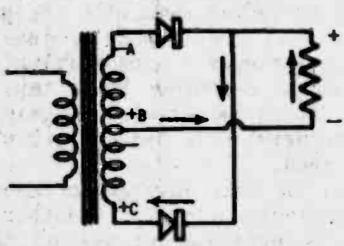
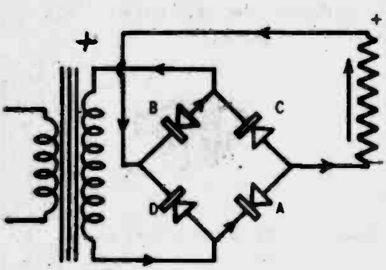


Fig.35 A full-wave rectifier circuit using two copper-oxide elements.

through the resistor and through the top rectifying element. During this time, the bottom element is idle. Then, when the bottom end of the secondary is positive, current will flow out of the center tap, upward through the load resistor and back through the bottom rectifying element. During this time, the top rectifying element is idle. It is apparent that this circuit operates in exactly the same manner as a full-wave vacuum tube rectifier circuit using two half-wave rectifier tubes. Only one-half of the secondary voltage is useful in producing a current flow through the load. The transformer must be designed to develop across its secondary a voltage slightly more than twice as much as the desired load voltage. The voltage produced across a rectifying element when it is non-conducting is equal to one-half the secondary voltage plus the voltage developed across the load. This may be seen by reference to the polarities in the diagram. In the figure, the bottom element is passing current; therefore, the voltage present across the top element is equal to the voltage from A to B plus the voltage across the load. This consideration limits the usefulness of this type of circuit, since the breakdown voltage of the elements is so low.

A type of rectifier circuit which partially eliminates these difficulties is illustrated in Fig. 36. It consists of four elements arranged in what is known as a bridge circuit.

Fig. 36 shows the direction of current flow when the top end of the secondary is positive and the bottom is negative. During



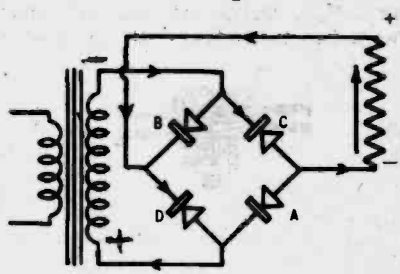


Fig.36 (Left) A full-wave rectifier circuit using four elements. The arrows show the direction of current flow when the top of the secondary is positive.

Fig.37 (Right) The direction of current flow when the bottom of the secondary is positive.

this alternation, the rectifying elements A and B pass current. Fig. 37 shows the direction of current flow during the next alternation when the top end of the secondary is negative and the bottom positive. During this alternation, the rectifying elements C and D pass current. This circuit reduces the voltage strain across each element to approximately one-half of that present in the center-tapped transformer circuit.

Most commercial contact rectifiers are constructed for operation in a bridge circuit. Although the last two figures illustrate the circuit connections and the direction of current flow through a bridge type rectifier using copper-oxide rectifying elements, the actual appearance of a commercial rectifier is more nearly like that of Fig. 38. The black discs represent the copper-oxide surface and the shaded discs, the copper itself. The rectifier consists of four elements connected in a bridge circuit. At first glance it is hard to realize that this circuit is connected in exactly the same manner as the one shown in Fig. 36. By tracing the current path, however, this is found to be true. The bolt which holds the elements together is in contact with the copper disc at either end and therefore connects these two discs together electrically. A fibre insu-

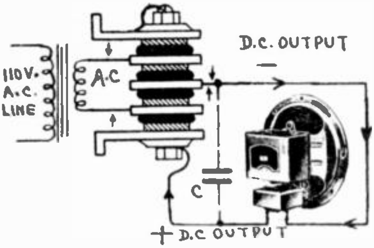


Fig.38 A commercial copper-oxide rectifier used to supply the field of a dynamic speaker.

lating bushing keeps the bolt from short circuiting the elements.

The copper-oxide rectifier is manufactured in a large variety of sizes ranging from discs about .5 inch in diameter to discs several inches across. The very small ones are used in conjunction with rectifier type meters for measuring alternating current. They rectify the alternating current and apply the resulting pulsating DC to a standard DC meter. This meter is so calibrated as to read the R.M.S. value of the original AC current or voltage. Fig. 39 shows two rectifiers to be used for this purpose.

Fig.39 Illustrations of copper-oxide rectifiers.

A little larger size is sometimes used to rectify alternating current for use in charging storage batteries. A transformer is employed to reduce the 110 volts AC to approximately 12 or 15 volts. This is then applied to the contact rectifier and the DC output may be used to charge a battery. Copper-oxide rectifiers have been used to provide the field excitation of dynamic speakers. They are very sturdy and if not subjected to abuse will maintain their operating characteristics over a period of years.

6. FILTERS. The output of a full-wave rectifier is a pulsating direct current which has a waveform as illustrated in Fig. 40.

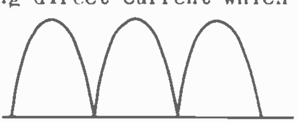


Fig.40 Waveform of the output voltage of a full-wave rectifier.

Before this pulsating direct current can be used to provide plate voltage for the various tubes of a receiver, its AC component must be filtered out, leaving only the pure DC component to be applied to the tubes. This operation is accomplished by the use of a low-pass filter such as studied in Lesson 14.

Low-pass filters for use in power supplies are of two general types, namely: the condenser input type and the choke input type.

In the former, the output of the rectifier is applied directly across a condenser as shown in Fig. 41. Before studying the action

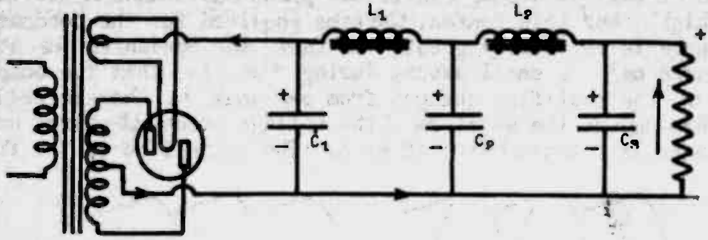


Fig. 41 Full-wave rectifier circuit connected to a filter.

of a filter, it is essential that something be learned about the process of charging and discharging a condenser through a resistor. To charge a condenser to an applied voltage requires the transfer of a certain number of coulombs of electricity around the circuit. The number of coulombs that needs to be transferred depends upon the applied voltage and upon the capacity of the condenser. To transfer a given number of coulombs requires that a current of a certain value flow for a definite length of time. If a resistance is included in the circuit with the charging source and the condenser, the amount of charging current is thereby decreased. Therefore, to charge the condenser to the applied voltage will require a longer time. In general, the larger the resistance, the longer will be the time required to charge the condenser to a given applied voltage. In like manner, the discharge of a condenser requires that a certain number of coulombs be transferred around the circuit. If the circuit includes resistance, the time required to discharge the condenser increases accordingly. The resistance in the circuit limits the current flow to a low value. Therefore, the transference of the required number of coulombs will necessitate that this current flow for a greater length of time. The output voltage or current of a full-wave rectifier is shown in Fig. 40. The current starts from zero and rises to a peak value. This current flows out of the center tap of the high-voltage winding; some of it goes to charge the first condenser, some to charge the second and third condensers and some flows through the load.

The greater part of this current, however, will be used to charge the first condenser. This condenser is being charged through a resistance. In this case, the resistance is the plate resistance of the rectifier tube . Since the plate resistance of all rectifier tubes is relatively low, the condenser charges to the peak voltage output in a very short interval of time. As the peak is passed, the current from the rectifier starts to fall to zero. The voltage applied to the condenser is now decreasing and so the condenser must discharge. The condenser is charged with its top plate positive and the bottom plate negative. It cannot discharge through the same circuit by which it was charged, since current can flow through the rectifier tube only from its filament to its plate and not in the reverse direction. In order for the condenser to discharge, current must flow out of the bottom plate, around through the load, through the two chokes and back to the top plate. The impedance of this path compared to the plate resistance of the tube is very high. For this reason, the time required for the condenser to discharge is relatively great. In fact, the condenser is able to discharge only a small amount during the time that the output voltage of the rectifier changes from one peak to the succeeding peak. This causes the waveform of the voltage across the first condenser to be like that of Fig. 42 at A. The solid line in the fig-

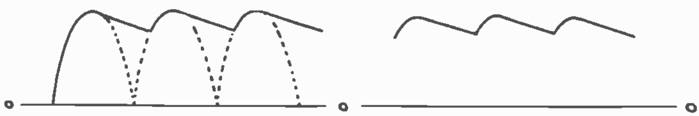


Fig.42 The dotted line represents the output voltage of the rectifier, and the solid line the voltage across the first filter condenser C_1. B shows the voltage across C_1 drawn separately.

ure represents the voltage across the first condenser, while the dotted line represents the voltage output across the rectifier. The voltage across the condenser is drawn separately in Fig. 42 at B. Notice that this voltage never falls to zero and is far less pulsating than either the voltage or current producing it. Or, since it varies through smaller amplitudes, it can be said that its AC component is of lesser value.

It is this voltage shown at B in Fig. 42 which now serves to force current through the first choke. Part of this current which passes through the first choke flows into the second condenser, thereby charging it. Thus, electrons flow from the bottom plate of the first condenser to the bottom plate of the second condenser. Likewise, electrons flow from the top plate of the second condenser through the choke and to the top plate of the first condenser. The voltage which appears across the first condenser tends to produce a varying current through the choke. The choke, due to its inductive reactance, sets up counter induced voltages which tend to prevent any current changes through it. The current which flows through the choke has a waveform as shown in Fig. 43. Notice that this cur-

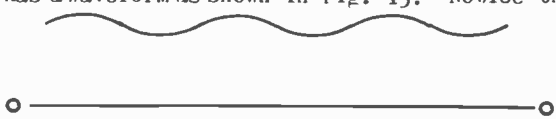


Fig.43 Waveform of the current which flows through the first choke L_1 of Fig.41.

rent varies through smaller amplitudes than the voltage which produced it. It is this current which charges the second condenser. By a similar method it is possible to prove that the voltage produced across the second condenser will vary through a smaller amplitude than the current which flows through the first choke. The current flowing through the second choke is, for all practical purposes, a pure direct current.

The output of a half-wave rectifier requires considerably more filtering than that of a full-wave rectifier. Its output consists of a pulse of current followed by an equal length of time, during which no current flows at all. Obviously, the voltage which would be produced across the first filter condenser would vary through a much greater amplitude and, in order to produce sufficient filtering, the condensers and chokes would need to be of much larger values, or else several more filter sections would have to be added. For this reason, half-wave rectifiers are seldom employed.

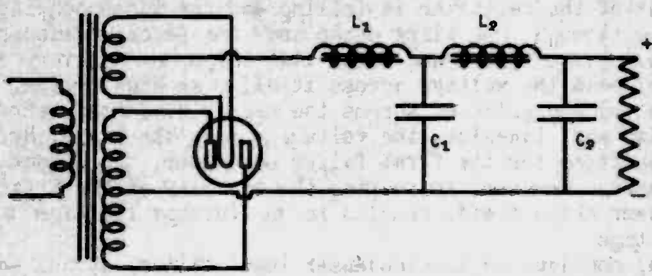


Fig.44 Full-wave rectifier circuit connected to a choke-input filter.

In Fig. 44 is illustrated a rectifier connected to a choke input filter. The output voltage of the rectifier is the same as that when using a condenser input filter. This output voltage produces a current flow which charges the first condenser through the first choke. The choke tends to prevent the current from rising to as high a maximum as it would if the choke were not present and also prevents the current from falling to a zero value. The actual current flowing through the choke is shown in Fig. 45. Since this cur-

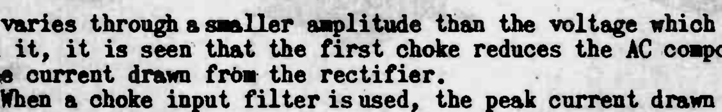


Fig.45 Waveform of the current flowing through the first choke of Fig. 44.

rent varies through a smaller amplitude than the voltage which produced it, it is seen that the first choke reduces the AC component of the current drawn from the rectifier.

When a choke input filter is used, the peak current drawn from the rectifier is not nearly as great as it is when a condenser input filter is used. Since the current is not as large, the voltage produced across the first filter condenser is not as high. This results in a smaller DC voltage being applied to the load. From this we can say that a condenser input filter will deliver a greater DC voltage to the load than will a choke input filter. However, we shall see in the study of rectifier circuits for use in transmitters that choke input filters have certain advantages which make them particularly adaptable for use with mercury vapor rectifier tubes. Since practically all receivers use the thermionic, high-vacuum, rectifier tube, nearly all of them employ a condenser input filter.

The output DC voltage of the filter will depend to some extent upon the capacity of the first filter condenser. If this capacity is too small, it will not acquire a very large charge when the output current of the rectifier is increasing. Likewise, when the output current of the rectifier is falling and the first condenser is discharging through the first choke and the second condenser, it tends to discharge faster and since its charge is not very great, it will not hold the voltage across itself at so high a value. This causes the voltage produced across the second condenser to be smaller in value and, likewise, the voltage across the load. By using larger capacities for the first filter condenser, the output voltage increases. However, increasing the capacity of the first filter condenser above 2 mfd. results in no further increase of the output voltage.

Again, considering the condenser input filter, it can be seen that the first filter condenser produces the largest part of the filtering action, the second condenser endeavors to take out whatever ripple is left and the third filter condenser remains in a charged condition across the load to supply any sudden surges of current which the plate currents of the vacuum tubes might require.

7. FILTER CHOKES. The filter chokes used in power supply filters have iron cores. In appearance, they resemble iron core transformers. (See Fig. 46.) However, since they consist of only one winding, they will have just two terminals. These two terminals do

Fig. 46 Illustrations of filter chokes.

not have any polarity and so it does not make any difference which terminal is connected to the positive side of the line. To provide sufficient filtering action, chokes should have inductances of 20 henries or more. Also, they must be designed so that they are able to carry the total current which passes through them without overheating. This total current includes the current drawn by all of the tubes of the receiver and, in addition, the current which flows through the voltage divider. All filter chokes are rated in their current-carrying ability as well as their inductance value. Thus, it is possible to purchase a 30-henry choke capable of carrying 50 ma., or another 30-henry choke which is capable of carrying 100 ma. When, in the servicing of a receiver, you find it necessary to replace a filter choke, always use a filter choke of the same current-carrying capacity and of the same inductance. A filter choke which is just barely able to carry the total current will operate at a dangerously high temperature and, in addition, since its resistance is greater than it should be, there will be a larger DC voltage drop across it than normal. This, of course, will reduce the available DC voltage across the load.

Most modern receivers employ the field of the dynamic speaker as the second choke in the filter system. This field consists of many turns of wire wound around an iron core. It, therefore, has considerable inductance and its use as a filter choke is very efficient. In Lesson 29, on loudspeakers, we will again refer to this use of the speaker field as a choke of the filter system.

8. FILTER CONDENSERS. The power supply filter of nearly all modern receivers uses electrolytic condensers. Electrolytic condensers have been constructed to withstand voltages of 500 volts and since the voltage requires for most receivers is not in excess of 300 volts, it is quite natural that they should be used; especially so, since they furnish large capacities with a minimum amount of cost and size. Fig. 47 shows several electrolytic condensers suit-

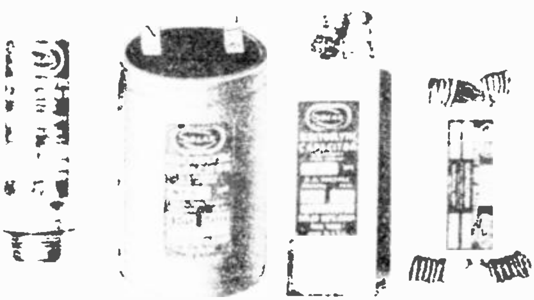


Fig. 47 Illustrations of filter condensers.

able for power supply filters. The two in the round containers are the wet type, while the two with rectangular containers are the dry type. The large round one has two 8 mfd. condensers in the same container. The dry electrolytic, which has four leads, is composed of two 4 mfd. condensers.

The three condensers used in the filter system are ordinarily of equal capacity. In most filter systems, this capacity is 8 mfd. each. While we have stated that using a condenser whose capacity is greater than 2 mfd. as the first filter condenser does not increase the DC voltage output, yet a condenser of 8 mfd. will probably provide better filtering action than would a 2 mfd. condenser. If there is to be a difference in the capacities of the three condensers, the smallest should be placed next to the filter and the largest across the voltage divider. To provide adequate filtering action, the second and third filter condensers should have capacities of 8 mfd. or greater.

The second filter condenser eliminates the ripple voltage not taken care of by the first filter condenser and choke. Therefore, its value should be at least 8 mfd.

It is the third filter condenser which tends to keep the voltage output of the power supply at a constant value. Suppose, for example, that the tubes of the receiver during a certain instant require considerably more than normal current. The third filter condenser, which is charged to the DC output voltage of the power supply, discharges enough to furnish this extra current. If this third filter condenser does not have sufficient capacity to furnish this extra current, then part of this current increase must be drawn from the rectifier through the chokes. The additional current drawn through the chokes produces a greater voltage drop across them and thereby reduces the voltage across the voltage divider. This causes all of the tubes to operate under a reduced voltage during the time this extra current is being drawn. It is, therefore, essential that this third filter condenser be quite large in capacity. For this reason some manufacturers use condensers in this position whose capacities are as high as 16 or 32 mfd.

The breakdown voltage of the second and third filter condensers must be great enough to safely withstand the DC voltage produced across the voltage divider. The first filter condenser, however, must have a breakdown voltage great enough to withstand the peak voltage of the output of the rectifier. Since the peak voltage is equal to 1.414 times the effective voltage, the first condenser must be able to withstand a voltage which is at least 1.414 times the voltage produced across the voltage divider. For example, if the voltage across the voltage divider is 300 volts, the first filter condenser should have a rated voltage breakdown of approximately 450 volts.

When replacing filter condensers, always make sure that their breakdown voltages are equal to or greater than the ones being replaced. Also, be certain that the condenser used to replace the first filter condenser has exactly the same capacity. The use of a lower capacity will reduce the output voltage and a higher capacity may increase it. In either case, the voltages applied to the plates of the tubes would not be correct. It makes no difference if you use larger capacity condensers in replacing the second and third filter condensers, since a large capacity in these positions will only serve to further the filtering action. Filter condensers are rated both for AC and DC voltages. The AC rating is usually only a little over half as much as the DC rating. This is due to the fact that the peak value of an AC voltage is 1.414 times its effective or R.M.S. value and the condenser, to be serviceable, must be able to withstand the peak.

If the power supply is to be designed to produce an output voltage much in excess of 300 volts, it may be necessary to connect two electrolytic condensers in series in order to reduce the voltage drop across them, This is shown in Fig. 48. With this connection, the effective capacity across the rectifier is reduced by half; therefore, the capacity of each of the condensers so connected must be twice that ordinarily used. In addition, equalizing resistors must be connected across each condenser. The necessity for using equalizing resistors was discussed in Lesson 11, at which time it was learned that the value of the resistor should be somewhat smaller than the leakage resistance of the condenser. Electrolytic condensers have leakage resistances of 100,000 ohms on the average and equalizing resistors of 25,000 ohms are about the correct value to be used.

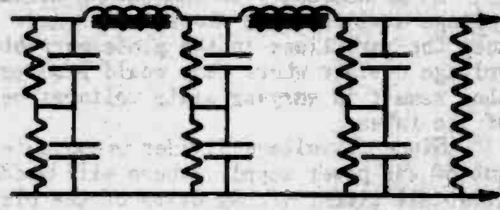


Fig.48 Method of connecting equalizing resistors across the electrolytic condensers when they are connected in series.

9. **VOLTAGE DIVIDERS.** The voltage divider consists of a tapped resistor or several untapped resistors connected in series. It is connected across the output of the filter system. The output voltage of the power supply will probably be in the neighborhood of 300 volts. The plate of the power tube of the receiver will probably require this much voltage; however, plate voltages for the remaining tubes are, ordinarily, considerably less. Current from the filter flows through the voltage divider, producing a voltage drop across it of about 300 volts. By tapping the voltage divider at various points along its length, lower voltages can be obtained for the plates of the various tubes of the receiver. Fig. 49 shows a complete power supply including the voltage divider. The total output voltage of this power supply is 300 volts. The voltage divider is in three sections, A, B, C. The A section reduces the voltage from 300 volts to 180 volts. Likewise, the B section reduces the voltage from 180 volts to 90 volts. All of these volt-

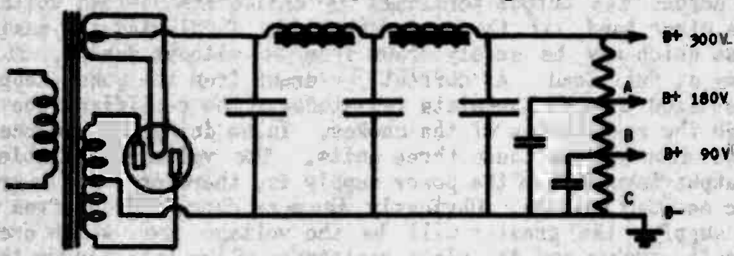


Fig.49 A complete full-wave rectifier circuit showing the voltage divider and its taps.

ages are, of course, considered with respect to B minus, which is grounded to the chassis in most cases. By grounding B minus (B-), considerable wiring is eliminated; all of the cathodes or center taps of the filaments of the set are connected to the chassis instead of using wire to return them to B minus.

It is necessary to connect a condenser between each tap of the voltage divider and B minus, or ground. These condensers serve to keep the variations in the plate currents from flowing through the voltage divider where they would produce varying voltage drops and thus result in varying plate voltages being applied to the plates of the tubes.

Since the voltage divider is connected directly across the output of the power supply, there will be some current flowing through it at all times, irrespective of the plate currents. *This current is known as the "bleeder current".*

Voltage dividers are usually designed for operation with a particular set. In that case, the taps on the voltage divider are fixed. It is possible, however, to purchase voltage dividers which have sliding taps. By loosening a set screw, a tap may be moved back and forth to either raise or lower the voltage between that tap and B minus. Two types of voltage dividers are illustrated in Fig. 50.

Fig. 50 Illustrations of voltage dividers.

10. VOLTAGE REGULATION OF A POWER SUPPLY. *By the phrase, "voltage regulation", is meant the ability of a power source to maintain a constant voltage at its output when various values of current are drawn from it.* If a power source is not furnishing any current, it is said to be working at no load and the voltage produced across its output terminals is called its no-load voltage. On the other hand, if the power source is furnishing the maximum current which may be safely drawn from it without damage, it is working at full load. As current is drawn from the power supply, it must flow through the plate resistance of the rectifier tube and through the resistances of the chokes. In so doing, it produces a voltage drop across these three units. The voltage available at the output terminals of the power supply is, therefore, not as great as the no-load voltage. Obviously, the more current drawn from the power supply, the greater will be the voltage drop which occurs across the chokes and the plate resistance of the tube and the lower will be the voltage at the output terminals. Voltage regulation is ordinarily expressed as a percentage and is calculated by the following formula:

$$\text{Percent Voltage Regulation} = 100 \times \frac{\text{No Load Voltage} - \text{Full Load Voltage}}{\text{No Load Voltage}}$$

For example, suppose that the no load voltage of a power supply is 300 volts and the full load voltage is 285 volts. This means that when the maximum current is being drawn from the power supply, 15 volts are lost in the internal resistance of the power source. Using these figures to calculate the voltage regulation, we have:

$$\text{Percent Voltage Regulation} = 100 \times \frac{300 - 285}{300}$$

$$= 5\%$$

It can be seen that a power supply which produces the same voltage at full load as it does at no load would have a voltage regulation of 0%. *The smaller the percentage of voltage regulation, the greater is the ability of the power supply to maintain a constant voltage at its output when full current is drawn from it.*

It is for this reason that a bleeder current is drawn from the power supply. By placing a continuous load on the power supply, its voltage regulating ability is increased. The bleeder current in flowing through the plate resistance and the resistances of the chokes produces a steady voltage drop across them; therefore, the output voltage is practically steady. Now, when a slight increase in current is demanded from the power supply, due to an increase in the plate currents of the tubes, this additional current, if it does have to flow through the rectifier tube and chokes, will produce only a small percentage change in voltage drop. If no bleeder current were allowed to flow, the output voltage of the power supply under no load might be as high as 500 volts. This would be liable to break down the filter condensers. The greater the value of bleeder current used, the better will be the voltage regulation of the power supply. The disadvantage of a large bleeder current is that it causes a fairly large current to flow through the chokes. These choke coils have iron cores and as learned in a previous lesson, when a direct current flows through a choke coil, it tends to saturate the iron core with magnetism. This causes the permeability of the core to decrease and in direct consequence thereof, the inductance of the choke coil. If the decrease of inductance is appreciable, the filtering action is less efficient. Care must be taken to make certain that the current drawn through the chokes is not great enough to saturate their cores. The average value of bleeder current used in most power supplies for receivers is from 10 to 20 ma. Voltage regulation in excess of 5% is liable to cause erratic operation of the receiver. If the power supply does not have a voltage regulation as good as this, it is necessary to use a very large capacity condenser across the voltage divider in order that variations in the current demanded by the tubes can be supplied by the partial discharge of this condenser and will not have to be drawn from the rectifier itself.

11. VOLTAGE DOUBLER. It is possible to construct a rectifier circuit in which the output voltage is equal to approximately twice the peak value of the AC voltage applied to the rectifier tube. Such a circuit is known as a voltage doubler. It was designed to be used in small portable receivers since it eliminates the power transformer. Although two half-wave rectifier tubes may be used in this circuit, a special full-wave tube called the 25Z5 is ordinarily employed for this purpose. This tube consists of two plates, two cathodes and a common heater. The heater requires 25 volts for its proper operation and is connected in series with the heaters of all the other tubes in the receiver. A line-dropping resistor is then employed to reduce the 110 volts AC to the voltage necessary for the series connected heaters. This line resistor is usually built into the AC supply cord. For this reason, the cord will become slightly warm during the operation of the set. This cord should never be shortened as this would reduce the value of the line-dropping resistor.

Let us say that we have a receiver which uses four tubes in addition to the rectifier tube and that each of these four tubes requires six volts for its heater. Since the four heaters are connected in series, the total voltage across the four of them should be 24 volts. The heater of the rectifier is then connected in series with these heaters and the voltage across it should be 25 volts. Therefore, the total voltage drop across all of the heaters is 25 plus 24, or 49 volts. The line voltage dropping resistor must, therefore, produce a voltage drop across itself of 110 less 49 volts or 61 volts. Fig. 51 illustrates the connection of the various heaters of the tubes and the voltage produced across each. Only

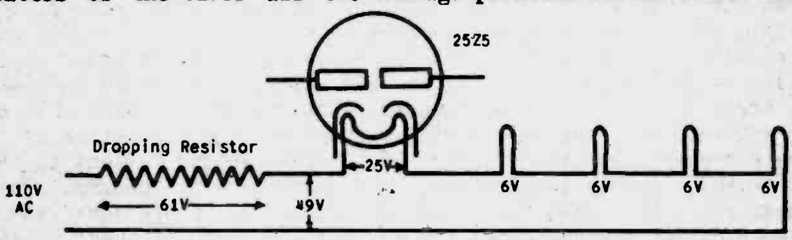


Fig. 51 Method of connecting the filament of a voltage doubling tube in series with the filaments of the other tubes.

those tubes which draw the same heater current may be connected in series in this manner. The 25Z5 requires .3 ampere heater current and, therefore, may be used with many of the present-day 6-volt tubes which draw this same current.

Fig. 52 illustrates the circuit used for voltage doubling. In order to simplify the diagram, the connections to the heater have been omitted. However, we are to assume that the heater is connected in the circuit and is heating the cathodes to a temperature sufficient to cause the emission of electrons from their surfaces. The rectifier is shown connected to an AC generator. This generator, of course, merely represents the 110-volt AC lighting supply. It is included in the diagram to help clarify the explanation. Let us first consider the instant when point A is negative with respect to point E. (See Fig. 53.) Current will then flow from point A, the negative terminal of the alternator, to point B, the right-hand cathode of the tube. Since the right-hand cathode is connected to

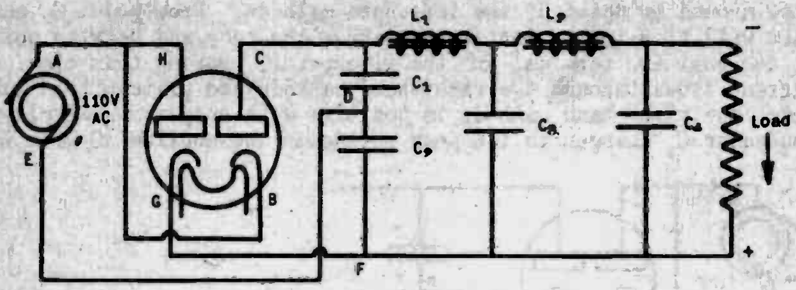
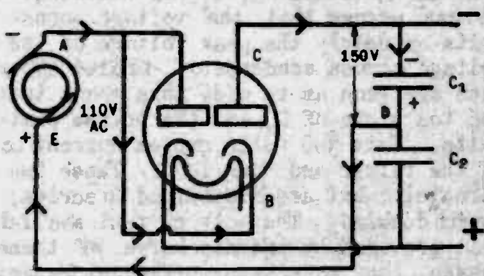


Fig.52 A voltage doubler circuit.

the negative terminal of the alternator, it is negative with respect to its plate and, therefore, this part of the tube conducts current. The current flowing through the right-hand cathode and plate of the rectifier tube now charges condenser C_1. Current flows from point C to the top plate of C_1. Current flows away from the bottom plate of C_1 from point D back to point E, the positive terminal of the al-

Fig.53 Direction of current flow when the right-hand plate and cathode conduct.



ternator. Thus the condenser C_1 charges to almost the peak value of the alternating voltage with its top plate negative and ite bottom plate positive. This is true since the plate resistance of the rectifier tube is very low. During this alternation, no current can flow between the left-hand plate and its cathode since this plate is negative with respect to its cathode. After the peak value of the alternating voltage has been reached, it starts to decrease to zero. The condenser C_1 now begins to discharge through the filter choke, the load and C_2. However, since the impedance of this path is very high compared to the plate resistance of the tube, the time required for the condenser to discharge is very great in comparison with the time required to charge it. It, therefore, discharges at a very low rate.

During the next alternation, point A of the alternator is positive with respect to point E. (See Fig. 54.) This makes point H, the left-hand plate of the tube, positive with respect to its cathode. Therefore, current will flow from point E to point D. Electrons will flow on to the top plate of condenser C_2 and an equal number will be driven off the bottom plate of this condenser to flow around to point G, the left-hand cathode. From point G, current will flow to the left-hand plate of the tube and back to point A, the positive terminal of the alternator. During this time, no current flows through the right-hand cathode and plate of this tube since the right-hand cathode is positive with respect to its plate. Condenser C_2 charges to the peak voltage of the applied AC with its

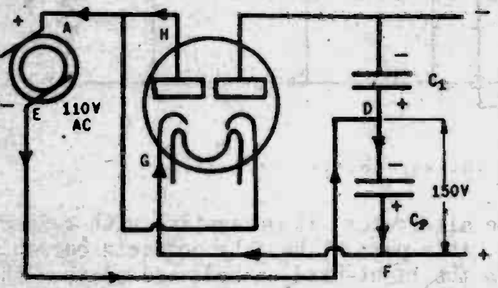


Fig.54 Direction of current flow when the left-hand plate and cathode conduct.

top plate negative and its bottom plate positive. During the time that C_2 is charging, C_1 has discharged only slightly. Therefore, we can assume that the voltage across condenser C_1 is about 150 volts or nearly the peak voltage of the applied AC. Likewise, the voltage across condenser C_2 is also 150 volts. Since their polarities are such as to add, this means that the total voltage between the top plate of C_1 and the bottom plate of C_2 is approximately 300 volts. This 300 volts causes current to flow through the remainder of the filter and the load. These two condensers are charged alternately, but are discharged in series; therefore, the output voltage is doubled. The only current available for the load circuit is that provided by the discharge of these two condensers. For this reason, they must have sufficient capacity to furnish the necessary load current without reducing the voltage across themselves appreciably between the times that they are charged. Condensers C_1 and C_2 should have a capacity of 32 mfd. each. Obviously, the greater the load current, the more the condensers will discharge and the less will be the average voltage across the two of them in series.

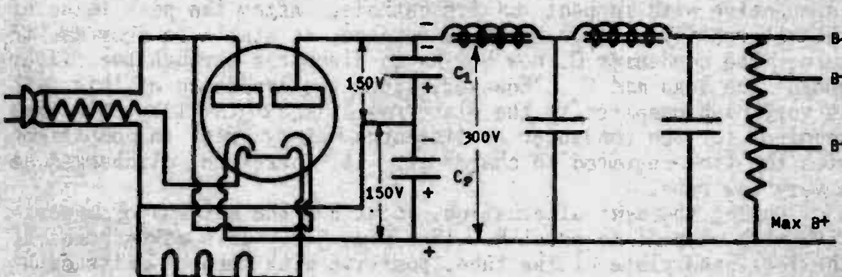


Fig.55 A complete voltage doubler circuit with filaments wired in and voltage divider attached.

A lower average voltage across the condensers causes the voltage drop across the load to be reduced. This type of circuit, therefore, has relatively poor voltage regulation. For exact characteristics, refer to the type 25Z5 tube in the manufacturer's manual.

Fig. 53 shows the direction of current flow when condenser C_1 is being charged and Fig. 54 shows the direction of current flow when the bottom condenser C_2 is charging. Fig. 55 illustrates a complete voltage doubler circuit showing the connections of the filament, the built-in line-voltage dropping resistor and the complete filter system.

The text of this lesson was compiled and edited by the following members of the staff:

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MIDLAND RADIO
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POWER & LIGHT BUILDING, KANSAS CITY, MISSOURI

UNIT NO. 1

DESIGN OF METERS FOR RADIO USE

LESSON NO. 17

HARD RIDIN',
STRAIGHT SHOOTIN'.

.......STICK TO THE SADDLE.....HOLD YOUR AIM!

In the days when the West was the 'tough' proving ground for man's mettle, you had to be a hard ridin', straight shootin' 'hombre' to live from one day to the next. Perhaps you wonder what this has to do with your training. Not a thing, except that it would be well for you to apply the same general principles to the pioneering of your success.

In testing the mettle of a man, it is not necessary to have a background of whooping Indians, yelping wolves or 'two-gun' bad men. Life itself is a battle.....every day that dawns brings fresh problems which can be overcome only by determination, ambition and the will to win. The cowboy of old stuck to his saddle as though he were glued on, even when the riding became toughest. He didn't give up and say 'What's the use'. When he was thrown by a horse, he came back for more, and more, until HE was the winner. Apply that same determination to your training. When you bump up against some tough going, stay in the fight, and FIGHT. If you can't get it the first time, STICK TO IT UNTIL YOU DO! KEEP COMING BACK FOR MORE AND YOU'LL BE THE WINNER!

Naturally, we don't expect you to pull a couple of 'six shooters' and start banging away. But we do advise you to take careful aim at your objective in life and to keep your sights trained on that objective always. When a frontiersman aimed his gun at the enemy, he held his aim even while other guns were banging away on all sides. You have set your sights on success in Radio and Television. You are aiming right at the center of the 'bullseye'.....a good job, a respectable income, a future. SEE THAT YOU KEEP YOUR SIGHTS ON THAT 'BULLSEYE' EVEN THOUGH A LOT OF OTHER TARGETS PRESENT THEMSELVES. You will never be a success if you aim at first one thing and then another.

STICK TO THE SADDLE LIKE A VETERAN COWPUNCHER..... SET YOUR SIGHTS ON SUCCESS.....THEN HOLD IT THERE AND 'BANG AWAY' WITH ALL THE PENT UP ENERGY AND AMBITION THAT'S IN YOU. AND REMEMBER THAT WE ARE HERE TO HELP YOU WIN YOUR BATTLE OF LIFE.....WE WANT YOU TO BE A SUCCESS IN RADIO!

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KANSAS CITY, MO.

Lesson Seventeen

DESIGN of METERS for RADIO USE

"Without the use of Meters, it would be impossible for us to ascertain how our equipment was working and to quickly locate the trouble when it occurred. Since in the practical application of Radio and Television you are going to use Meters to a very large extent, it is absolutely essential that you have a thorough understanding of their construction and operation.

"The devices used for the indication of electrical quantities were very crude and inaccurate during the early stages of electrical development. However, today, measuring instruments have been perfected to a high degree and each of these instruments represents an interesting study."

The need of instruments for measuring voltage and current was recognized by the early scientists whose experiments have made possible this modern age of electricity. Observed phenomena do not become a science until their effects can be accurately measured and their future actions under other conditions thereby predicted. Unlike other commodities, electricity cannot be seen, heard, tasted, or smelled; and while it may, if of sufficient strength, be felt, this is by no means an accurate or a desirable method of determining its intensity. In order that electricity may be measured, some of its effects must be converted into actions which influence the human eye.

The three principal manifestations of an electric current are its chemical, heating, and magnetic effects. Theoretically, any one of these could be used to measure an electric current. For example, it would be possible to measure the volume of hydrogen gas liberated by the passage of an electric current through a quantity of water. Since each gram of hydrogen liberated requires the passage of a definite number of coulombs, the intensity of the current flowing could be determined by noting the time required to collect a definite amount of this gas. Even though it were possible to accurately measure the weight of the gas collected and the time required for its liberation, this method would be far from satisfactory. The equipment needed would not be portable and the time required to make a measurement would be prohibitive for practical purposes. Devices of this kind have been used in the past; they are called "coulombmeters" since they measure the quantity of electricity, rather than its rate of flow. Due to their inherent disadvantages, they have no practical application.

The second observable effect of an electric current is the fact that its passage through a circuit is accompanied by the generation of heat. This property is made use of in the construction of hot-wire meters and thermocouple meters. They will be studied in detail in subsequent paragraphs of this lesson. The fact that the information obtained by this method is sometimes vitiated by extraneous influences accounts for its limited use, except for the measurements of very high-frequency currents where the other two effects cannot be employed.

The majority of all electrical measuring instruments utilize the magnetic effect for their operation.

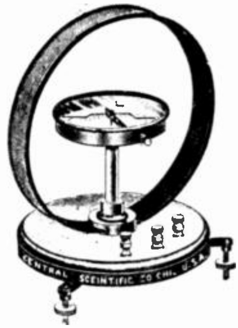
1. **THE TANGENT[1] GALVANOMETER.** The constituent parts of a tangent galvanometer comprise a large-diameter coil of wire mounted in a vertical plane with a small compass needle fixed in a horizontal position at its center. When not in use, the compass needle is attracted by the earth's magnetic field and therefore places itself in a north and south direction. If the plane of the coil is set in a north-south direction, the magnetic field produced by a current flowing through it is at right angles to the field of the earth. The compass needle will, therefore, experience two forces; one, the earth's magnetic field which attempts to make the north pole of the compass point north; the other, the field produced by the current flowing through the coil which is attempting to move the compass needle to an east-west direction. The resultant of these two magnetic forces depends upon their relative strength. If, for example, the field of the coil is directed toward the east and is equal to the field of the earth, the compass needle will come to rest in a northeast position. A smaller current will produce a weaker magnetic field about the coil and the compass needle will point in a more northerly direction, somewhere between north and northeast. Likewise, a greater current will produce a magnetic field about the coil stronger than that of the earth and the compass needle will place itself in a direction somewhere between northeast and east. The scale beneath the compass needle is usually calibrated directly in amperes and, in order to use the instrument, the coil must first be rotated until the compass needle is on zero of the scale. Since the amount of deflection is not directly proportional to the value of current flowing through the coil, the scale is not divided into equal units.

While the tangent galvanometer is relatively simple, it suffers many disadvantages. As can be seen from the illustration in Fig.

[1] The instrument derives its name from the mathematical relation between the amount of deflection and the value of the current. The tangent of the angle of deflection is directly proportional to the current.

1, it is not easily portable. Before a reading may be taken, it must be carefully leveled by means of the three leveling screws in its base. It is easily affected by external magnetic fields which cause its readings to be inaccurate. The time required to take a reading is rather long, due to the fact that the coil must first be placed in a north-south direction and several seconds are required for the compass needle to settle down to its final position. Finally, its accuracy is dependent upon the strength of the earth's magnetic field, which is slightly different at various points on the earth's surface and which changes its value at any one spot from time to time, especially during magnetic storms, etc. For these reasons, the instrument is obsolete, having been superceded in every instance by the Weston type meter.

Fig. 1 A tangent galvanometer



2. DC AMMETERS. Recognizing the many disadvantages of the tangent galvanometer, scientists made every effort to produce a more accurate and convenient current-measuring instrument. Perhaps the most sensational improvement was due to D'Arsonval. His instrument, which is called a D'Arsonval galvanometer, is still used in scientific laboratories for the measurement of minute currents.

Realizing that the magnetic field of the earth is subject to considerable variation, he did not use it in his galvanometer. From the illustration shown in Fig. 2, the principal parts of the D'Arsonval galvanometer may be seen. It consists of a permanent magnet, in the form of a horseshoe, between the poles of which a small, light coil of wire is suspended by a very thin, flat and narrow ribbon of phosphor bronze. The normal plane of the coil coincides with that of the magnet. When a current is passed through the coil, a magnetic field is set up about it which interacts with the field of the permanent magnet, rotating the coil in an attempt to bring its north pole opposite the south pole of the permanent magnet and vice versa. The coil rotates until the restoring force produced by the twisted phosphor-bronze ribbon is equal to the magnetic force rotating the coil. The larger the current that is passed through the coil, the greater will be the amount of rotation. Affixed to the phosphor-bronze ribbon, above the coil, is a small, circular mirror. A beam of light is reflected from this mirror onto a semi-circular scale, graduated in millimeters. By noting the position of the light spot on this scale, the amount

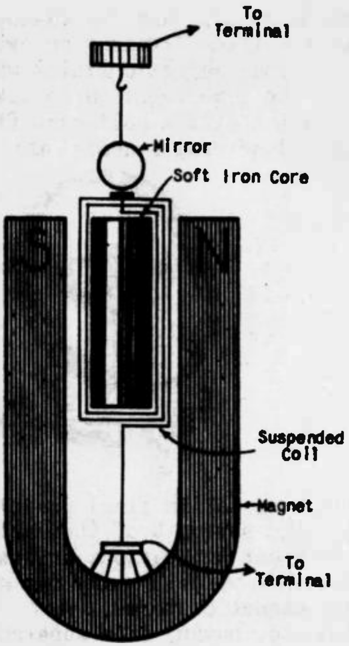
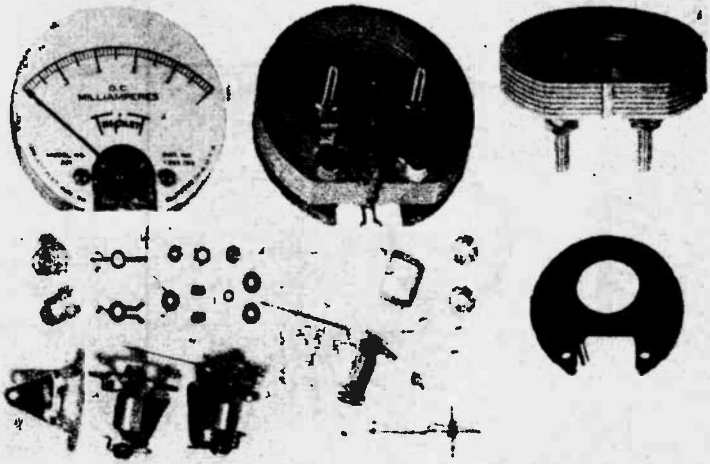


Fig.2 Construction of D'Arsonval galvanometer.

of rotation and, in direct consequence thereof, the value of the current flowing through the coil may be measured. Since the D'Arsonval galvanometer is only a transitional stage in the development of the modern meter, it will not be given further consideration.

Meters in use today have what is known as the "Weston movement". It is an improved form of the D'Arsonval meter and was developed by Dr. Weston in his series of experiments which began about 1885. The Weston meter is not, like some inventions, the result of a fortuitous discovery. It is the outcome of several years of extensive experimentation which finally culminated in the present-day meter.

A comprehensive idea of the construction of a Triplett meter and a Weston meter may be gained from an inspection of Figs. 3 and 4. The various parts include a permanent magnet made of a magnetic alloy, capable of retaining its magnetism without any weakening throughout a period of many years. Attached to the poles of the magnet are soft iron pole pieces having circular, concave faces of such a size as to completely encompass the moving coil. Within the space between these pole pieces, there is placed a cylindrical, soft iron core which leaves an air gap between the pole pieces and the core of .05 inch in width. It is this annular air gap through which the moving coil travels. The lines of force surrounding the permanent magnet with the pole pieces and core are shown in Fig. 5. Notice that the addition of the pole pieces and core has served to produce an intense magnetic field within this air gap.



Courtesy Triplett Elec. Inst. Co.

Fig.3 An exploded view of a Triplett DC meter.

In the smaller instruments, the movable system weighs less than .007 ounce. The coil is made of several turns of very fine wire, wound upon an aluminum frame. Its construction may be seen in Fig. 6. On its upper and lower surfaces are hardened steel pivots which rest in jeweled bearings. These pivots and bearings are so placed that the coil may rotate in the air gap between the permanent magnet and the core. Current is carried to and from the coil by means of two light, spiral hairsprings mounted on either end of the coil. They are for the purpose of returning the needle to zero; they exert a restoring force upon the needle which is proportional to the amount of deflection. Since they are wound in opposite directions, any temperature change which would increase or decrease their length is compensated for by the fact that one

Fig.4 The DC Weston movement.

Courtesy "Weston Instruments"

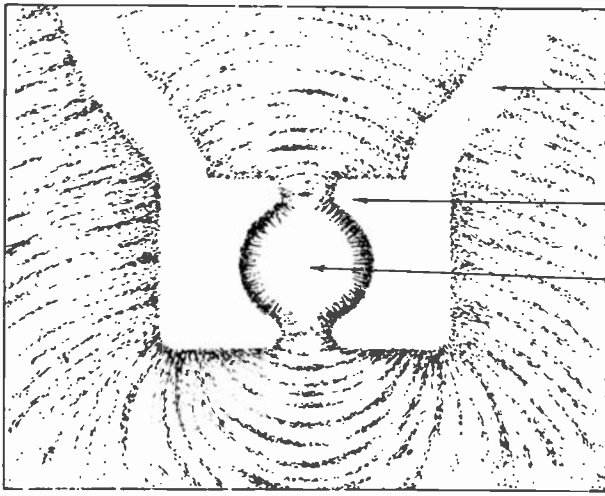


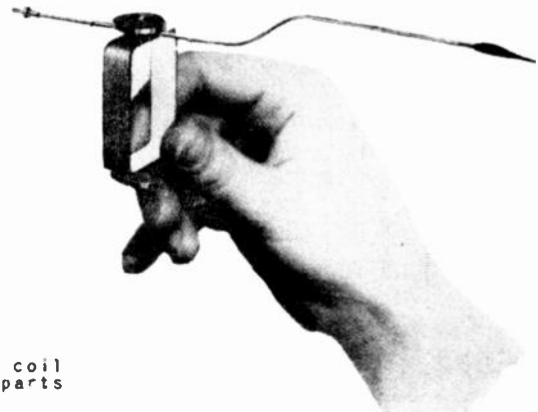
Fig.5 Magnetic lines of force in circular air gap of Weston movement. (Courtesy Weston Instruments)

exerts the restoring force by pulling the coil and the other by pushing it. A long, hollow aluminum pointer is fixed to the upper surface of the coil. Its end moves over a graduated scale by means of which the value of current flowing through the coil may be read. Sometimes a counter weight is attached on the opposite end of the pointer, if it is needed to balance the moving assembly.

When a current is passed through the coil in the proper direction, a magnetic field is set up about the coil which makes one face of it north and the other south. The north pole of the permanent magnet repels the north pole of the coil and vice versa. The coil, therefore, rotates from its normal position until the restoring force of the spiral hairsprings is equal to the forces of magnetic attraction and repulsion which are producing the rotation. The coil finally comes to rest in such a position that the amount of deflection produced is proportional to the value of the current flowing through the coil. The more sensitive of these instruments such as used in Radio and Television work require only 1 ma. (sometimes less) through the coil to produce full-scale deflection. To compensate for any changes which might be produced in the spiral hairsprings, a screwhead protrudes through the glass cover of the meter by which the zero position of the pointer may be adjusted. In order to produce the maximum sensitivity possible, the permanent magnet must have a very strong magnetic field and the moving coil assembly must be made very, very light. Friction must be minimized whenever possible and the air gaps made exceedingly small.

When the moving coil rotates, the aluminum frame upon which it is wound cuts through the magnetic lines of force in the airgap. This induces a voltage in the frame which causes current to circulate through it. The current flowing in the aluminum frame is known as an "eddy current" and the magnetic field which it produces tends to prevent the rotation of the coil.[1] This causes the needle to come to rest quickly and a reading of the meter can be immediately taken. This effect is known as "damping". If it were not present, the needle would overshoot its mark and oscillate back and forth, requiring several seconds to come to rest. Since these eddy currents flow only while the coil is in motion, they do not change the amount of deflection that a given current will produce, but only cause the pointer to settle down more quickly.

Instruments such as just described may be used as very sensitive milliammeters by connecting them in series with the load through which the current is flowing. As will be explained later in this lesson, when larger currents are to be measured, shunts must be used.



Courtesy
"Weston Instruments"

Fig.6 The moving coil and its associated parts of a large meter.

3. DC VOLTMETERS. A DC voltmeter is of exactly the same construction as the DC milliammeter previously described. If a voltmeter having a maximum range of 100 volts is to be constructed, a DC milliammeter which requires 1 ma. to produce full-scale deflection may be used by connecting a large multiplier resistance in series with the meter. When the meter and resistor are connected between two points across which there is a voltage difference, the amount of current flowing through the meter is directly proportional to the voltage between these two points. The scale of the meter, therefore, can be calibrated directly in volts. If a voltage of 100 volts is to send a current of 1 ma. through the meter and multiplier resistance, their combined resistance as found by Ohm's Law is 100,000 ohms. A very small part of this resistance is that of the moving coil of the meter. Most of it is contained in the multiplier resistance. If the meter is to be accurate, the value of the multiplier resistance must be very exact. Ordinary carbon

[1] Circulating "eddy currents" set up a magnetic field in accordance with Lenz's Law. Refer to Section 4, Lesson 10.

or wire-wound resistors are not suitable. A precision type of resistor whose tolerance is .5% of its rated value must be used.

The sensitivity of a voltmeter is expressed as so many "ohms per volt". This expression is obtained by dividing the value of the multiplier resistance in ohms by the full-scale reading of the voltmeter in volts. In the example just given, this is:

$$100,000 \div 100 = 1,000 \text{ ohms per volt}$$

Voltmeters to be used in Radio and Television experiments must have a sensitivity at least this great. Voltmeters used in power distribution work have lower sensitivities; the average is 300 or 400 ohms per volt. One of the newest meters on the market which is extraordinarily sensitive has a rating of 20,000 ohms per volt. This meter requires only .05 ma. or 50 microamperes to produce full-scale deflection.

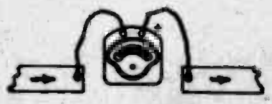


Fig.7 A milliammeter connected in a circuit. All of the current flows through the meter.

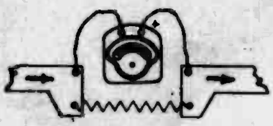


Fig.8 A shunt connected across a meter. Only a part of the total current flows through the meter.

4. EXTENDING THE RANGE OF DC MILLIAMMETERS. If a milliammeter, which requires only 1 ma. for full-scale deflection, is to be used to measure a maximum current of 10 ma., a shunt must be used to divert the greater part of the current from the meter.

Fig. 7 shows a milliammeter connected in a circuit without a shunt. The maximum current that can flow through this circuit without endangering the meter is 1 ma. Fig. 8 shows a meter across whose terminals there is connected a low-valued resistor or shunt. When 10 ma. are flowing through the circuit, 1 ma. flows through the meter and 9 ma. flow through the shunt resistor. Since the current flowing through the shunt is 9 times as large as that flowing through the meter, the shunt resistance must be $\frac{1}{9}$ that of the meter. If the resistance of the meter is 27 ohms, the shunt must have a value of 3 ohms.

The word "shunt" means to turn aside, or sidetrack; and by the use of one, the majority of the line current is sidetracked around the meter. Although the total current does not flow through the meter, a definite proportion of it does, and the meter is calibrated to read the total current flowing. Sometimes shunts are constructed of "manganin". It is an alloy whose resistance changes vary little with variations of temperature. A shunt is not constructed of one solid piece of this material, but, rather, is made of several parallel strips between which air spaces are left. This method of construction greatly increases heat radiation and reduces the temperature effect upon the resistance of the shunt. All milliammeters and low-range ammeters hwve self-contained shunts; that is, the shunt is placed within the case of the meter. High-range ammeters require shunts of such a size that it is neither convenient nor desirable to place them within the meter cases. The appearance of various shunts is illustrated in Fig. 9. The current-carrying capacity of the smallest shown in the figure is 200 amperes, while that of the largest is 6,000 amperes.

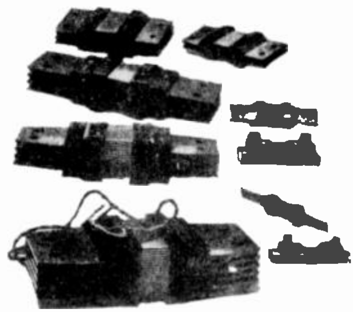


Fig.9 Various sizes of shunts.

Courtesy "Weston Instruments"

capacity of the smallest shown in the figure is 200 amperes, while that of the largest is 6,000 amperes.

The size of the shunt to be used to extend the range of any milliammeter to a larger value may be calculated as follows: Let R_M equal the resistance of the meter; R_s the required resistance of the shunt; I_M the present maximum scale reading in milliamperes or amperes; and I the new maximum scale reading in milliamperes or amperes. Then, R_s may be found by this formula:

$$R_s = \frac{I_M \times R_M}{I - I_M}$$

Let us now demonstrate an application of this formula.

Example 1: An 0 - 1 ma. meter has a resistance of 30 ohms. If it is desired to convert this meter into an 0 - 50 ma. meter, what is the resistance of the shunt which must be connected across the meter terminals?

Solution: In this case, R_M is 30 ohms; I_M is 1 ma.; I is 50 ma. By substituting in the formula, we obtain:

$$R_s = \frac{1 \times 30}{50 - 1} = \frac{30}{49} = .612 \text{ ohm}$$

When a shunt of this value is placed across the meter and the meter is connected in series with a load carrying 50 ma., 1 ma. will flow through the moving coil of the meter and the remaining 49 ma. will flow through the shunt. The meter will be calibrated from 0 to 50 ma. In case the dial of the meter is not graduated from 0 to 50 ma., we must remember to multiply any reading obtained with this meter by 50. (This number is called the multiplying factor and is found by dividing the new maximum reading by the original maximum reading.)

Example 2: An 0 - 20 ma. meter is to have its range extended to read a maximum value of 200 ma. What value of shunt resistor must be placed across the meter?

Solution: Since this meter has a present full-scale reading of 50 ma., it very likely employs a shunt. Therefore, we will determine the resistance of an additional shunt which must be connected across the meter to extend the range to 200 ma. We shall assume that the resistance of the meter and its present shunt is 2 ohms. Therefore, R_M is 2 ohms; I_M is 50 ma.; I is 200 ma. Substituting these values, we have:

$$R_s = \frac{50 \times 2}{200 - 50} = \frac{100}{150} = .667 \text{ ohm}$$

When a shunt of this size is connected across the meter, all its scale readings are multiplied by 4, since its new maximum value (200) is four times its previous maximum value (50 ma.).

If the resistance of the meter is not known, it can always be obtained from its manufacturer, or the following method for determining the size of the shunt resistor may be used. To convert a 5 ma. meter into a 25 ma. meter, a circuit such as shown in Fig. 10 is used. The meter and a variable resistance are con-

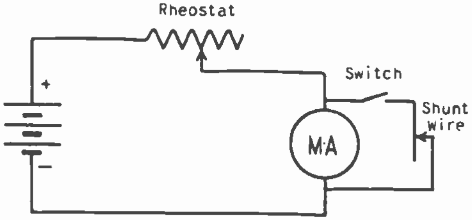


Fig.10 Circuit used to determine the value of a shunt when the resistance of the meter is not known.

nected in series with a battery. Across the meter, there is connected the shunt and a switch in series. With the switch opened, the variable resistance is changed until the meter reads exactly 5 ma., or full-scale deflection. For small meters, the shunt is often made of manganin wire, having a definite resistance per inch. The switch is now closed and various lengths of this manganin wire are shunted across the meter until its reading is exactly 1 ma. Since it now reads 1 ma., its deflection is ⅕ of that previously obtained; that is, when 5 ma. flow from the battery, the meter reads 1 ma. Therefore, when 25 ma. flow from the battery, the reading of the meter will be full scale. This means the scale readings of the meter have been multiplied by 5 and when the meter indicates full-scale deflection or 5 ma., there is actually 25 ma. flowing through the circuit, the greater part of which is passing through the shunt. When the correct length of shunting wire has been found, it is carefully cut and this length of wire is then connected across the meter.

The terminals of nearly all meters are bolts which extend from the back of the case and the shunt wire may be bolted to these two terminals. It must not, however, be wrapped around the terminals, as its effective length will then be too short. Either the tip of each end of the shunt wire should be bolted to the meter, or the shunt wire should be cut slightly longer than the desired value and the extra length wrapped around the bolt. If the shunt wire is very long, it may be coiled between the terminals. If it is too short to reach between the meter terminals, wire of very low resistance should be used to extend its length. If this connecting wire has appreciable resistance, the shunt will be too great in value.

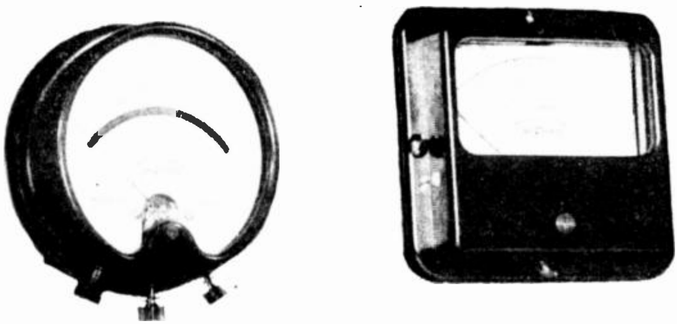


Fig.11 A DC voltmeter and a CC milliammeter

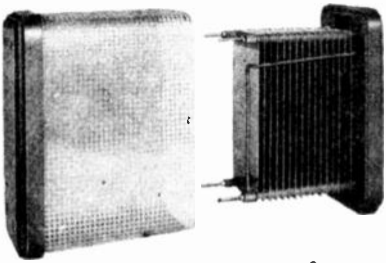
The foregoing method may be used to extend the range of any direct current milliammeter or ammeter. The wattage rating of the shunt must be great enough to insure "cool" operation; otherwise, its resistance may change if the temperature is raised appreciably.

The general appearance of a DC meter may be seen in Fig. 11. Notice that one of the instruments contains a small mirror directly beneath the scale. When reading a meter of this type, the observer should stand directly over the meter so that the needle completely covers its image in the mirror. Thus, inaccuracies due to parallax are avoided. A parallax error is caused by reading the meter from one side or the other. When reading meters which do not have this mirror, the observer should keep his eye directly over the needle.

5. **EXTENDING THE RANGES OF DC VOLTMETERS.** To extend the range of a DC voltmeter, it is only necessary to insert an additional multiplier resistance in series with the meter. If it is desired to make a voltmeter whose maximum reading is 10 volts from a meter which requires 1 ma. for full-scale deflection, enough resistance must be inserted in series with the meter to limit the current through it to 1 ma. when a voltage of 10 volts is applied across the meter and multiplier resistance. This necessary multiplier resistance can easily be determined by using Ohm's Law.

$$R = \frac{E}{I} = \frac{10}{.001} = 10{,}000 \text{ ohms}$$

This 10,000-ohm resistor must have a very low temperature coefficient of resistance[1]. For extreme accuracy, the resistance of the meter must be taken into account, although ordinarily the meter resistance is so small compared to that of the multiplier that it is neglected.



Courtesy "Weston Instruments"

Fig.12 A large external voltmeter multiplier resistor.

To convert this 10-volt voltmeter into an instrument with a maximum range of 100 volts, the following formula may be used:

$$R_S = \frac{(R_M \times E) - (R_M \times E_M)}{E_M}$$

Where:
- R_S is the additional series resistance to be added;
- R_M is the present multiplier resistance plus the resistance of the meter;
- E_M is the present maximum scale reading in volts;
- E is the new desired maximum scale reading in volts.

In this case, R_M is 10,000 ohms, E_M is 10 volts, and E is 100 volts. Substituting in this formula, we obtain:

$$R_S = \frac{(10{,}000 \times 100) - (10{,}000 \times 10)}{10} = \frac{900{,}000}{10} = 90{,}000 \text{ ohms.}$$

This is the value of the series resistance which must be added to increase the range of the voltmeter to 100 volts.

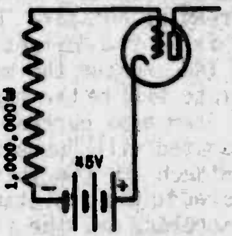
Fig.13 A small multiplier resistor which fits inside the meter case.

Some multiplier resistors are contained within the meter cases, but many are not, since they are made large enough to radiate considerable heat and thus minimize temperature effects. Fig. 12 illustrates a large multiplier resistor, and Fig. 13 a small one.

[1] Refer to page 20, Lesson 3, Unit 1.

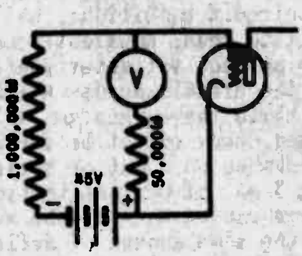
As previously stated, the sensitivity of a voltmeter to be used for Radio and Television work must be at least 1,000 ohms per volt. The greater the sensitivity of a voltmeter, the less current it requires to give a reading. Since a voltmeter draws some current from the circuit across which it is connected, it may be that this additional current taken by the voltmeter is sufficient to change the circuit conditions and the actual voltage read by the voltmeter may not be the true value. An example will make this

Fig.14 A vacuum tube with its grid bias applied through a 1 megohm resistor.



clear. Fig. 14 shows a circuit of a vacuum tube in which the grid bias of 45 volts is applied through a 1,000,000-ohm resistor. Since the grid is negative with respect to its cathode, no grid current will flow. The actual voltage existing between the grid and the cathode is, of course, 45 volts, the voltage of the C battery. Now, if a voltmeter whose maximum range is 50 volts is connected between the grid and the cathode in an attempt to measure the grid bias as

Fig.15 Using a voltmeter in an attempt to measure the grid bias.



shown in Fig. 15, the voltmeter will draw current from the battery. This current will flow from the negative side of the battery, through the 1,000,000-ohm resistor to the negative terminal of the voltmeter, through the voltmeter and its multiplier resistor back to the positive terminal of the battery. If the voltmeter has a sensitivity of 1,000 ohms per volt, its multiplier resistance is 50,000 ohms. The total resistance in series with the 45-volt battery is 1,000,000 + 50,000 = 1,050,000 ohms. The amount of current that will flow in this circuit may be found by Ohm's Law:

$$I = \frac{E}{R} = \frac{45}{1,050,000} = 42.9 \text{ microamperes}$$

This amount of current, in flowing through the voltmeter and its multiplier resistance, will produce a voltage drop of:

$$E = I \times R = .0000429 \times 50,000 = 2.15 \text{ volts}$$

Therefore, the voltmeter will read 2.15 volts. while the actual voltage between the grid and the cathode, when the voltmeter is disconnected, is 45 volts. The voltmeter has drawn enough current from the battery to produce a very large change in the circuit conditions. It is often impossible to measure the grid bias of a vacuum tube for this very reason. When such is the case, the voltmeter should be connected directly across the C battery and, if the voltage reading obtained is normal, it can be assumed that the grid bias is at its correct value.

The greater the sensitivity of the voltmeter, the more nearly accurate will be the reading obtained. However, since any voltmeter must draw some current in order to produce a reading, any reading so secured will be slightly less than the true value. Unless the resistance of the voltmeter and its multiplier resistor is large compared to the resistance across which the voltage is being measured, the accuracy of the reading obtained will be low. Since higher range voltmeters have larger multiplier resistors, readings taken with a high-range voltmeter will be more accurate than those obtained with a low-range meter. Of course, it would probably be impossible to read accurately a value of 1 volt on a scale with a maximum of 1,000 volts, yet if this 1 volt were developed across a 1,000-ohm resistor and a voltmeter with a range of 1 volt were used to obtain the reading, it would most likely be very inaccurate. Thus, a low-range instrument may cause inaccuracies due to upsetting circuit conditions, while a high-range instrument may be difficult to read; apparently a compromise must be made. The theoretically perfect voltmeter would be one which did not draw any current from the circuit across which it was connected.[1]

While the ranges of voltmeters and milliammeters may be increased, they cannot be decreased below the full-scale reading obtained when no shunt or series multiplier resistor is used. If it takes 1 ma. of current to produce full-scale deflection on a meter, nothing can be done to the meter to cause a lower current to produce the same amount of deflection.

Both DC milliammeters and voltmeters have polarity. One of their terminals is marked "plus" and the other "minus". Care must be taken to connect them in the circuit in the proper manner; that is, the positive side of the meter should be connected toward the positive side of the voltage source and the negative side of the meter toward the negative side of the voltage source. Failure to observe this precaution may result in the passage of current through the moving coil in the wrong direction. This would tend to cause a reverse rotation of the coil and the meter needle is very liable to be bent.

6. **METERS WITH SEVERAL RANGES.** Very often a milliammeter is constructed to have several current measuring ranges. For example, the lowest range may be 1 ma., the next range 10 ma., and the third

[1] A "vacuum tube voltmeter" is extremely close to this ideal instrument. It will be discussed in Lesson 3, Unit 2.

range, 100 ma. A rotary switch may be used to change the range of the meter. The circuit diagram of such a meter is shown in Fig. 16. It may be seen that when the switch is in position 1, there is no shunt connected across the meter. In this position, its maximum range is 1 ma. When the switch is moved to position 2, a shunt of such a value as to increase the range to 10 ma. is connected across the meter. In the third position, the proper size shunt is placed across the meter to allow it to measure a maximum current of 100 ma.

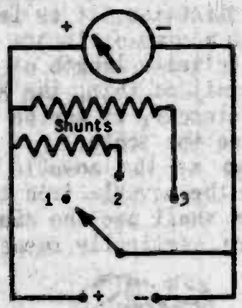


Fig.16 A milliammeter having several ranges. The rotary switch selects the proper shunt.

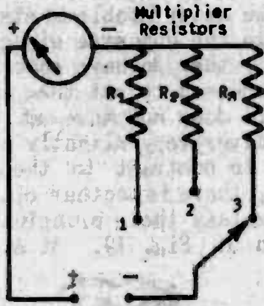
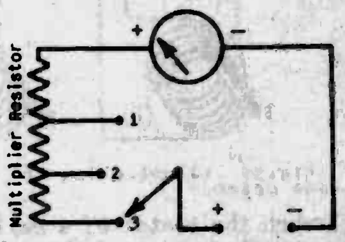


Fig.17 A voltmeter with several ranges. The rotary switch selects the proper multiplier resistor.

In a like manner, a voltmeter may be constructed to have several ranges. One arrangement used in accomplishing this is shown in Fig. 17. Resistor R_1 has a value of 1,000 ohms and when connected in the circuit by means of the rotary switch, the meter has a range of 1 volt. Likewise, resistances R_2 and R_3 have values of 10,000 and 100,000 ohms respectively and, when connected in the circuit, can be used to restrict the range of the meter to 10 volts or 100 volts.

Fig.18 Using a single resistor as the multiplier and tapping it at various points to obtain different ranges.



Some instruments do not use separate series resistors for each range, but employ one resistor whose value is equal to that needed for the maximum range of the voltmeter and is tapped at various points along its length. By connecting to any one of these various taps, different ranges of the voltmeter may be obtained. (See Fig. 18.)

In other meters, the rotary switch is not used; instead, a separate terminal for each range and a common terminal for all are provided.

7. MOVABLE IRON AC METERS. The type of meter which we have been discussing cannot be used to measure an alternating current. When such a current is allowed to flow through this type of meter, one alternation of the current produces a magnetic field about the coil which tends to rotate it in the proper direction. The next alternation, however, flows through the moving coil in the reverse direction and the magnetic field produced tends to rotate the moving coil oppositely. The alternations succeed each other at a rapid rate, even with low-frequency currents, and before the pointer of the meter is able to start rotating in one direction, it is impelled in the opposite direction. Although its moving parts are very light, they do have some inertia and a very definite length of time is required to set them in motion. As a result of this, the meter needle does not move at all. If examined closely, it may be seen to quiver very slightly over the zero mark on the scale.

In contrast to the Weston meter, known as the movable coil type, there is another class of meters called the movable iron type. To explain their principle of operation, we shall use the diagram shown in Fig. 19. At A, two iron bars are vertically suspended

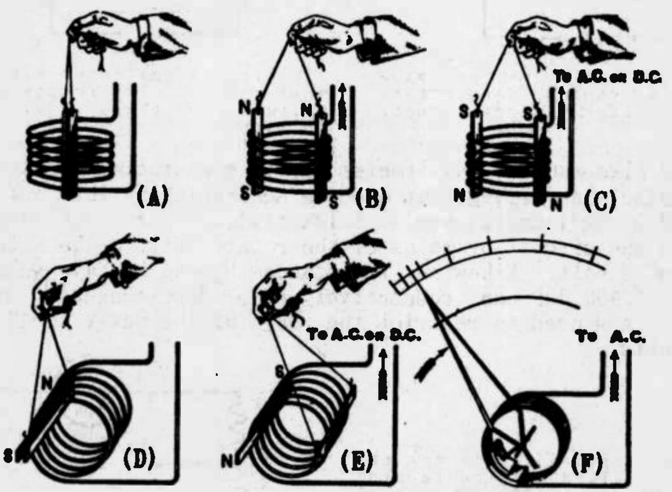


Fig.19 Illustrating the principle of the movable-iron or iron-vane meter.

through the center of a coil in which no current is flowing. When a current is passed through the coil, one of its ends becomes a north pole and the opposite end a south pole. Let us say that the current is in such a direction as to make the top end a north pole. The magnetic lines of force, in flowing through the iron bars, will magnetize them, making their two top ends north and their bottom ends south. Since like poles repel each other, the iron bars will be forced apart as shown at B.

Now if the current flowing through the coil is rapidly reversed, the top end of the iron bars will become south poles and there will be the same repulsion between them as before. If an alternating current is passed through the coil, it will reverse its direction so rapidly that the two iron bars will remain apart.

Now let the coil be placed horizontally and let one of the iron bars be attached permanently to the inside of the coil. The other iron bar is suspended in a horizontal position close to the fixed bar. When a current is sent through the coil, whether DC or

Fig. 20 Construction of an iron-vane AC ammeter.

Courtesy "Weston Instruments"

AC, the two iron bars will be magnetized and a repulsion will exist between them which forces the bar, which is free to move, over to the opposite side of the coil. These conditions are shown at D and E in the figure. At F in the diagram, the movable iron piece is attached so that it can move only by rotation. To the movable iron

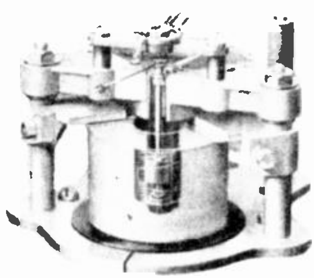


Fig. 21 Construction of an iron-vane AC voltmeter.

Courtesy "Weston Instruments"

is affixed a pointer which travels over a scale as current passes through the coil. A spiral spring is attached to the shaft upon which the movable iron piece is fixed and by its action, rotation of the movable iron piece is opposed. Therefore, the movable iron and pointer will move over the scale until the restoring force of the spiral spring is equal to the force of the magnetic repulsion between the two pieces of iron.

Views of the commercial form of this type of meter are shown in Figs. 20 and 21. Fig. 20 is an AC ammeter. In the ammeter, the coil consists of a few turns of relatively large wire. The size

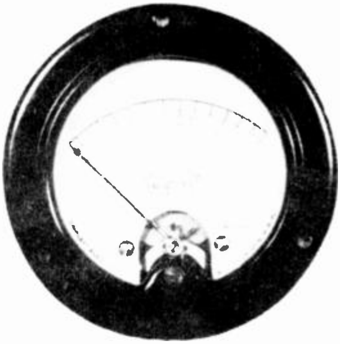
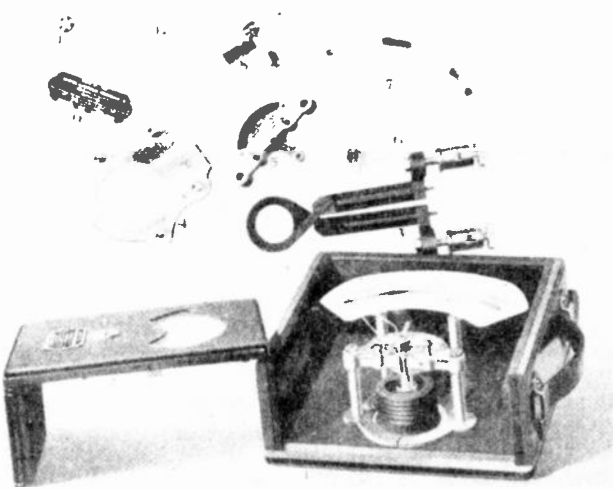


Fig.22 An iron-vane AC voltmeter.

Courtesy "Weston Instruments"

of the wire and the number of turns will depend upon the range of the meter. The coil of the voltmeter (Fig. 21) is composed of many turns of comparatively small wire and must, of course, be used with a series, multiplier resistance as is the DC voltmeter. As may be seen in Fig. 20 or Fig. 21, the movable iron is cylindrical in shape, while the fixed iron is roughly triangular. The uniformity of the scale depends upon the shape of this fixed piece of iron. It is, of course, desirable to have the scale as uniform as possible. However, even when the fixed piece of iron is of the shape shown, the scale is not truly uniform. From the illustration of a movable iron type AC voltmeter shown in Fig. 22, it is seen that the scale is more crowded at the left end than throughout the middle or right end. When using this type of meter, one should always use such a range that the deflection will be at least half scale since the



Courtesy "Weston Instruments"

Fig.23 Illustrating the various parts of a movable-iron meter.

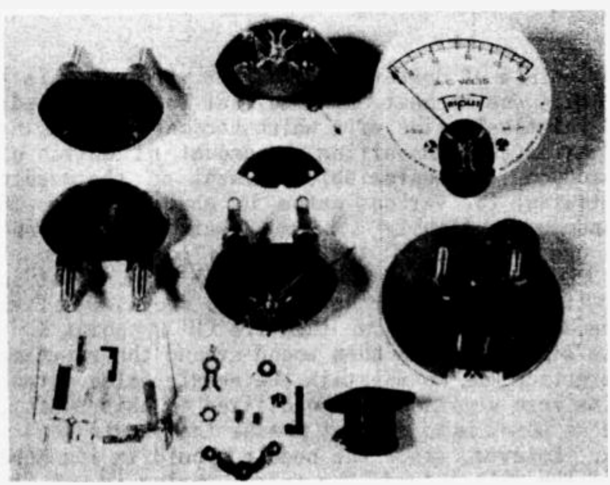
crowding at the lower left end makes it difficult to accurately read this part of the scale.

Movable iron meters, as well as all other AC meters, are calibrated to read effective or R.M.S. values, since it is this value rather than the average or peak which is of most interest.

Damping in this type of instrument is accomplished by mechanical, rather than electrical, means. The principal parts of the damper are a damper box and a vane. The damper box is a one-piece casting with a recessed chamber in which the vane moves. A cover plate encloses the damper box except for a small opening on the inner edge of the vane, which permits the fastening of the vane to the moving shaft. The exploded views shown in Figs. 23 & 24 clearly illustrates these parts. The damper box is labeled 5; the cover, 6; and the shaft and vane, 8, in Fig. 23.

The vane is a thin piece of lightweight alloy stiffened by ribs stamped into it. When a current is sent through the meter, the pointer moves over the scale and the vane is rotated within the damper box. Since the vane fits closely, it compresses the air ahead of it as it rotates and, in a like manner, it decompresses the air behind it. The compressed air leaks from one side of the vane to the other, through the small space provided by the attachment of the vane to the moving shaft. The amount of damping secured depends upon the degree of this air leakage. The design of the damper box in these instruments has been so perfected that practically ideal damping is obtained with only a few overswings of the pointer.

The moving shaft rotates in jeweled bearings as does the DC meter. This type of instrument will operate on either direct or alternating current, but is more accurate on alternating current. On ordinary power frequencies, these meters have an accuracy of



Courtesy Triplett Elec. Inst. Co.

Fig.24 An exploded view of a Triplett iron-vane meter.

5%. They cannot, however, be used on audio or radio frequencies since reactance effects at these frequencies make the readings of the meter inaccurate.

Movable-iron meters, like DC meters, may have their ranges extended by the use of shunts or series resistors, depending upon whether they are ammeters or voltmeters. Iron-vane meters are not as sensitive as those of the moving-coil type. It generally takes at least 15 ma. to produce full-scale deflection on an iron-vane meter. Thus a voltmeter of this type would have a sensitivity of 67 ohms per volt.

8. **HOT WIRE METERS.** Meters which operate upon the magnetic principle cannot be used to measure frequencies above several hundred cycles per second. The inductive reactance of the coil used in the magnetic type of meters varies as the frequency is changed and, thereby, introduces errors. Even if the iron vane meter were able to accurately indicate the value of a high-frequency current, its connection in a circuit would upset the circuit's balance and change the voltage and current relations. The only practical method of measuring high-frequency currents is by the amount of their heating effect. Two different types of meters have been designed which will accomplish this purpose. They are the hot wire meter and the thermocouple meter.

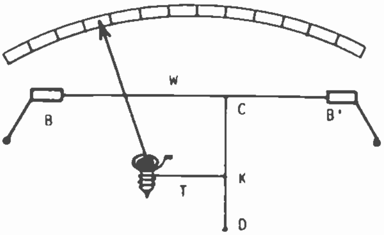


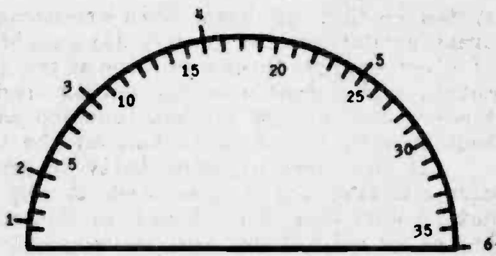
Fig.25 The principle of operation of a hot wire meter.

The principle of operation of a hot wire meter is the expansion of a wire due to heat. The current to be measured is passed through a relatively fine wire which becomes hot and expands. A mechanical arrangement magnifies the amount of motion of the wire and thus produces an appreciable movement of the needle. A diagram illustrating the various parts is shown in Fig. 25. W is a fine platinum wire tightly stretched between two copper blocks, B and B'. One terminal of the meter is connected to block B and the other to B'. Attached to the wire W at a point somewhat to the right of its center is another wire CD. Point D is firmly fixed. A silk thread T is joined to the wire CD at point K. The other end of this silk thread is then wound around the rotating shaft in such a direction as to maintain the needle, also attached to the shaft, at its zero position. Also affixed to this shaft is a spiral hairspring so wound as to attempt to make the needle read full-scale deflection. However, since the needle is held in its zero position by means of the silk thread, the spiral spring is not free to act. When a current passes through the wire W, its temperature increases, the wire expands and sags slightly. As the wire sags, the tension on silk thread T is slackened. When this occurs, spiral spring S moves the pointer over the scale and, in so doing, winds more of the silk thread on the shaft. When the needle has moved far enough to make the silk thread again taut, it can move no farther, since the thread now opposes the motion given to the needle by the spiral spring. The greater the amount of current flowing through the hot platinum wire, the more it will sag and the greater will be the slackening of the silk thread T and the farther the needle can move. A zero-adjusting screw not shown in the diagram must be provided to set the needle to its zero position before a measurement is made. Since a meter of this type is affected somewhat by room temperatures, this zero adjusting should be done before each reading is taken.

This meter depends only upon the heating effect of the electric current and, therefore, may be used with current of any frequency or with direct current without appreciable error. The meter is quite delicate and must be handled very carefully. It is not a fast meter and several seconds must elapse before the final reading is obtained. This is due to the fact that it requires a definite time for the platinum wire to expand. Compared to DC meters, its accuracy is quite low and it cannot be successfully used to measure voltages.

When a hot-wire meter is used to measure large values of radio frequency current, shunts are not employed; instead, several wires are connected between the two copper blocks B and B' and they thus divide the total current flowing. With this construction, the wire CD is firmly attached to all of the platinum wires so connected.

Fig.26 Illustrating the construction of a scale to be used with a hot wire or thermocouple meter.



The deflection is proportional to the expansion of the platinum wire. In turn, the expansion is proportional to the heat produced and the heat is proportional to the square of the current. Therefore, the deflection is directly proportional to the square of the current; that is, a current of 2 amperes will produce four times as much deflection as will a current of 1 ampere. For this reason, the scale is not uniform, but is very crowded at its lower end. Fig. 26 shows how a scale of this type is constructed. If the maximum range of the meter is to be 6 amperes R.M.S., the scale is marked off in 6^2 or 36 equal units. Since these 36 units correspond to the current squared, the actual value of current will be the square root of each of these values as shown in the upper scale. Thus, while full scale is 6 amperes, half scale is somewhat more than 4 amperes. In taking a measurement, one should always use a range which will give a deflection of at least half scale, since readings taken on the lower end of the scale are inaccurate, due to this crowding effect.

The hot-wire meter has been largely superceded by the more accurate thermocouple meter, except in those instances where economic consideration makes the more inexpensive hot-wire type the more desirable.

9. **THERMOCOUPLE METERS.** The principal element of the thermocouple ammeter is the thermocouple itself. The meter used with the thermocouple is an ordinary sensitive DC Weston movement. For this reason, the explanation of this type of meter will be confined to the operation of the thermocouple.

If two dissimilar metals such as iron and copper are joined together and their opposite ends connected by a wire to a sensitive DC galvanometer, the application of heat to the junction of the two metals will produce an electromotive force which will be indicated by a current flow through the galvanometer. This phenomenon is illustrated in Fig. 27. Since the only energy added to the

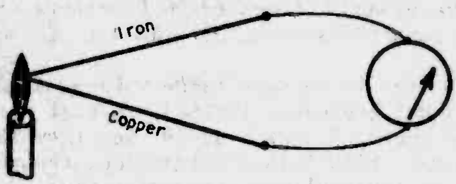


Fig.27 Conversion of heat energy directly into electrical energy.

system is that of heat, this arrangement constitutes a method of transferring heat energy directly into electrical energy. The amount of electromotive force generated at the junction of the two dissimilar metals will depend upon the metals used and upon the difference in temperature between the hot junction and the points where the connecting wire is joined to each of the two metals.

It has been experimentally determined that there will be an electromotive force generated at the junction of two dissimilar metals when they are placed in contact, whether this junction is heated or not. Thus, when a copper bar is placed in contact with a zinc bar as shown in Fig. 28, a contact potential of .41 milli-

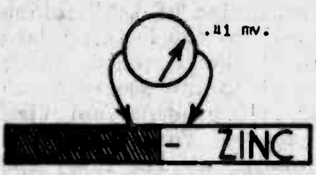


Fig.28 Production of a contact voltage between copper and zinc.

volt will be generated at the junction of the two metals and the copper will be positive with respect to the zinc. Fig. 29 shows a circuit in which a copper bar is in contact with a zinc bar and the opposite ends of the two bars are connected together by means of an iron wire. As just explained, there will be an electromotive force of .41 millivolt generated at the junction of the zinc and copper which is in such a direction as to force a current in a clockwise direction around this circuit. Also, at the junction of the zinc and iron wire, there is developed an electromotive force of 2.52 millivolts. This potential also attempts to force a current in a clockwise direction around the circuit. At the junction of the iron wire and the copper, a contact potential of 2.93 millivolts is generated. This potential, however, is in such a direction as to force a current counter-clockwise around the circuit. It may be seen that the total potential attempting to force a current clockwise is equal to the potential attempting to force a current counter-clockwise. The two voltages balance and no current flows in the circuit. This is always true of any arrangement of dissimilar metals when all the junctions are at the same temperature.

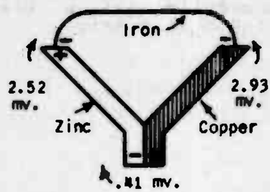


Fig.29 Voltages at junctions of dissimilar metals when all junctions are at the same temperature.

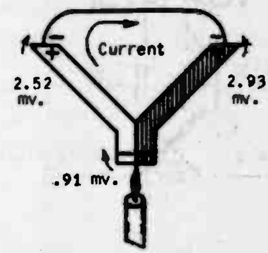


Fig.30 Voltages at junctions of dissimilar metals when the temperature of one junction is increased.

When heat is applied to the copper-zinc junction, this delicate balance is upset and the potential generated at this junction increases to .91 millivolt. (See Fig. 30.) Thus, the voltage attempting to force a current clockwise is now greater than that attempting to force a current counter-clockwise and this net voltage of .5 millivolt sends a very small current around the circuit in a clockwise direction. This current will be maintained as long as the copper-zinc junction is kept at a higher temperature than the other two junctions. The amount of current which flows in this circuit depends upon the difference in temperature between the copper-zinc junction and the other junctions of the circuit. Such currents are known as "thermo-electric currents" and the combination of the dissimilar metals is known as a "thermocouple". Since the voltages developed and the currents which flow are very small, this method of generating an electromotive force has few commercial applications other than its use with DC meters to measure radio-frequency currents and in the construction of certain types of thermometers.

The metals usually used for thermocouples are constantin and copper, or advance and manganin. These combinations will give a somewhat greater thermo-voltage than will a copper and zinc thermocouple. When a thermocouple is to be used with a direct current meter for the measurement of high-frequency current, it may be arranged as shown in Fig. 31. Two dissimilar metals are electrically welded together at the center. The high-frequency current to be measured passes from one terminal to the junction of the dissimilar metals and then to the other terminal of the meter. In flowing

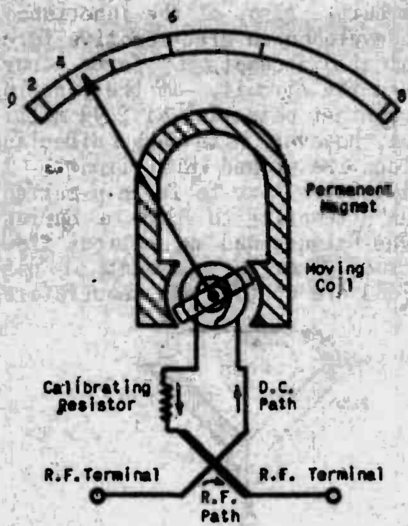


Fig.31 Illustrating the connection of a thermo-couple to a meter.

through this junction, it generates heat, which raises the temperature at this point. The thermo-voltage generated by the heating of this junction causes a direct current to flow through the meter and the calibrating resistor. The deflection of the DC meter is proportional to the amount of heat produced at the junction, which in turn is proportional to the square of the high-frequency current.

Fig.32 Photograph of a thermocouple

Courtesy Triplett Elec. Inst. Co.

For this reason, the scale of the meter will not be uniform, but will be crowded at its lower end as in the case of the hot-wire meter. To produce full-scale deflection of the meter usually requires a generated voltage of from 15 to 25 millivolts. A photograph of a thermocouple is shown in Fig. 32 and the symbol often used for a thermocouple instrument is shown in Fig. 33.

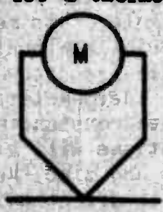
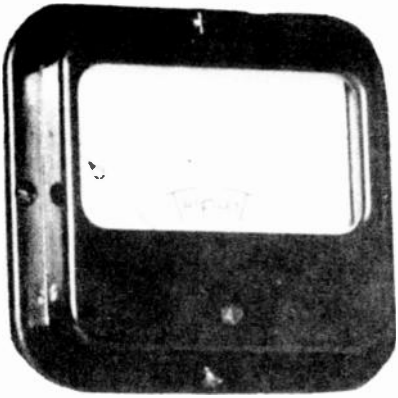


Fig.33 Symbol of a thermocouple meter.

Thermocouples are usually operated at very near the burn-out point and even the slightest overload is liable to ruin them, although the meter movement is not ordinarily damaged. Thermocouples

Fig.34 A thermocouple ammeter used for the measurement of high-frequency currents.

Courtesy Triplett Elec. Inst. Co.

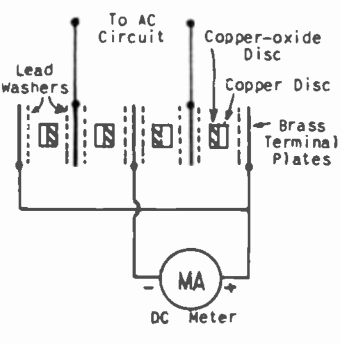


may be bought separately and when one burns out, the entire meter does not need to be replaced. Since the average thermocouple, irrespective of the meter, costs from $5.00 to $10.00, it is worthwhile to take especial care in using these meters. When the thermocouple is replaced, it will be necessary to recalibrate the meter by means of the calibrating resistor, as the characteristics of the new thermocouple are probably different from the old one. Since the reading of the meter is not affected by frequency, calibration can be made at 60 cycles.

The range of a thermocouple ammeter may be extended by soldering a short copper wire between the thermocouple lugs. All shunts on high-frequency meters of this kind should be as short as possible and should be placed parallel and close to the thermocouple. If they are placed outside of the case of the instrument, the readings on high frequency will not be the same as on low frequency.

Thermocouple meters are manufactured in ranges from 100 ma. to 1,000 amperes. They are considerably faster in action than hot-wire meters and, although more expensive, are far more accurate. An illustration of a modern thermocouple ammeter appears in Fig.34 Notice the crowding at the lower end of the scale, due to the fact that the deflection is proportional to the square of the current.

Fig.35 Illustrating the connection of a copper-oxide rectifier to a meter.



10. RECTIFIER TYPE METERS. The types of AC meters previously studied are not suitable for the measurement of very low alternating currents or voltages. For this purpose, the rectifier type meter has been designed. It consists of a DC Weston movement meter used in conjunction with a copper-oxide rectifier. The copper-oxide rectifier is composed of four rectifying elements arranged in a bridge circuit. It is provided with four terminals, two of which connect to the AC circuit and the others to the DC milliammeter. Such a combination is shown in Fig. 35. The copper-oxide rectifier converts the alternating current into a pulsating direct current. The pulsating direct current, which flows through the meter, varies so rapidly that the meter needle is unable to follow its variations, but, instead, deflects an amount which is proportional to the average value of this pulsating direct current. Although the deflection of the meter is proportional to the average value of the alternating current, the meter is calibrated to read R.M.S. values, as are all other AC meters. A rectifier is shown in Fig. 36.

Fig.36 Photograph of a rectifier.

Courtesy Triplett Elec. Inst. Co.

When a rectifier meter is to be used as a milliammeter or ammeter, it is connected in series with the circuit as are DC ammeters. A rectifier type voltmeter must be used with a multiplier resistance. This resistance is placed on the AC side of the rectifier as shown in Fig. 37. The only difference between the voltmeter and the ammeter is the use of the series resistor and the difference in the calibration of the scale. The meter movements themselves are exactly alike as are direct current instruments.

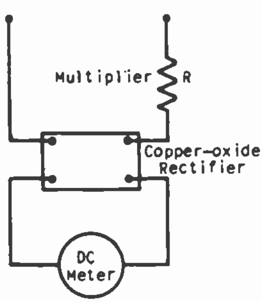


Fig.37 Showing how a multiplier resistor should be connected to a rectifier type voltmeter.

The resistance of the rectifier is not constant, but varies with temperature and with the amount of current flowing through it; hence, the scale of the meter is not uniform. It is somewhat crowded at its lower end, although not as much as the scales of thermocouple or iron-vane meters.

At ordinary power frequencies, the accuracy of a rectifier instrument is about 5%. As the frequency of the current is increased, the reading of the meter drops below the true value. The additional inaccuracy is about .5% for each 1,000 cycles up to 35,000 c.p.s. Thus, in measuring a 6,000-cycle current, the meter would read 6 × .5 or 3% below the value which an equivalent current of a power frequency would produce. Above 35,000 c.p.s., the capacitive effect between the rectifying elements becomes great enough to cause considerable inaccuracy, the amount of which cannot be easily expressed.

All alternating current instruments are calibrated with current which has a pure sine wave form, and if used to measure non-sinusoidal waveforms, they will develop inaccuracies, the amount of which will depend upon how great the waveform departs from a true sine wave.

Rectifier type meters are quite often employed in radio set analyzers to measure the output voltage of radio receivers. When so used, they are called "output meters", and may be employed to determine the amount of amplification secured by a vacuum tube, to find the power output of a radio receiver, or in the alignment of the tuned circuits, processes which will be fully described in later lessons. An output meter is shown in Fig. 38.

Fig. 38 A rectifier type AC voltmeter having three ranges. This meter may also be used as an output meter.

Courtesy Triplett Elec. Inst. Co.

11. **DYNAMOMETER TYPE METERS.** A current and voltage measuring instrument which may be used on either AC or DC is the dynamometer. Its principle of operation is very similar to that of the Weston DC movement. It consists of a moving coil through which current is passed and which rotates in the magnetic field produced not by a permanent magnet, but by an electromagnet. As mentioned before, the Weston DC movement cannot be used with AC since one alternation of the AC tends to rotate the moving coil in one direction and the next in the opposite direction. If the field of the permanent magnet could be reversed at the same time that the current through the moving coil changes direction, the rotating force would still tend to rotate the coil in the proper manner. This may be accomplished by replacing the permanent magnet by an electromagnet which is energized by allowing the current to be measured to flow through it.

During one alternation, a repulsion will exist between the moving coil and the electromagnet and the coil will rotate. Then, during the succeeding alternation, when the current through both reverses, the magnetic fields of both will change polarity and the same repulsion will exist as on the preceding alternation. Doubling the amount of current to be measured doubles the strength of the field about both the electro-magnet and the moving coil; hence, the amount of deflection is quadrupled. Thus, this instrument has a non-linear scale, crowded at the lower end, since the deflection is proportional to the square of the current.

The electromagnet consists of two fixed coils mounted on either side of the moving coil as shown in Fig. 39. The moving coil and the air gap in which it rotates is much larger than in the Weston DC movement; therefore, this instrument is not as sensitive as a DC meter.

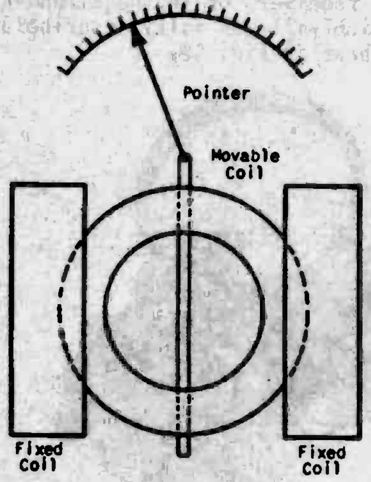


Fig.39 Schematic diagram of a dynamometer.

Dynamometer voltmeters can be constructed with an accuracy of 1% when used with low-frequency currents. They give the same reading on DC as on AC; hence, a direct current may be used to calibrate them. They are more accurate than iron-vane meters, but are somewhat more expensive.

Ranges as low as 15 ma. are available in the dynamometer milliammeter instruments. For measuring low currents, the fixed and movable coils are connected in series.

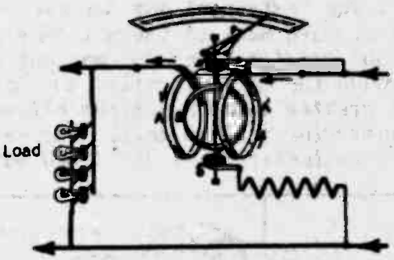
The principal use of the dynamometer type meter, however, is for the measurement of power. Such an instrument is called a wattmeter, and is sufficiently important to be given special consideration.

12. WATTMETERS. The measurement of power in a direct current circuit may be accomplished by use of a voltmeter and an ammeter. The ammeter, or milliammeter, is placed in series with the load which is dissipating the power and the voltmeter is connected across the load. If the voltage (in volts) is multiplied by the current (in amperes), the product is the power (in watts) dissipated by the load, ($W = E \times I$). In an alternating current circuit, an AC voltmeter and an AC ammeter may be used to determine the power if the load is a pure resistance. When the load is a pure resistance, the current flowing through the circuit is in phase with the applied voltage and the power factor is 1. In this case, the true power is equal to the apparent power.

If there is any net reactance in the circuit, either inductive or capacitive, the current will not be in phase with the applied voltage, the power factor will be some value less than 1, and the true power will be less than the apparent power. When this is the case, the product of the current and the voltage does not give the power dissipated by the load.

An instrument known as a wattmeter may be used to measure the power in either a direct or an alternating current circuit. The wattmeter is a device which automatically multiplies the current by the voltage and always indicates the true power in the circuit whether the current is in phase with the voltage or not. Thus, when using this meter, you do not have to calculate the power factor of the circuit.

Fig.40 A schematic diagram of the construction of a wattmeter.



The construction of a wattmeter is shown in Fig. 40. It consists of two coils: One, the current coil and the other, the voltage coil. The current coil, marked A in the Figure, is divided into two parts. It is fixed in position and is wound with heavy wire. The two terminals of the current coil are connected in series with the load just as an ammeter would be connected. The voltage coil (marked B) is fastened to a shaft which rotates within the current coil. At the top of the shaft there is affixed a needle and a spiral hairspring which holds the needle in the zero position. In series with the voltage coil is a multiplier resistance. The two terminals of the voltage coil are connected across the load as a voltmeter would be connected.

Since the total current flowing through the load also flows through the current coil, the magnetic field produced around the current coil is proportional to the current flowing through the load. The current which flows through the moving coil or voltage coil is proportional to the voltage across the load and, therefore, its magnetic field is proportional to this voltage. The magnetic force which rotates the needle is proportional to both of these magnetic fields; hence, it is proportional to the product of the voltage and the current.

The rotating force at any instant is equal to the product of the voltage across the load and the current through the load at that instant. Since the meter needle is unable to follow the rapid fluctuations of the current, it assumes a position which is equal to the average rotating force supplied by the interaction of the two magnetic fields; or the voltage coil rotates until the restoring force of the spiral spring is equal to that of the magnetic force producing the rotation. The average rotating force is equal to the average of all of the instantaneous values and, if at some part of the cycle, the voltage is positive and the current negative, or vice versa, as will be the case when the voltage and current are not in phase, this negative power produces a rotating force opposite to that produced when both voltage and current have like signs. Thus the average rotating force is the average of all these instantaneous values, some positive and some negative, and the fact that during part of the cycle, the load may be returning power to the generator is automatically taken into account. Therefore, the wattmeter indicates the true power consumed by the load no matter what the phase angle or power factor of the circuit may be.

The instrument may be used on either DC or AC. In using the meter, care must be taken to see that the current through the load is not greater than the maximum allowable current which may flow through the current coils, or that the voltage across the load is not greater than the maximum allowable voltage which may be applied across the voltage coil. For example: The maximum scale reading of a wattmeter might be 1,000 watts; the maximum permissible cur-

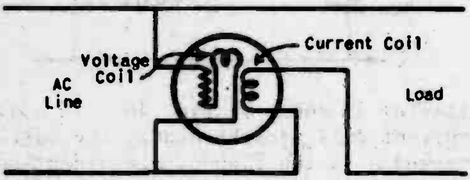
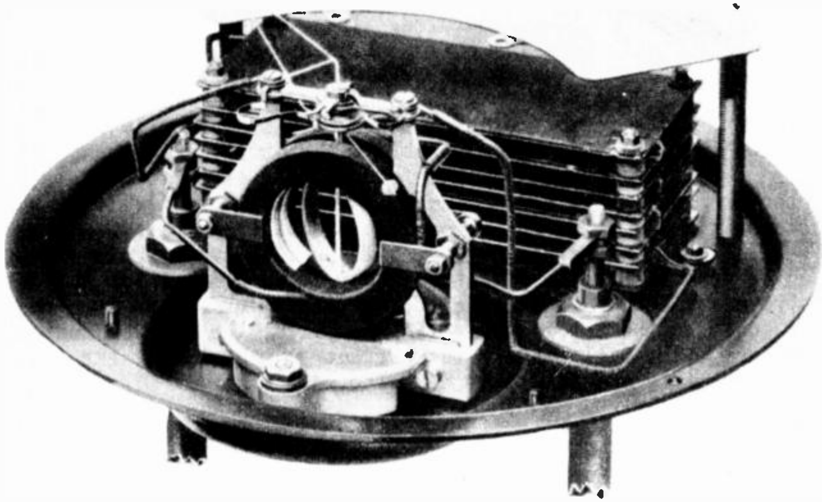


Fig. 41 Illustrating how a wattmeter should be connected.

rent through the current coil, 10 amperes; and the maximum voltage across the voltage coil, 100 volts. If this wattmeter were connected to a load through which 5 amperes of current flowed and across which there existed a voltage of 150 volts, the meter would indicate a power of 5 × 150 or 750 watts (assuming unity power factor). This instrument, however, would be overloaded since a voltage greater than 100 volts is being applied to the voltage coil. The voltage coil would, very likely, overheat and might possibly burn out.

The voltage coil should be so connected that the current which it draws does not have to pass through the current coil. The proper connection is shown in Fig. 41. A photograph of a wattmeter with a maximum range of 150,000 watts appears in Fig. 42. In the photograph, the two current coils, placed parallel to each other and connected in series, may be easily distinguished. Between them, with a shaft through its center, is the voltage coil. The several large, flat, parallel plates which are stacked in the background constitute the series multiplying resistor used with the voltage coil.



Courtesy Weston Instrument Co.

Fig. 12 A wattmeter capable of measuring 150 kilowatts.

13. USE AND CARE OF METERS. Modern meters are quite rugged and, with careful handling, will maintain their calibration over a period of many years. The Weston type DC movement meter which employs a permanent magnet is accurate to within 1%. Care must be taken that a meter of this type is never severely jarred, as this action is liable to weaken the field of the permanent magnet, thereby changing the calibration. In addition, jars are apt to bend the light shaft on which the moving coil is mounted or may crack the jewel bearings.

When using an ammeter, make sure that the current to be measured is less than the maximum range of the meter you intend to use. If you do not know the value of the current flowing, use the largest range of ammeter or milliammeter available. If an accurate reading cannot then be obtained, a smaller range may be used to secure the correct reading.

Always remember, of course, that an ammeter or a milliammeter must be connected in series, while a voltmeter must be connected in parallel with the circuit. If the polarity of the line is not known, extreme caution should be observed in allowing current to flow through the meter. If the meter should happen to be connected with the wrong polarity, the needle might be damaged by the backward thrust of the moving coil.

Before using any meter, make certain that the needle is at its true zero position. If it is not, use the zero adjusting screw to bring it exactly over the zero mark. Finally, always make sure that your eye is directly over the needle when taking a reading.

For measuring direct current, a meter using a Weston DC movement is practically always employed. Iron vane meters and dynamometers are commonly used for the measurement of low-frequency currents not exceeding a few hundred cycles. Frequencies higher than this, up to 20,000 c.p.s., may be measured with a rectifier type instrument, while radio frequencies as high as ordinarily used for communication purposes are measurable with hot wire or thermocouple meters. Thus, it may be seen that for any type of current, there is a meter most suitable for its measurement. It is true that the frequency range of the meters overlap and, in some cases, any one of several of the various types could be employed. However, it would be unprofitable to purchase a thermocouple meter for the exclusive measurement of 60-cycle AC, as a less expensive iron vane meter could do the job just as well. Likewise, the most economical instrument which will measure the current of any particular frequency accurately should always be selected.

APPROXIMATE RESISTANCES OF STANDARD MILLIAMMETERS AND SENSITIVITIES OF AC VOLTMETERS

TRIPLETT.

D. C. Milliammeters

Models 221, 223, 321, 324, 325, 326, 421, 521, 524, and 525.

Range	Approx. resistance	Range	Approx. resistance
0-1	33.0 ohms	0-300	.10 ohms
0-1.5	22.0	0-400	.08
0-3	11.0	0-500	.06
0-5	8.5	0-750	.04
0-10	3.1	0-1,000	.03
0-15	2.0	.5-0-.5	33.00
0-25	1.2	100-0-100	.15
0-50	.6	150-0-150	.10
0-75	.4	0-1-10	33-3.00
0-100	.3	0-1-25	33-1.20
0-150	.23	0-15-150	2-0.23
0-200	.15	0-25-250	1.2-.12
0-250	.12		

D. C. Microammeters

Models 221, 223, 321, 324, 325, 421, 521, 524, and 525.

Range	Approx. resistance	Range	Approx. resistance
0-200	360.00 ohms	0-500	156.00 ohms

A. C. Milliammeters

Models 231, 233, 331, 334, 335, 336, 431, 531, 534, and 535.

Range	Approx. resistance	Range	Approx. resistance
0-10	1950.00 ohms	0-100	23.00 ohms
0-15	1125.00	0-200	5.00
0-25	325.00	0-250	4.00
0-50	85.00	0-500	.80

WESTON.

D. C. Milliammeters

Model 301

Range	Approx. resistance	Range	Approx. resistance
0-1	105.00 ohms	0-15	2.00 ohms
0-1.5	27.00	0-20	2.00
0-2	27.00	0-25	1.20
0-3	18.00	0-30	1.20
0-5	12.00	0-50	2.00
0-10	9.30	0-100	1.00

D. C. Microammeters

Models 600, and 301*

Range	Approx. resistance	Range	Approx. resistance
0-30	2,000.00 ohms	0-100	1,300.00 ohms
0-50	2,000,00		
0-75	1,800.00	*0-200	660.00

A. C. Milliammeters

Model 476

Range	Approx. resistance	Range	Approx. resistance
0-15	2,000.00 ohms	0-50	175.00 ohms
0-25	690.00		

A. C. Microammeters

Models 600, and 301*

Range	Approx. resistance	Range	Approx. resistance
0-100	4,000.00 ohms	*0-200	2,200.00 ohms
0-200	1,565.00	*0-500	1,030.00

TRIPLETT
A. C. Voltmeters
Models 231, 233, 331, 334, 335, 336, 431, 531, 532, and 535

Range	Approx. sensitivity in ohms per volt.	Range	Approx. sensitivity in ohms per volt.
0-1.5	4.00	0-300	166.00
0-3	8.00	0-500	166.00
0-5	10.70	0-750	166.00
0-6	10.70	0-1000	166.00
0-10	16.00	0-15-150	33.00
0-15	16.00	0-150-300	110.00
0-25	33.00	0-150-750	110.00
0-50	60.00	0-7.5-15-150	33.00
0-100	110.00	0-7.5-150-750	33.00
0-150	110.00	0-7.5-15-150-750	33.00
0-250	166.00	0-250-750	110.00

WESTON
A. C. Voltmeters
Model 476

Range	Approx. sensitivity in ohms per volt.	Range	Approx. sensitivity in ohms per volt.
0-1.5	3.00	0-100	105.00
0-2	4.00	0-130	105.00
0-3	6.00	0-150	105.00
0-5	10.00	0-250	167.00
0-8	10.50	0-300	167.00
0-10	14.00	0-400	167.00
0-15	14.00	0-500	167.00
0-20	26.00	0-600	167.00
0-25	26.00	0-750	167.00
0-30	26.00	0-1000	167.00
0-50	52.00		

Notes

(These extra pages are provided for your use in taking special notes)

The text of this lesson was compiled and edited by the following members of the staff:

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MIDLAND RADIO
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INC.

POWER & LIGHT BUILDING, KANSAS CITY, MISSOURI

UNIT NO. 1

VACUUM TUBE DETECTORS

LESSON NO. 18

GEORGE STEPHENSON

"........AND WEALTH POURED IN ON HIM."

Discouraged at the very outset by a schoolmaster from whom he sought to learn how to read and write, George Stephenson, like many other famous men, virtually lifted himself by his bootstraps to fame, fortune and success.

Starting life in a home that was a hovel, with a clay floor, mud walls and bare rafters, young Stephenson had nothing but his own determination to encourage him. At the age of five, he was herding cows, later working in a mine picking stones from coal, and finally graduating to the job of driving the horse that drew coal from the mine. At eighteen, he had followed in his father's footsteps and was a fireman. He could take his engine apart and make repairs, and in this way he secured the initial knowledge that started him on the road to fame. Eagerly seeking an education, he devoted his spare moments to writing with a piece of chalk and in a short time could read, write and do simple mathematical problems.

Realizing that the engine with which he worked was far from perfect, he began to figure out how to improve it and made models of engines in clay. Then, in 1815, he actually planned and built his first locomotive..... a very real triumph for a lad of only twenty years. But Stephenson was not satisfied. He wanted to build a better engine.....one that would go much faster. He planned, studied and built models and finally constructed another engine which was used by the company for which he worked.

In 1821, he was appointed Chief Engineer for the Stockton and Darlington Railroad. Here he had greater opportunity to carry on the work to which he had dedicated his life. Locomotive followed locomotive, each being an improvement on the other. Greater speeds were attained and fuel consumption reduced. Then Stephenson decided to try for the tremendous speed of 12 miles an hour. One of his friends upon learning this asked, "Suppose while it is running, a cow should stray upon the track. Would it not be a very awkward circumstance?" Stephenson replied, "I should think it might.....for the cow."

As time passed, George Stephenson's triumphs continued to skyrocket. He became chief or consulting engineer of practically every railway project. Wealth in abundance flowed upon him. Wise men sought his friendship. Medals were heaped upon him. His King offered him a knighthood, but he preferred to remain just plain George Stephenson.....the father of modern railway transportation.

While we all cannot be famous or fabulously rich, we can be successful enough to enjoy life completely. And the surest way to such an accomplishment is thorough, modern training that prepares for profitable employment in an industry that always needs trained men. You have made your decision to be a success. SEE THAT YOU STICK TO IT!

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Lesson Eighteen

VACUUM TUBE DETECTORS

"Before the discovery and perfection of the vacuum tube, crystals and a crude device known as the 'coherer' were used to detect radio signals. The lack of sensitivity of these devices prevented a rapid growth of the then struggling wireless industry.

"After the invention of the vacuum tube, the radio industry began to grow by leaps and bounds. The first use of the vacuum tube was as a detector. The detector circuit in a radio receiver can actually be considered to be the most important circuit in the entire set. Without this one circuit, the balance of the radio receiver would be useless. Since detection is so important, I suggest that you study the material contained in this lesson very thoroughly."

1. **AT THE STUDIO AND TRANSMITTER.** The process of transmitting intelligence by means of Radio depends upon the simultaneous operation of several circuits. All of the electrical circuits at the broadcasting station must be in working order and properly adjusted to radiate radio signals from the transmitting antenna. Then, too, the various circuits contained within the radio receiver must be functioning properly in order to amplify the radio signal received from a broadcasting station and reproduce the desired sound from the loud speaker.

As well as the necessity for proper adjustment and operation of all circuits, it is also essential to establish a "cooperation" between the receiver and transmitter. This cooperation is secured when the radio receiver is tuned. The process of tuning consists of adjusting the radio receiver so as to coincide or "cooperate" with the energy being radiated from the desired broadcasting station. Having established this condition, the receiving set is capable of reproducing the intelligence transmitted from that particular station. The ability of the radio receiver to convert the received radio energy into sound waves depends to a large extent upon the operation of the detector stage in the receiver. The detector is situated in the electrical center of the radio receiving circuit, having a radio-frequency amplifier preceding it and is followed by an audio-frequency amplifier.

To obtain a clear conception of the job demanded from the detector, it is necessary to briefly review the transmission of a radio signal.

In Fig. 1, the essential portions of a radio transmitting circuit are shown in block-diagram form. The equipment necessary for the transmission of radio signals consists mainly of two parts: the studio equipment and the transmitting equipment. The most elementary stage in a radio transmitter is the "oscillator", which serves to generate the high-frequency carrier wave necessary for

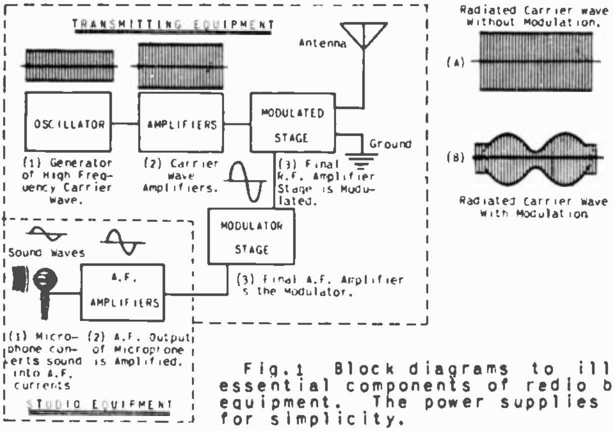

Fig.1 Block diagrams to illustrate the essential components of radio broadcasting equipment. The power supplies are omitted for simplicity.

transmission. Following the oscillator, several amplifier stages are employed for the purpose of increasing the radio-frequency power delivered to the input of the amplifier from the oscillator. These amplifiers do not change the frequency which was originally generated by the oscillator. Following the amplifiers, the amplified radio-frequency carrier wave is delivered into the final R.F. amplifier, often called the "modulated stage". The output of the modulated stage is then delivered into the antenna.

The second main portion of the broadcasting station consists of the studio equipment. The sound waves striking the diaphram of the microphone create audio-frequency currents in the microphone circuit. These currents are of very low amplitude; hence, they must be amplified before being delivered into the transmitter proper. The audio-frequency amplifiers shown following the microphone in Fig. 1 serve to increase the amplitude of the audio frequency without changing its wave form in any way. The amplified audio frequency from the studio amplifiers is then fed to the input of the "modulator stage". This modulator stage is a high-powered audio-frequency amplifier and is sometimes called the "final A.F. stage" The output of the modulator is then delivered into the plate or grid circuit of the modulated stage. In the modulated stage, the audio-frequency current and the radio-frequency current are combined. The effect of this combination on the appearance of the carrier wave is shown at B in Fig. 1. When no audio-frequency current is fed into the modulated stage, the amplitude of the carrier wave remains constant (as at A), but when audio frequency is delivered, the amplitude of the carrier wave is caused to rise and fall in direct accordance with the audio-frequency current.

The process of varying the amplitude of the carrier wave in accordance with the sound wave originally actuating the diaphram of the microphone is known as modulation. Modulation refers to the combination of the audio frequency with the radio frequency, and the result is a variation in the amplitude of the radio-frequency carrier wave at the audio-frequency rate. It is necessary to employ a high-frequency carrier wave for transmitting or "carrying" the audio from the broadcasting antenna to the receiving antenna, because the audio-frequency current alone is not capable of producing a radiation of energy from the transmitting antenna.

Fig. 1 and the associated discussion serve to illustrate the important process of *modulation*. The reverse of this process, demodulation, is necessary at the receiver.

2. AT THE RECEIVER. When the modulated carrier wave radiated from a broadcasting station strikes the receiving antenna, a modulated R.F. voltage will be induced therein. This induced voltage will be extremely weak, having a maximum amplitude of only a few micro or millivolts. The R.F. amplifier portion of the receiver amplifies the weak voltage and also provides the necessary tuning circuits which make it possible to select the desired station. The output of the R.F. amplifier is exactly the same in wave form as the input, differing only in amplitude.

Following the R.F. amplifier, it is necessary to separate the audio-frequency wave from the modulated R.F. carrier wave. Since this is exactly the opposite function which occurred at the transmitter, it is often called "demodulation". The term "detection" is the most common expression for this demodulation process.

Detection consists of separating the audio frequency from the modulated R.F. carrier wave. The input to the detector stage is a modulated R.F. voltage, but the output contains only the audio-frequency voltage which was originally impressed on the carrier wave. The R.F. portion of the modulated carrier wave is not present in the output of the detector.

The audio-frequency voltage supplied by a detector is generally less than one volt. Audio frequency of this low amplitude is not capable of producing appreciable volume from a loud speaker; however, it can give satisfactory headphone operation. Since loud speakers are employed with most modern sets, the weak audio-frequency output of the detector must be passed through an audio-frequency amplifier to increase the audio power (A.F. voltage and A.F. current). The high audio-frequency power output is then delivered to the loud speaker, and the loud speaker reproduces the original sound wave which was set up in the studio before the microphone.

Fig. 2 illustrates the essential portions of a radio receiver with block diagrams.

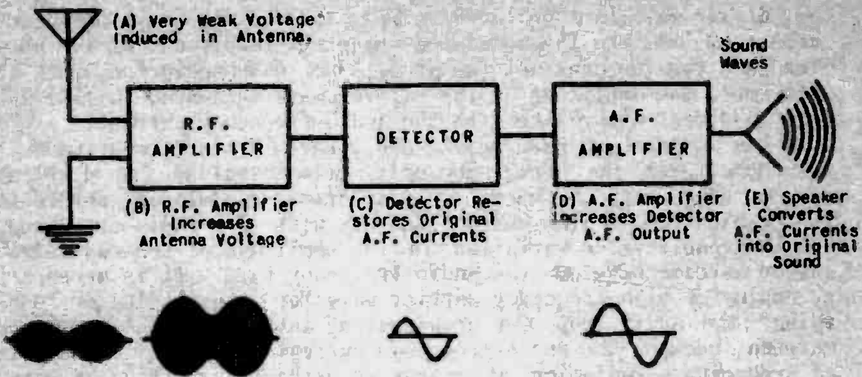

Fig.2 Block diagrams to illustrate the essential components of a radio receiver. The power supply is omitted.

3. **REQUIREMENTS OF A DETECTOR.** In the process of detection, it is necessary to subject the modulated R.F. carrier wave to a circuit which is capable of performing two operations. These are:

1. Rectifying the modulated R.F. wave.
2. Filtering the rectified wave.

To illustrate the changes the signal must undergo through the detector stage, let us refer to Fig. 3. At A in Fig. 3, the modulated R.F. carrier wave is shown. This is the appearance of the wave as fed into the detector and it is desired to extract the audio

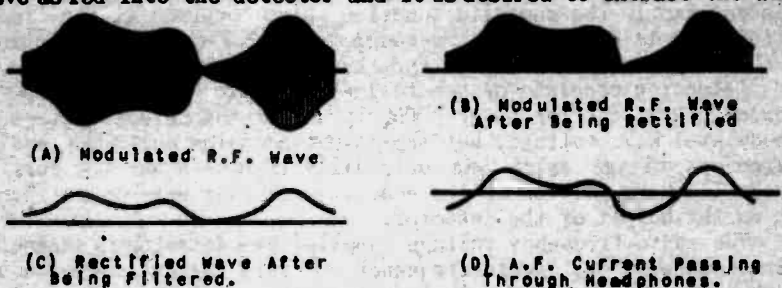

Fig.3 Diagrams to illustrate the process of demodulation.

frequency from it. The audio frequency is represented by the variation in amplitude of this wave. The drawing at B illustrates the appearance of the modulated R.F. carrier wave after it has been rectified. Notice that the only difference between the rectified wave and the original wave is that the negative alternation has been eliminated on the rectified wave (the positive alternations are exactly as before). After rectification, it is necessary to filter the rectified wave, thereby securing its average value. The appearance of the rectified wave after it has been filtered is shown at C in Fig. 3. Notice that the filtering has eliminated all of the R.F. variations, and we have remaining only the average of the rectified wave. This average value varies in amplitude exactly the same as the original carrier wave; hence, it is the desired audio frequency. Upon passing the wave shown at C through a coupling circuit, such as a transformer, the A.F. wave as shown at D will be secured. This wave should be exact in every detail with the audio frequency originally created in the microphone circuit at the broadcasting station. It is, however, small in amplitude, so if loud speaker operation is desired, it must be built up through an audio-frequency amplifier.

In addition to rectifying and filtering the incoming signal, the detector must also fulfill other conditions if it is to be satisfactory. Distortion of the audio-frequency wave is exceedingly undesirable; therefore, the entire detector circuit must be designed so as to produce an output audio-frequency current which coincides with the amplitude change of the modulated R.F. carrier wave as closely as possible. All types of detectors are apt to produce a slight amount of *wave form distortion*, but with extreme care in circuit design, the distortion can be minimized.

As well as wave form distortion, it is also possible that some of the audio frequencies originally impressed on the carrier wave will not be produced in the output of the detector. This is called *frequency distortion*. Discrimination against the high and low audio frequencies is a defect common to all types of detectors. The method of detection used and the values of the various parts contained in the circuit affect the frequency distortion to a large extent.

Another requirement of the detector which demands recognition is the *detector's sensitivity*. The sensitivity refers to the ratio of the audio-frequency output to the radio-frequency input. With a given R.F. voltage input applied to the grid circuit of the detector, the higher the audio-frequency power output secured in the plate circuit, the greater will be the detector's sensitivity.

4. **THE CRYSTAL DETECTOR.** A study of the various types of detector circuits should begin with the one that is simplest in operation. This is the crystal detector circuit, and, as you know, it was employed long before vacuum tubes were available for radio communication purposes. A diagram showing the essential components for a crystal detector circuit is shown in Fig. 4. The radio-frequency amplifier has been excluded from this circuit and the signal from the antenna is fed directly into the crystal detector circuit. By using headphones, it is possible to eliminate the audio-frequency amplifier.

As the radiated energy from the broadcasting station is intercepted by the antenna wire, there will be a weak, modulated, radio-frequency voltage induced in the antenna. The antenna circuit is completed to ground through the primary of the R.F. transformer L_1;

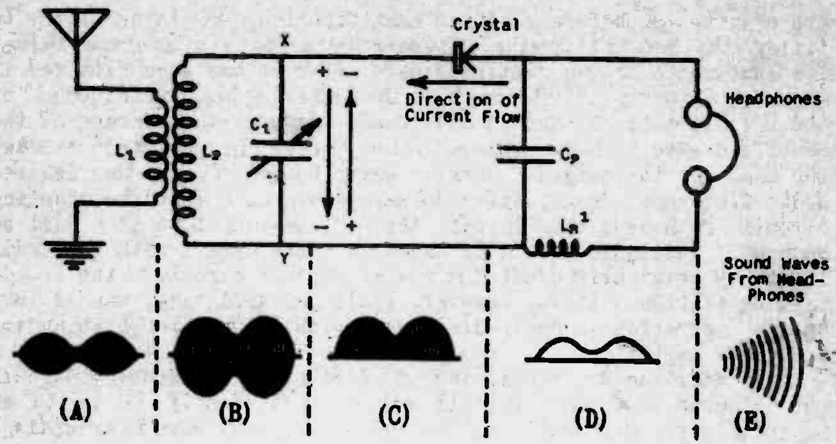

Fig.4 Circuit diagram of a crystal detector.[1]

hence, a modulated radio-frequency current will flow through L_1. As this current passes through L_1, it causes a corresponding magnetic field to be set up around it. The secondary of the R.F. transformer, L_2, is located within the varying magnetic field around the primary; thus, there will be a modulated radio-frequency voltage induced in the secondary winding. The secondary L_2 has a variable condenser, C_1, connected across it. The condenser C_1, in conjunction with the inductance L_2 forms a resonant circuit. When the capacity of C_1 is adjusted until its reactance is equal to the coil's reactance at the frequency desired to receive, the current flow through the series resonant circuit (L_2C_1) will be opposed only by the resistance of the circuit. This results in a large amount of radio-frequency current flowing in this series resonant circuit and correspondingly large voltage drops will be developed across it.

A complete description of a series resonant circuit was covered in Lesson 14. Therein it was found that the voltages produced across a series resonant circuit were greater than the initial voltage applied. For this reason, the modulated radio-frequency voltage produced across L_2C_1 will be higher in amplitude than the radio-frequency voltage originally induced in L_2 from the primary. The wave form, however, has not been changed; so the original modulation is still present on the higher-amplitude R.F. voltage. This phenomenon is often referred to as "gain in a resonant circuit"; it should be remembered as one source of voltage amplification in any radio-frequency circuit.

The modulated R.F. voltages across the resonant circuit are now applied to the remainder of the circuit, consisting of the crystal, the headphones, and the filter L_3C_2. The electrical properties of the crystal are of considerable importance. It has been found that certain natural-occurring minerals such as galena (lead

[1] In some diagrams of crystal detector circuits, the R.F. choke, L_3, is shown in series between the crystal and the phones; either position gives equivalent results.

sulphide), iron pyrites (iron sulphide), carborundum, molybdenite, etc., possess the property of allowing an electric current to pass through them easily in one direction, but of offering a high resistance to the passage of current in the opposite direction. These crystals, as they are called, compare in this respect to the copper-oxide contact rectifier which was studied in Lesson 16. It will be recalled that current flows easily from the copper to the oxide, but with great difficulty from the oxide to the copper. Similarly, current can easily flow from the crystal to the cat-whisker[1], but with great difficulty from the cat-whisker to the crystal. This property of the crystal provides the necessary rectification which was previously given as one of the essential operations for detection.

Referring again to Fig. 4, when the R.F. voltage across the resonant circuit is in such a direction as to make the bottom (Y) of the resonant circuit minus, and the top (X) plus, current will flow from the bottom of the resonant circuit through L_3, the headphones, through the crystal, and return back to the top of the resonant circuit. On the next alternation, the top of the resonant circuit (X) is minus and the bottom (Y) is plus. A voltage is now applied across the crystal in the direction opposite to that which it is capable of passing current. For this reason, no current will flow on these alternations of the modulated R.F. voltage across the resonant circuit. Rectification is thus accomplished by the selective action of the crystal. The rectified-modulated carrier waves are shown at C below the diagram in Fig. 4.

As the rectified-modulated R.F. current attempts to flow from Y to X, it encounters the filter circuit, consisting of the inductance, L_3, and the capacity C_2. These inductance and capacitance values are chosen so as to constitute a low-pass filter. Generally the inductance is from 5 to 50 millihenries, and the capacitance around .00025 microfarads. Calculation of the inductive and capacitive reactance of these two parts will show that the inductance offers a high opposition to the passage of a high-frequency current (in the neighborhood of 1,000 kilocycles), but a low opposition to the passage of an audio-frequency current (around 2,000 cycles). The capacitance, on the other hand, offers a relatively low impedance path for the radio frequency, but a high impedance path for audio frequency. Considering the opposite characteristics of these two parts, it is evident that the low-frequency component of the rectified waves will pass through the inductance L_3, through the headphones, and return to the top of the resonant circuit (X) through the crystal. The high-frequency component due to the low-capacitive reactance of the condenser C_2, and the high inductive reactance of the inductance L_3, will pass through the condenser C_2 and return through the crystal to the top of the resonant circuit.

Thus the inductance L_3 and the capacitance C_2 serve to filter the rectified waves produced in portion C of the detector circuit, and allow only the average value as shown at D to pass through the

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[1] The "cat whisker" is the fine wire used to make contact with the desired spot on a crystal.

headphones. It will be noticed that the wave form of the current which passes through the headphones varies in amplitude exactly as the modulated radio-frequency voltage that was induced in the antenna. This current, then, represents the audio frequency which we desire to reproduce. As the audio-frequency current passes through the windings of the headphones, it causes their diaphrams to be set into vibration and audible sound waves are produced.

Before leaving the crystal detector circuit, it is well to point out a few of its characteristics. Due to the extreme simplicity of the circuit, it is easy to construct. Consistent headphone reception operation may be secured if the set is located sufficiently close to a broadcast station. The only amplification obtained in the entire circuit is the gain in voltage across the resonant circuit; hence, the sensitivity is very low and all possible precautions must be taken to prevent the loss of radio-frequency energy. A long, high antenna must be erected to pick up as much signal voltage as possible and low-resistance coils and wiring must be used throughout. The headphones must be sensitive for satisfactory operation and the crystal should be a high-grade type.

It is possible to remove the inductance L_s and the capacity C_s from the crystal detector circuit and still obtain reception in the headphones. At first thought, this may seem rather absurd because it is essential to provide a filter circuit to separate the audio- and radio-frequency components. After the removal of the actual filter circuit, by necessity other inductance and capacity distributed throughout the detector circuit are required to perform this job. The coil windings in the headphones (see Fig. 5)

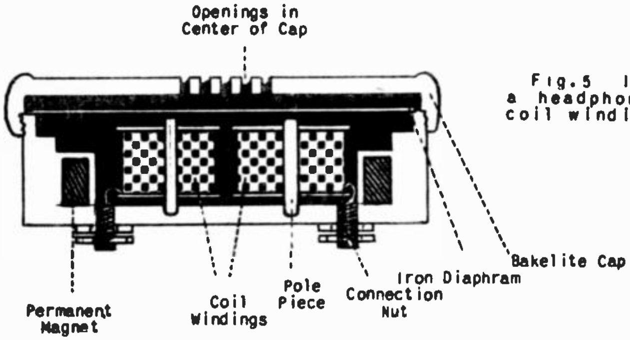


Fig.5 Internal view of a headphone to show the coil windings.

serve in place of the removed inductance, and the capacity distributed throughout the circuit wiring and in the headphones takes the place of C_s. The filtering is not as efficient as before and the tone quality suffers to a certain extent, but the audio-frequency sound waves will still be heard from the phones.

Ordinarily, well-constructed crystal detector receivers produce excellent tone quality; however, its disadvantages—lack of sensitivity and lack of selectivity—have been responsible for its obsolescence.

5. **DIODE DETECTOR CIRCUITS.** One of the first applications of the vacuum tube to radio was its use as a diode detector. The

"Fleming Valve" was used as a detector for many years before the three-element tube was perfected. The two-element tube (diode) was merely substituted in place of the formerly used crystal. The main advantage gained by substituting the diode for the crystal was that more complete rectification of the modulated R.F. signal voltage was secured. Crystal formations, like the copper copper-oxide rectifier, have a tendency to allow current to pass through them in the reverse direction to a certain extent. When this occurs in a detector circuit, the efficiency of the circuit is somewhat decreased, which results in a lower amplitude of audio-frequency output. The use of a two-element tube as the rectifier entirely eliminates the flow of current on the reverse alternation, thus the amplitude of the average value of the rectified wave is increased and a greater audio-frequency output is secured.

The diode detector is of great importance in our study of Radio and Television because, at the present time, this method of detection is more popular in modern radio receivers than any other. Prior to 1934, nearly all commercial receivers used either the grid-leak or grid-bias method of detection, so it is interesting to note the return of the formerly discarded diode detector. Several reasons are associated with its use in modern receivers and these will be pointed out in future lessons.

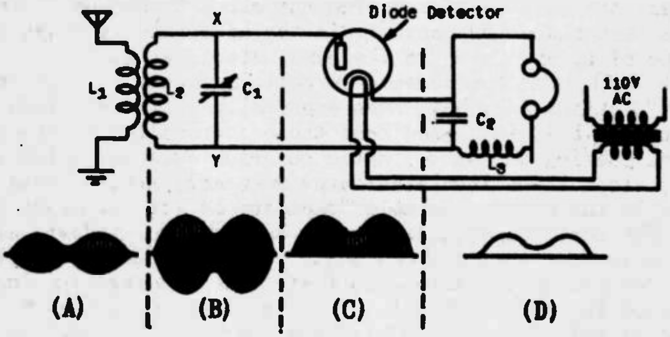


Fig.6 Circuit diagram of a diode detector.

A simple circuit illustrating the construction of a diode detector is shown in Fig. 6. A modulated R.F. signal voltage is delivered to the primary L_1 of the R.F. transformer. This modulated R.F. signal voltage may be secured directly from an antenna or possibly from the output of an R.F. amplifier. Regardless of its origination, the modulated R.F. current passing through L_1 will create magnetic field variations around the winding which cut through the turns of L_2 and induce a modulated R.F. voltage therein. L_2 is in parallel with the variable condenser C_1; hence, when these two reactances are made equal at the frequency desired to receive, the resonant circuit will offer only resistance as opposition to the flow of a modulated R.F. current between them. The flow of a radio-frequency current between the inductance L_2 and the capacitance C_1 results in modulated R.F. voltages appearing across the series resonant circuit. If the bottom (Y) of the series resonant circuit is negative and the top positive, current will flow through

L_2, the headphones, through the tube from the cathode to the plate, then return to the top of the series resonant circuit (X). On the negative alternation of the R.F. signal voltage, when the top of the resonant circuit is negative and the bottom positive, current cannot flow because it is impossible for current (electrons) to flow from the plate to the cathode through a vacuum tube. Rectification is thus secured through the action of the two-element tube.

As the rectified-modulated R.F. wave shown at C encounters the filter circuit consisting of L_2 and C_2, a separation of the low-frequency and high-frequency components of this wave occur. The higher-frequency component (R.F.) finds an easier path through the capacity C_2, and the lower frequency component (A.F.) encounters least opposition when passing through the inductance L_2. This division of the two components of the rectified wave results entirely from the relative reactances of the inductance and capacity.

Since the audio-frequency component (average) takes the path through L_2, the phones, and the tube, the diaphrams of the headphones are caused to vibrate in exact accordance, thus producing the desired sound waves.

As in the crystal detector circuit, it is possible to remove the inductance L_2 and the capacity C_2 from the circuit and still obtain reception. Extracting these constants does not necessarily remove all the filter effects from the circuit because there still persists inductance and capacity in the headphone windings to take the place of L_2 and to serve the same purpose as C_2.

All coil windings possess a certain amount of "distributed capacity", unless they have been especially designed. Each of the turns on a coil is insulated from those surrounding it by a varnish or enamel coating or by a fabric covering such as cotton, silk, cambric, etc. These insulated turns are nearly always close enough together to cause a measurable "capacity effect" to exist between them. The small capacities formed between the individual turns are additive, so the total capacity possessed by the entire coil winding becomes quite large when there are hundreds or thousands of turns on the coil. This total "distributed capacity" is really in parallel with the coil's windings and tends to counteract the effect of the coil toward retarding the passage of an AC current. A headphone winding consists of several hundred insulated turns of fine wire, and its distributed capacity is sufficiently high to by-pass the R.F. component of the rectified signal current in case the filter condenser C_2 is removed.

Any three-element tube can be used as a diode detector (two-element detector) by connecting the grid to the plate, the grid to the cathode, or the plate to the cathode.

6. DETECTION WITH THREE-ELEMENT TUBES. The advantage of using a three-element tube as a detector is that amplification of the signal is obtained as well as demodulation. This increases the detector sensitivity, which was previously stated as being an important requisite of any detector circuit.

Triode detectors are divided into two general classifications; namely, grid-bias detectors, and grid-leak detectors. In a grid-bias detector circuit, all of the demodulation occurs in the plate circuit of the tube, whereas, in a grid-leak detector, the signal is rectified in the grid circuit, then filtered in the plate circuit. Both of these methods of detection will be described in detail in subsequent paragraphs of this study.

To prepare for a thorough understanding of the grid-bias method of detection, it is necessary to examine the grid voltage-plate current characteristic curve for a typical three-element tube. In connection with vacuum tube amplification (Lesson 12), this curve was studied purely from the standpoint of obtaining undistorted voltage amplification. At this time, we shall see how this same type tube can be used as a detector.

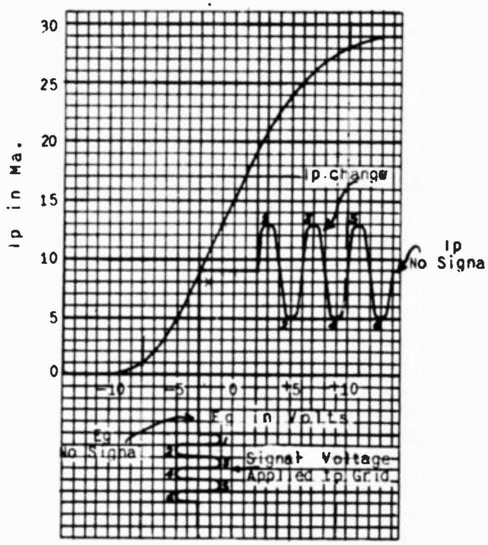


Fig.7 Operating a tube on the straight portion of the Eg-Ip curve for amplification.

In Fig. 7, the grid voltage-plate current characteristics of a typical three-element tube are shown. On this graph, the operating point has been placed at the center of the straight portion of the characteristic curve (point X); hence, the tube will function properly as a voltage amplifier when a signal voltage is applied to the grid circuit. Since this tube is working on the straight portion of its characteristic, even changes in grid voltage above and below the no-signal, grid-bias value (3 volts) will cause corresponding even changes in plate current. It will be noticed from the graph that when the grid voltage is decreased to -1 volt, the plate current increases to 13 milliamperes, and when the grid voltage is increased to -5 volts, the plate current is decreased to 5 milliamperes. These points are marked 1 and 2 respectively on the grid-voltage and plate-current variations. As long as the signal voltage applied to the grid circuit remains constant in amplitude, each increase in plate current above normal and each decrease in plate current below normal will be of equal amplitude; hence, the average value of the plate current will remain constant at 9 milliamperes. By the average value of the plate current, we mean the average of the increases and decreases or the value which will be in-

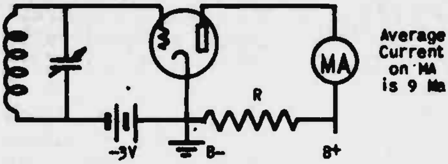


Fig.8 Diagram to show that the average plate current does not change when a tube is operated properly as an amplifier. R represents the bleeder resistance on the output of the rectifier circuit.

dicated on a milliammeter connected in the plate circuit. Fig. 8 shows an outline circuit diagram of this amplifier tube. With an applied grid signal voltage as shown in Fig. 7, the average plate current on the milliammeter in the plate circuit will remain constant at 9 milliamperes. The plate current variations are similar in waveform to the voltage variations applied to the grid. This condition must exist for undistorted amplification.

By using this same circuit, and making only one change, it is possible to alter the relationship between the grid voltage and the plate current. This change consists of increasing the negative bias applied to the grid. The graph in Fig. 9 shows the operating point at Y on the characteristic curve. With -8 volts applied to the grid, only 1 milliampere of plate current will be flowing when no signal voltage is applied to the grid circuit. Now let us assume that the same signal voltage is applied to the grid circuit as before, making the grid first less negative by 2 volts, then more negative by 2 volts. On the first alternation, as the grid is made less negative, the plate current will rise to approximately 3¾ milliamperes. On the negative alternation of this signal voltage, the grid is increased to -10 volts, at which time the plate current decreases to approximately ¼ of a milliampere. Succeeding cycles of the grid voltage excitation will cause corresponding changes in plate current since the amplitude of the grid exciting voltage remains constant.

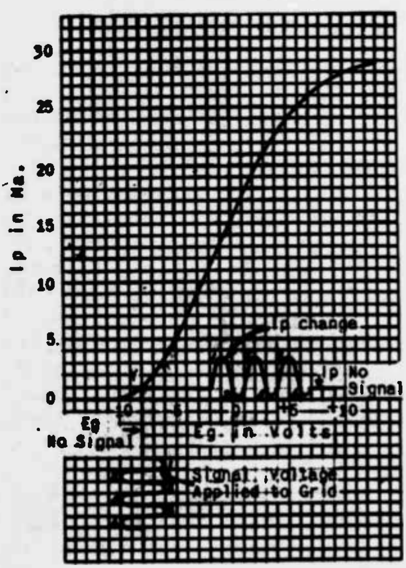
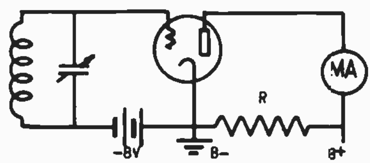


Fig.9 Operating a tube on the curved portion of the Eg-Ip curve for detection.

Under these conditions of operation, the average plate current will not be the same as the plate current which flows when no voltage is applied to the grid circuit. Whereas only 1 milliampere of plate current was flowing with no grid signal voltage, the average plate current will be approximately 2 milliamperes when the signal voltage is applied. The average is secured by adding the maximum plate current to the minimum plate current, then dividing by 2. Using the values on the graph in Fig. 9, the maximum plate current was $3\frac{3}{4}$, the minimum was $\frac{1}{4}$. Adding, we have $3\frac{3}{4} + \frac{1}{4} = 4$. $4 \div 2 = 2$ (average plate current).

It will be noticed that the average value of the plate current increased above the normal no-signal plate current. An investigation of the characteristic curve will reveal the reason for this increase. Upon increasing the negative bias to -8 volts, the operating point was shifted from the straight portion of the grid voltage-plate current characteristic to the curved portion. When operating on the curved portion of the characteristic, the relation between grid-voltage and plate-current variations is not linear, which means that changes in grid voltage will not cause corresponding changes in plate current. This non-linearity relationship results in greater plate current increases above normal than decreases below normal, with the over-all result that the average plate current rises.



Average Current on MA is 2 Ma

Fig.10 Diagram to show that the average plate current increases above normal when grid signal voltage is applied.

The circuit shown in Fig. 10 is the same as shown in Fig. 8, except that the negative bias is increased. When the grid signal voltage is applied in Fig. 10, the plate current will be 2 milliamperes and when the signal voltage is removed from the grid circuit, the plate current will drop to 1 milliampere.

The discussion involving Figs. 8 and 10 assumed that the grid exciting voltage remained constant in amplitude. Now let us investigate the conditions which would exist if the grid exciting voltage were varied in amplitude. This would be the case if a modulated R.F. signal voltage were being applied. The characteristic curve shown in Fig. 11 is a duplicate of those in Figs. 7 and 9, and the operating point is placed at the same position as in Fig. 9. With only the negative grid bias of -8 volts applied to the grid, there will be 1 milliampere of plate current flowing. The signal voltage applied to the grid in Fig. 11 varies from 1 volt on each alternation to 4 volts on each alternation, gradually rising from minimum to maximum, then decreasing back to minimum. When studying this figure, keep in mind that a modulated R.F. wave varies in this same manner. On the positive alternation of the first cycle of grid exciting voltage, the grid is made -7 volts negative and the plate current rises to 2 milliamperes. On the negative alternation of this first cycle, the grid is made -9 volts, causing the plate current to decrease to approximately $\frac{1}{2}$ milliampere. The next posi-

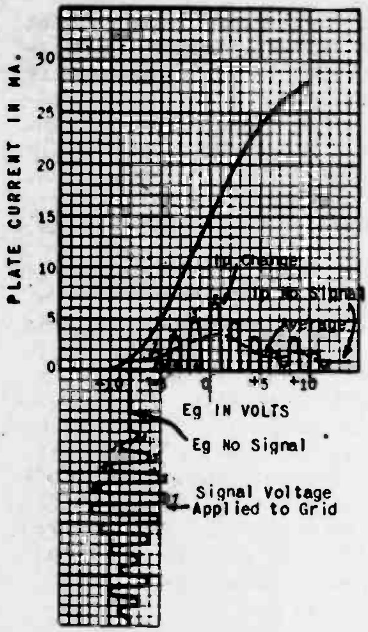


Fig.11 Applying a varying signal voltage to the grid circuit.

tive alternation (3) will cause a plate current increase to about 32 milliamperes, and the next negative alternation (4) will cause a plate current decrease to zero. The peak of the next positive alternation (5) causes the plate current to rise to 5 milliamperes and the negative alternation of this cycle causes the plate current to cut off entirely. The succeeding alternations of the grid exciting voltage should be studied and the corresponding variations produced in plate current observed from the graph.

The plate current pulses are considerably different from those in Figs. 7 and 9. When the grid exciting voltage varies in amplitude, the pulses produced in plate current will change, but the wave form of the plate current pulses is not similar to the wave form of the grid voltage excitation. The average value of the plate current changes will increase as the amplitude of the pulses increases, and will decrease as the amplitude of the pulses decreases. Hence, if the amplitude of the grid excitation varies, the average value of the plate current, as measured on a plate current milliammeter, will likewise change, (this is assuming that the amplitude variations are sufficiently slow for the needle on the milliammeter to follow). Fig. 12 shows the circuit associated with the graph in Fig. 11, and, as indicated, the average current on the plate circuit milliammeter will vary with the amplitude of the grid signal voltage.

By close observation, it can be seen that the circuit shown in Fig. 12 is operating as both a rectifier and amplifier. The graphical analysis in Fig. 11 serves to illustrate this. The tube is operating as a rectifier because it is suppressing the negative alternations of the grid exciting voltage, and is working as an amplifier because it is reproducing and increasing the positive alternations. When any vacuum tube is operated in an over-biased condition, the AC voltage applied to the grid circuit will be rectified, due to the fact that the operating point is on the curved portion of the grid voltage-plate current characteristic. When worked on this curve, the decreases of plate current will never be as high in amplitude as the increases, and the resulting recti-

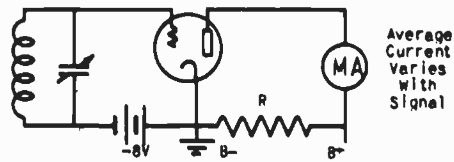


Fig.12 The average plate current will vary with the amplitude of the grid signal voltage in this circuit.

fication takes place. The rectifying action is not perfect (that is, not complete) because on the negative alternations of the grid exciting voltage, there is still a little plate current flowing. When the grid potential becomes excessively negative, however, the plate current is "cut off" entirely. As this rectification occurs, the average value of the plate current will rise and fall with the increases and decreases in amplitude of the grid exciting voltage. Simultaneous with this rectification, amplification of the positive alternation of the grid exciting voltage occurs because of the inherent amplifying ability possessed by any triode tube.

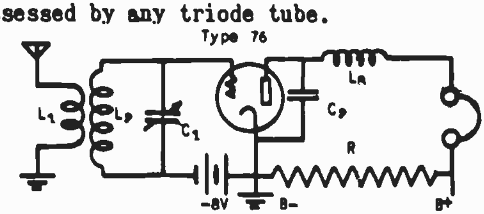


Fig.13 Typical grid-bias detector circuit.

7. **GRID BIAS DETECTION.** The discussion just concluded illustrates the operating conditions necessary for grid bias or "plate" detection. It is obvious that the bias voltage must be adjusted until the operating point is well down on the curved portion of the grid voltage-plate current characteristic curve. When adjusting the grid bias voltage, bear in mind that the plate voltage also affects the plate current; hence, these two voltages (both plate and grid) must be properly adjusted to set the operating point at the desired position on the curve. It is assumed that normal filament or heater voltage is applied to the tube during these voltage adjustments, and that the heater voltage does not change during operation.

The circuit diagram of a complete grid bias detector circuit is shown in Fig. 13. The modulated R.F. voltage induced in the antenna will cause a modulated R.F. current to pass through the primary L_1 of the R.F. transformer. This modulated R.F. current will set up a changing magnetic field which induces a corresponding modulated R.F. voltage across the secondary L_p. By varying the capacity of C_1, the circuit may be properly adjusted to receive the signal from the desired station. Modulated R.F. voltages will then appear across the resonant circuit. These modulated R.F.

voltages are between the negative side of the 8-volt C battery and the grid of the tube; hence, they will be superimposed upon the steady DC bias voltage and cause the grid potential to vary in exact accordance. These grid potential variations are shown on the graph in Fig. 14.

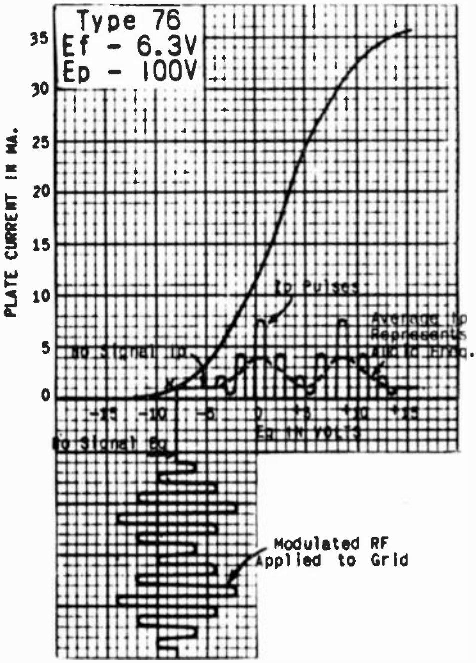


Fig.14 Showing relation between grid signal voltage and plate current variations in grid-bias detector circuit.

A type 76 tube is being used in this grid-bias detector circuit. When a plate voltage of 100 volts is applied to this tube, a grid bias voltage of -8 volts is necessary in order to place the operation on the curved portion of the characteristic curve. The operating point is X in Fig. 14. As the grid potential is made less negative, the plate current rises, and as the grid potential is made more negative, the plate current will decrease. The decrease, however, will not be in proportion to the increase, due to the curvature of the tube's characteristic throughout this region. The resultant plate current will flow in the form of pulses, the pulses reaching a high value on the peaks of the positive alternations, and reaching a low value as the amplitude of the modulated R.F. voltage applied to the grid decreases. From previous discussion, we know that the average plate current flowing through the plate circuit will rise and fall with the amplitude of the plate current pulses. The average plate current is shown by the dotted line in Fig. 14.

Now refer to Fig. 15. At A in Fig. 15, the instantaneous plate current pulses are shown exactly as they appear on the graph in Fig. 14. In order to eliminate the R.F. pulses or "ripples" in the plate current, it is necessary to provide a filter circuit that is capable of smoothing these pulses into their average value. Such

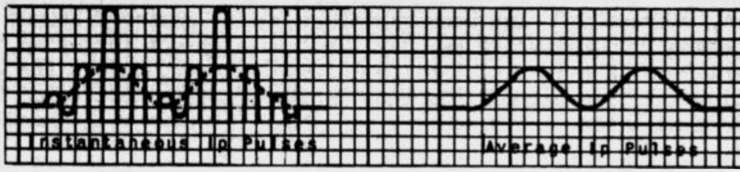


Fig.15 (A) Instantaneous plate current pulses created in the plate circuit. The dotted line is the average value.
(B) Average plate current changes after filter has removed the R.F. pulses. This is same as dotted line in (A).

a filter circuit is shown in Fig. 13, consisting of the R.F. choke[1] L_3 and the by-pass condenser C_2. The values for L_3 and C_2 are properly chosen so as to constitute a low-pass filter. A low-pass filter will permit the lower-frequency component to pass through the choke and cause the high-frequency component to be by-passed through the condenser. As a result of this plate circuit filter, the actual current which passes through the inductance L_3 will appear as shown at B in Fig. 15. It can be seen that the average current passing through L_3 increases and decreases in amplitude in exact accordance with the modulation impressed on the incoming signal. Of course, this represents the audio frequency which we desire to reproduce. For the plate current to complete its circuit, it must pass through the headphones and the bleeder resistance R, then return back to the cathode (plate current flows from cathode to plate through a vacuum tube). As this audio-frequency current passes through the headphones, it causes the diaphrams to vibrate at a corresponding rate. Vibration of the diaphrams sets up sound waves which are audible to the ear.

Assuming that there has been no distortion produced, the sound waves emanating from the headphones will be exactly the same as the sound waves originally impressed on the carrier wave.

From this discussion, it is evident that a grid-bias detector circuit is capable of *rectifying and amplifying* the incoming modulated R.F. signal. Since amplification is obtained, the detector *sensitivity* will be quite high. This type of detection is often called "plate detection" because all of the demodulation takes place in the plate circuit of the tube. In the discussion to follow on grid-leak detection, it will be found that rectification of the signal occurs in the grid circuit of the tube and the filtering occurs in the plate circuit. For this reason, the grid-leak detector circuit is often called a "grid-circuit" detector.

Grid-bias detection experienced considerable popularity in broadcast receivers for several years. The general trend in radio receiver design at the present time is toward a revived use of the diode detector circuit.

8. **GRID LEAK DETECTION.** A typical grid-leak detector circuit is shown in Fig. 16. A filament type tube is being used in this

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[1] When an air-core coil offers an excessively high opposition to the passage of an R.F. current, it is called an "R.F. choke".

circuit, whereas, it has been customary in preceding diagrams of this lesson to employ the cathode type. The object for using the filament type tube is to simplify the explanation. After the explanation of this circuit has been concluded, the adaption of the cathode type tubes for grid-leak condenser circuits will be discussed.

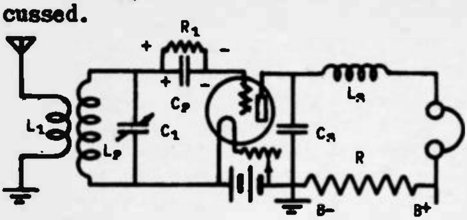

Fig.16 Grid-leak detector circuit.

The appearance of the plate circuit in the grid-leak detector is the same as the grid-bias detector circuit; however, the grid circuit has been altered considerably. It will be noticed that the lower end of the resonant circuit is connected to the positive side of the filament battery, and that the upper end of the resonant circuit is *not* connected directly to the grid of the tube. The condenser C_2 in series to the grid of the tube is called the *grid condenser*, and the resistance R_1 connected across this condenser is called the *grid-leak resistance*. Rectification of the incoming signal depends entirely upon the characteristics of this grid circuit. The rectified signal voltages applied to the grid of the tube will appear amplified in the plate circuit. When the modulated R.F. signal voltage is applied to the grid circuit, the average potential of the grid will vary in direct accordance with the variation in amplitude of the incoming signal. These grid voltage variations will appear amplified in the plate circuit, and the plate circuit filter L_3C_3 will remove the radio-frequency ripples in plate current, thus allowing only the average or audio frequency to pass through the headphones. The only difference between this type of circuit and those previously studied is the manner in which rectification occurs in the grid circuit. This action will now be explained.

First, note that the bottom of the resonant circuit is connected to the positive terminal of the filament battery. Since the positive terminal of the filament battery is 6 volts positive with respect to the negative side of the filament, the grid will tend to be at a 6-volt positive potential with respect to the negative side of the filament. With the grid made positive, a flow of grid current occurs, taking the path from the filament to the grid, through the grid-leak resistance, through the coil L_2, then back to the filament battery. As the grid current flows through the grid-leak resistance R_1, a voltage drop is produced across it with the right side negative and the left side positive. A voltage across the grid-leak resistance in this direction tends to make the grid of the tube negative with respect to the negative side of the filament. Hence, we have two forces simultaneously tending to adjust the potential of the grid with respect to the negative side of the filament. The voltage drop across the grid leak resistance tends to make the grid negative, whereas the connection to the positive terminal of the filament battery tends to make the grid positive. The overall result of these two forces is to establish a compromise in such a manner that both are properly satisfied. This compromise generally occurs when the grid potential is only a few tenths of a volt positive with respect to the negative part of the filament. A slight amount of grid current flows continuously through the grid circuit when no signal voltage is being applied and there is a normal voltage drop across the grid leak resistance R_1 nearly equal in value to the voltage of the filament battery. The grid current flowing with no signal voltage applied is extremely low, being in the neighborhood of a few microamperes.

Rectification in the grid circuit of the tube depends on the fact that current can easily flow from filament to grid, but not from grid to filament. A grid voltage-grid current curve for a type 201-A tube is shown at A in Fig. 17. The operating point has been arbitrarily placed at .4 of a volt and an unmodulated radio-fre-

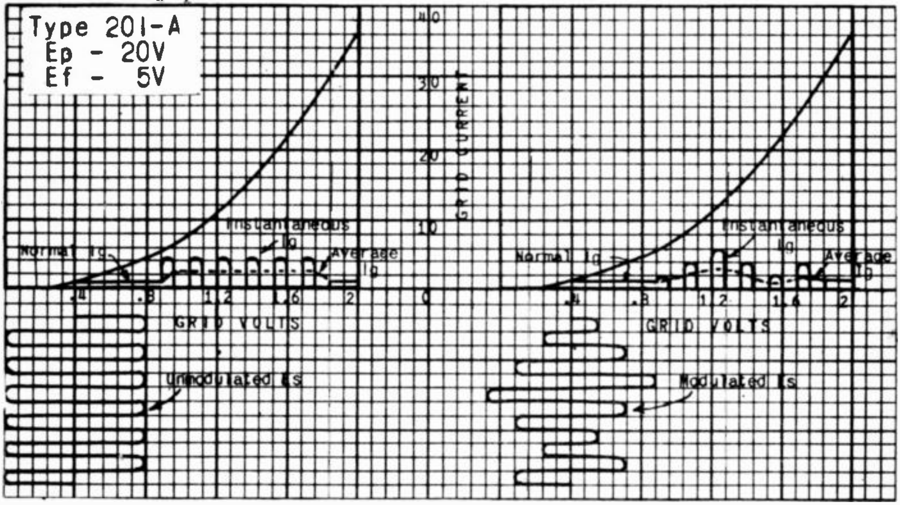

Fig.17 (A) Grid signal voltage is constant in amplitude, so the average grid current remains constant.
(B) Grid signal voltage varies in amplitude (modulated), so the average grid current varies in accordance.

quency signal voltage applied to the grid circuit. Since the E_g–I_g characteristic is not a straight line, the positive alternations of the grid signal will cause greater increases in grid current than the negative alternations cause decreases in grid current. This results in the average grid current being higher in value when the grid signal is applied than the normal grid current which flows when no signal voltage is applied to the grid circuit. Notice that when the amplitude of the R.F. signal voltage does not change, the average grid current remains constant. This produces a voltage drop of constant value across the grid-leak resistance, hence a steady bias on the grid.

When the incoming R.F. signal voltage is modulated with an audio frequency, the instantaneous grid current appears as shown at B in Fig. 17. Since these pulses are varying in amplitude, the average grid current changes in accordance; that is, at an audio-frequency rate. As these average A.F. grid current changes pass through the grid-leak resistance, corresponding voltages will be developed across it, thus changing the average grid bias in accordance with the modulation on the incoming R.F. signal. This action will now be explained in greater detail.

A modulated R.F. voltage induced in the antenna will cause a corresponding R.F. current to pass through the inductance L_1 to ground. By mutual induction, a corresponding voltage will appear across L_2. The secondary L_2, in conjunction with the variable condenser C_1, forms a resonant circuit whereby selectivity of the desired station may be secured. The modulated radio-frequency voltages appearing across the resonant circuit are now applied to the grid circuit of the tube. Let us assume that the wave form appears as shown in Fig. 18. Since the grid of the tube is already slightly positive, the positive alternation of the first R.F. cycle of the incoming signal will cause the grid to draw an increased current. This increased grid current must pass through the grid-leak resistance R_1. On the negative alternation of the incoming radio-frequency signal, the positive potential of the grid is decreased. If the incoming signal is sufficiently strong, the grid potential will be made zero or even negative with respect to the negative side of the filament. Under these conditions, the grid current

Fig.18 Modulated R.F. voltage applied between grid and filament.

Fig.19 Grid current pulses. Rectification occurs because grid current can flow in only one direction

will be decreased, dropping to zero when the grid is made negative. The next positive alternation of the incoming signal is higher in amplitude than the preceding one; hence, the grid is made more positive and more grid current will flow than on the previous positive alternation. The next negative alternation will drive the grid of the tube more negative than before; hence, no grid current will flow. Thus, grid current flows on the positive alternations of the incoming signal, and decreases to zero on the negative alternations. Rectification of the incoming signal is taking place insofar as the relationship between the grid voltage and the grid current is concerned. The pulses of grid current created in the grid circuit appear in wave form as shown in Fig. 19. The amplitude of the grid-current pulses rise and fall in direct accordance with the modulation impressed on the incoming signal. Now let us see what happens when these grid current pulses pass through the grid-leak resistance R_1. R_1 is always a very large resistance, generally several megohms; therefore, this resistance offers a tremendous opposition to the passage of a current through it. Even though the resistance is high, if a slight amount of current is successful in passing through R_1, the voltage drop produced across it ($E = I \times R$) will be rather high. The presence of the grid condenser C_2 in parallel with the grid-leak resistance prevents the grid current from flowing through R_1 in the form of pure pulses as shown in Fig. 19. As the current through R_1 increases and the voltage across it becomes greater, then the condenser C_2 becomes charged. In charging, electrons are accumulated on the right plate of the condenser and driven from the left plate. This higher voltage across the grid condenser causes the grid potential to be made more negative with respect to negative filament than previously. Now as the pulse of grid current recedes, condenser C_2 should discharge. To discharge, electrons must pass from the right plate through the resistance R_1 to the left plate. Due to the several megohms resistance offered by R_1, C_2 cannot become completely discharged during the small fraction of a second required for the grid current pulse to decrease to zero. Since C_2 is not allowed to discharge, the potential of the grid will not return to its previous positive value. The next positive alternation of the incoming signal voltage is higher in amplitude than the preceding alternation, and a greater amount of grid current will flow. This higher grid current will develop a higher voltage drop across the grid leak resistance R_1, thus causing condenser C_2 to become charged to a higher voltage. During the fall of the second positive alternation, again the grid condenser is not permitted to completely discharge, thus causing the average potential of the grid to be increased in the negative direction. Succeeding pulses of grid current cause a similar action to occur and when the maximum amplitude of the modulated R.F. signal voltage is reached, the average potential of the grid has been made considerably negative. In effect, the action of the grid leak-grid condenser has been to partially smooth the R.F. grid current pulses through R_1 into their average value. The average "negative drift" in grid potential follows directly with the increase in amplitude of the R.F. signal voltage; hence, it may be stated that the average grid potential has been made increasingly negative at an audio-frequency rate. This average increase in negative grid potential causes the average plate current to be decreased from its normal no-signal value in direct accordance. The tube is operating over the straight portion of its grid voltage-plate current characteristic curve.

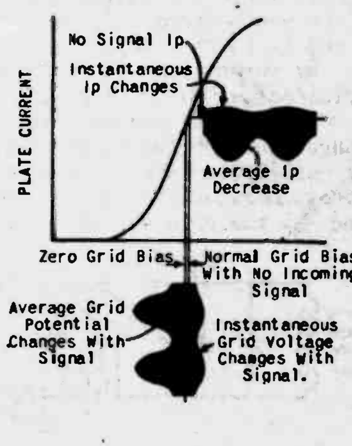

Fig.20 Showing the relation between the grid signal voltage and the plate current in a grid-leak detector.

As the incoming, modulated, radio-frequency voltage decreases in amplitude, the successive cycles will not cause as much voltage to be applied to the grid on each positive alternation; therefore, less grid current will flow on each positive alternation. The lower grid current will produce lower voltages across the grid-leak resistance and ample time will be available for the grid condenser to properly discharge through this resistance. This allows the average grid potential to gradually return to normal because the electrons which were accumulated as the amplitude of the R.F. signal increased, are now permitted to "leak" through the high resistance and return to the filament. As the average grid potential returns to its initial no-signal value, the average plate current will likewise return to its normal value because the tube is working on the straight portion of its grid voltage-plate current characteristic.

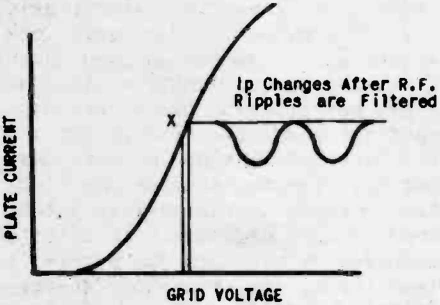

Fig.21 Appearance of the plate current after the filter has removed the R.F. pulses.

The manner in which the grid voltage variations affect the plate current can be seen by reference to Fig. 20. Starting with a slightly positive bias, the average potential of the grid is driven back in a negative direction, thus causing the average plate current to decrease in accordance. Bear in mind that the tube is operating on the straight portion of its grid voltage-plate current characteristic. Fig. 21 shows the appearance of the plate current changes after the radio-frequency "ripples" have been filtered out by the plate-circuit filter. The plate-circuit filter consists of L_3 and C_3 in Fig. 16.

By inspection, it can be seen that the resulting plate-current variations shown in Fig. 21 follow with the changes in amplitude of the incoming signal (Fig. 18). Having secured plate current changes through the headphones which vary in exact accordance with the amplitude of the incoming modulated radio-frequency signal, the process of detection has been completed. The signal has been rectified in the grid circuit by the action of the grid leak and grid

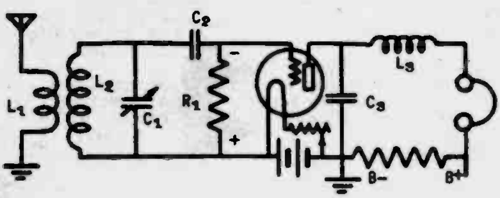

Fig.22 Grid-leak detector with the grid-leak resistance R_1 connected directly from the grid to the filament.

condenser, then amplified and filtered in the plate circuit, thus completing the demodulation and the audio frequency may be heard from the headphones.

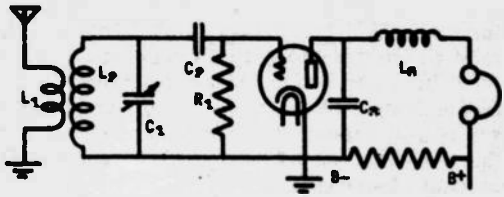

Fig. 23 Grid-leak detector using a cathode type tube.

9. ADDITIONAL GRID-LEAK DETECTOR CIRCUITS. The grid-leak detector circuit shown in Fig. 22 is the same as Fig. 16, except that the grid-leak resistance R_1 is connected directly from the grid to the positive side of the filament instead of across the grid condenser C_2. The operation of the grid-leak detector circuit is not affected in any manner by this change in the position of the grid-leak resistance. The grid current must pass through the grid-leak R_1 in Fig. 22, and the grid condenser C_2 must charge and discharge through R_1 the same as before. In Fig. 22, the secondary L_2 is also in the discharge path of C_2; however, its resistance is negligible. Either method of connecting the grid resistance is satisfactory, both giving practically the same operation.

Fig. 23 shows a grid-leak detector circuit employing a cathode type tube. In this case, the grid-leak resistance R_1 and the bottom of the resonant circuit are both returned directly to the cathode. When using a cathode type tube, the grid is generally held at a slightly negative potential with respect to the cathode instead of being slightly positive, as was assumed in the preceding explanation. This has no particular effect on the operation of the grid-leak detector circuit. It may seem rather peculiar that grid current will flow through the grid-leak resistance when the grid is slightly negative with respect to the cathode; however, this is precisely the existing condition. In Lesson 12, the fact was mentioned that when the electrons are being attracted to the plate, they must pass through the grid. If the grid does not offer sufficient repulsion, some of these electrons will strike the grid wires and a slight flow of grid current will result. This always occurs when the grid is at the same potential as the cathode, and it has been found that in a type 27 tube, a measurable grid current flows until the grid potential is at least 1 volt negative with respect to the cathode. Other tubes which differ in construction have different characteristics, and in some it may be found that a measurable grid current flows when the grid potential is even more than 1 volt negative. The grid voltage-grid current characteristic curve for a type 27 tube, when the grid is negative with respect to the cathode, is shown in Fig. 24. When this tube is being used in a grid-leak detector circuit, the size of the grid-leak resistance is generally chosen so that the tube is operated with a normal negative grid potential of approximately .3 of a volt.

10. COMPARISON OF GRID-LEAK AND GRID-BIAS DETECTION. In a grid-bias detector circuit, the normal current which flows through

the plate circuit when no signal voltage is applied to the grid, is rather low because of the high negative bias employed. Conversely, in a grid-leak detector circuit, the normal no-signal plate current will be rather high because the normal grid bias will be very close to zero, either slightly positive or negative.

In a grid-bias detector circuit, the application of a modulated radio-frequency signal voltage to the grid circuit causes the average plate current to rise, whereas in a grid-leak detector circuit, the application of the signal voltage results in an average plate current decrease.

The sensitivity of a grid-leak detector circuit is much greater than the grid-bias type, because the full amplifying ability of the tube is realized in the former case. Amplification of the R.F. signal is obtained in a grid-bias detector, but due to the fact that this amplification takes place near the bottom of the characteristic curve, it will not be nearly as much as that obtained with the grid-leak detector, where the tube is operating over the linear portion of the grid voltage-plate current characteristic curve.

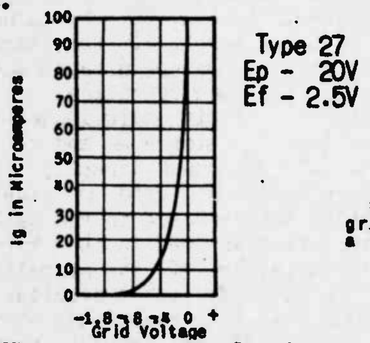

Fig.24 Grid voltage-grid current curve for a type 27 tube.

When a comparatively strong radio-frequency signal voltage is applied to the grid circuit of a grid-bias detector, less distortion will appear in the plate circuit than when a corresponding signal voltage is applied to the grid circuit of a grid-leak detector. It is mainly for this reason that grid-bias detection supplanted grid-leak detection in broadcast radio receivers prior to the renewed use of the diode-detector circuit.

Grid-leak detection has experienced a more popular use in short-wave receivers than any method of detection because of its high sensitivity. In short-wave receivers, the amount of distortion produced is not so important as the sensitivity.

11. WEAK SIGNAL AND POWER DETECTORS. Weak signal detectors are often known as "square law" detectors. They are called "square law" detectors because a weak R.F. signal voltage input develops a rectified current which is proportional to the square of the input voltage. A radio-frequency signal is considered to be weak if it has a maximum potential less than 1 volt. Both the grid-leak and grid-bias type detectors operate on this square law principle when rectifying weak radio-frequency voltages. The "square law" relationship exists between the grid voltage and plate current in

a grid-bias detector, and between the grid voltage and grid current in a grid-leak detector. The grid voltage-grid current curve is not a straight line (refer to Fig. 17), but shows a distinct curve, especially near the bottom of its characteristic.

When a strong radio-frequency signal voltage (greater than 1 volt) is applied to the grid circuit of either grid-bias or grid-leak detectors, the distortion produced in the plate circuit will not be as great as with weak signals. Of course, in order to accommodate a strong radio-frequency signal voltage input, it is necessary to properly adjust the grid and plate voltages in the bias detector circuit, and to select the proper values for the grid leak and grid condenser in a grid-leak detector circuit. In both cases, if all conditions are satisfied properly, the audio-frequency distortion produced in the plate circuit will be at a minimum, but, of course, will not be entirely absent. Detectors that are adjusted to accommodate a strong radio-frequency signal-voltage input are commonly known as "power detectors". Do not conclude that a power detector does not produce any distortion of the modulation impressed on the original signal, because there is certain to exist a slight amount. Regardless of the maximum strength of the input voltage, the tube will still be operating over a curve in the characteristic when the amplitude of the incoming signal falls to a low value. On the peaks of the modulated signal, however, the tube is working over the straight portion of its characteristic, and the distortion produced will be very low.

In a grid-bias detector, care should be exercised in the selection of the plate voltage and bias voltage applied to the grid. An attempt should be made to place the operating point at the most desirable position on the tube's characteristic curve. This desirable position is directly at the pronounced bend on the lower end of the characteristic curve. The load impedance in the plate circuit of a grid bias detector tube should be in the neighborhood of 5 times the tube's plate resistance. A pure resistive load in the plate circuit results in less distortion than when an inductive load is employed. It is found that better tone quality is secured when the plate circuit filter consists of a radio-frequency choke having an inductance of from 20 to 85 millihenries and a by-pass condenser from plate to the cathode (or ground) with a capacity of about 250 mmfd. By removing the R.F. filter from the plate circuit of any detector, it will be found that reception of the audio frequency is still possible. If the circuit were previously adjusted for best operation, however, the tone quality will decrease when the plate circuit filter is removed. The reason is quite obvious, the purpose of the plate circuit filter is to remove the radio-frequency ripples in the average plate current changes, thus permitting pure audio-frequency current to pass through the headphones.

The main adjustments in a grid-leak detector circuit consist of the proper selection for the grid-leak and grid-condenser combination. The value of these two parts will affect the sensitivity and tone quality of the detector circuit to a large extent. The average audio-frequency voltages produced across the grid leak and condenser in a grid-leak power detector can decrease only as fast as the condenser charge is capable of leaking off through the grid-leak resistance. If this leakage is slower than the rate at which the amplitude of the modulated incoming signal decreases, then the condenser voltage cannot follow the variations in amplitude of the incoming signal; the result will be a distortion of the audio-frequency current in the plate circuit. If, however, the charge on the grid condenser is capable of leaking off through the grid leak as fast as the incoming signal decreases in amplitude, the percentage of distortion produced in the plate circuit will be quite low. The rapidity at which this charge can leak off is determined primarily by the relative sizes of the grid leak and condenser. The least distortion will be produced when the grid-leak resistance and the grid-condenser capacity are both small. There is a limit, however, to the extent to which these values may be decreased. When the grid condenser is exceedingly small, there will be a large R.F. voltage drop across it when the incoming radio-frequency signal is received. The voltage drop which occurs across the grid condenser subtracts from the R.F. voltages actually applied to the grid; hence, the higher the voltage drop across the grid condenser, the lower will be the average grid potential variation. This means that if the grid condenser is small in value, the sensitivity of the detector circuit will be decreased. For these reasons, it is necessary to compromise between the sensitivity and the wave form or amplitude distortion. In power detectors, the grid-leak resistance is generally from about ¼ to ½ megohm and the grid condenser approximately 100 micro-microfarads. These values constitute a good compromise between distortion and sensitivity.

In short-wave receivers, the distortion is of little consequence and high sensitivity is desired, so the grid condenser is generally made approximately 250 micro-microfarads and the grid-leak resistance several megohms. This arrangement works best for receiving very weak signals and the over-all sensitivity of a detector circuit using these values is surprisingly high. Since the normal grid bias is about zero, a low plate voltage must be used on all grid-leak detectors to prevent an excessive plate current. This limits the strength of the input R.F. signal, which can be accommodated without causing the grid circuit to become overloaded or "blocked". This is the reason for the following statement, as made on a preceding page: "Grid-bias detection has supplanted grid-leak detection in broadcast radio receivers....."

The percentage of modulation of a radio-frequency signal means the extent to which the amplitude is varied by the impressed audio frequency. If the amplitude of the carrier wave is increased to twice its normal value (on the positive alternation of the impressed audio frequency), then decreased completely to zero (on the negative alternation of the impressed audio frequency), the carrier wave is said to be 100% modulated. Lower percentages of modulation cause less variation in amplitude of the carrier wave.

It has been determined that detector circuits (grid leak and grid bias) will produce a greater percentage of audio-frequency wave form or amplitude distortion when the received radio-frequency signal is modulated to a high percentage. This is due mostly to the "square-law" relationship because of the curvature in either the grid voltage-grid current or the grid voltage-plate current characteristic. By mathematical derivation, it can be shown that the percentage of distortion produced in the plate circuit due to this square-law action is equal to $M^2 + 4$, where M is the percentage of modulation (expressed as a decimal). Hence, if the incoming signal is modulated 100%, the distortion produced on the audio frequency in the plate circuit will be approximately 25%. (Solution: $1^2 = 1$; $1 + 4 = \frac{1}{4}$; $\frac{1}{4} \times 100 = 25\%$.) However, if the incoming signal were modulated only 75%, the resulting amplitude distortion produced in the plate circuit would only be around 14%. (Solution: $.75^2 = .5625$; $.5625 + 4 = .1406$; $.1406 \times 100 = 14.06\%$.)

The chief differences in the performance of weak-signal and power detectors are in the efficiency and linearity of rectification. Power detection is much more efficient, giving at least several times as much output voltage in proportion to the applied signal amplitude as does weak-signal detection. This makes it possible to obtain a desired output with less amplification. At the same time, power detection requires more amplification before detection (radio-frequency amplification) and less after (audio-frequency amplification) than does weak-signal detection, which may or may not be an advantage, depending upon the circumstances. When the R.F. signal being received is a modulated wave, power detection is always preferred, because power detectors have a nearly linear characteristic and so give a rectified output that produces the audio frequency with a minimum amount of amplitude distortion.

12. **DETECTORS IN MODERN RECEIVERS.** All modern broadcast receivers employ a radio-frequency amplifier, generally consisting of several stages, between the antenna and the input of the detectors. This amplifier is necessary from the standpoint of selectivity and sensitivity. Since the radio-frequency amplifier increases the amplitude of the modulated wave, the R.F. voltage applied to the grid of the detector will generally be greater than 1 volt. From previous discussion, we know that a power detector must be employed if good tone quality is to be secured.

Modern receivers also employ a loud speaker for reproduction of the sound rather than headphones; hence, an audio-frequency amplifier is used to increase the audio-frequency output of the detector. The various ways in which audio-frequency amplification can be secured will be thoroughly discussed in the following lesson.

A properly designed diode detector circuit produces less audio-frequency distortion than a grid-bias or grid-leak power detector. The desire to eliminate this distortion as much as possible is responsible for the extended use of diode detectors in present day receivers. Even though no amplification of the signal is obtained from a diode detector circuit, the use of modern high-mu amplifier tubes easily compensates for the loss. Special types of tubes, such as the 75, 85, 55, 6Q7, 6R7, and others, have been developed specifically for diode detection. These tubes also contain a triode section which amplifies the audio-frequency output of the diode detector. The total audio output of these tubes (after being amplified through the triode section) is equal to, and in some cases greater than, that secured from a grid-leak or grid-bias detector circuit. A complete description of various types of modern diode detector tubes and circuits will be given in Lesson 30.

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UNIT NO. 1

AUDIO-FREQUENCY AMPLIFIER CIRCUITS

LESSON NO. 19

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Lesson Nineteen

AUDIO - FREQUENCY AMPLIFIER CIRCUITS

"The addition of Audio Frequency Amplifiers to the detector circuits described in the previous lesson was mainly responsible for the radio becoming a home entertainment unit.

"When only a detector was used, headphones were necessary because of the low audio output of such a stage. However, with the addition of an audio amplifier, a loudspeaker may be operated, thus enhancing the value of the received radio programs.

"In this lesson, we are studying Audio Frequency Amplifiers only as they pertain to radio receivdrs. In later lessons, you will learn more concerning the amplifier's use in public address systems, television amplifiers and broadcast stations."

1. INTRODUCTION. The types of audio-frequency amplifiers to be discussed in this lesson are those commonly employed in radio receivers to amplify the audio-frequency output of the detector. These detector signals must be amplified until they are of sufficient amplitude to properly operate the grid of the power tube which in turn drives the loudspeaker. Such audio-frequency amplifiers are commonly known as "voltage amplifiers". Power amplifiers will be discussed in Lesson 28.

Audio-frequency voltage amplifiers are subdivided into the following general types:

1. Transformer coupled
2. Resistance-capacity coupled
3. Impedance-capacity coupled
4. Direct coupled

Each of these different types of audio-frequency amplifiers will be discussed separately, then a comparison made as to their relative merits in the latter part of the lesson.

To properly understand the operation of any vacuum tube as an amplifier, it is necessary to conceive the action of the tube as being similar to an AC generator. This discussion follows.

2. THE VACUUM TUBE AS A GENERATOR. From previous discussions we have learned that when changing voltages are applied to the grid circuit of a vacuum tube, changes in plate current are created due to the controlling action of the grid. These current changes are effectively superimposed upon the DC current flowing through the plate circuit as supplied from the plate supply source. The plate supply source may be either a battery or a vacuum tube rectifier circuit. It is well understood that all of the current which leaves the negative pole of the plate supply source must return to the positive pole in order to complete its circuit. Without a completed circuit, no DC current would flow. The same is true for the changing current in the plate circuit caused by the voltage changes applied to the grid. These current changes originate within the tube, so the tube itself should be considered as their source, the same as the battery or rectifier circuit is regarded as the source of the DC current. The plate of the tube is the positive terminal of the tube insofar as the current changes are concerned and the cathode or filament is the negative terminal. Hence, the current *changes* as created in the plate circuit by the vacuum tube will leave by way of the plate, pass through the external circuit, then return back to the cathode.

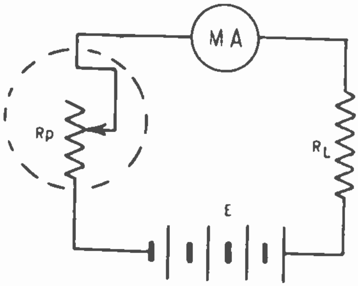


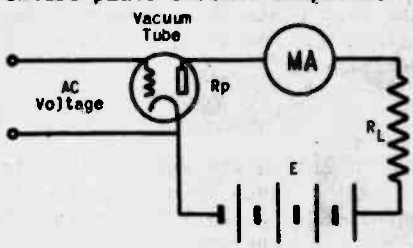
Fig.1 A simple resistance circuit. DC current is supplied by E, but the current variations are created by a change in Rp.

In the plate circuit of any vacuum tube, the power supply is the source of only the DC component of the plate current. The AC component or plate current changes are created by the varying potentials on the grid of the tube; hence, the tube may be considered their source. For an illustrative example, consider the circuit shown in Fig. 1. Here, the two resistors R_P and R_L are connected across the voltage source E. R_P is variable and R_L is fixed. As long as R_P remains at a constant value, the current passing through the circuit is a pure DC current and the milliammeter will read a steady value. If, however, the resistance of R_P is changed, the current through the circuit will be changed in accordance. Should it be varied at an audio or radio-frequency rate, the current through the circuit would change accordingly.

The source of the pure DC current in Fig. 1 is the battery E; however, the current changes are being created by the action of the rheostat R_P. Fig. 2 shows the similarity between the simple resistance circuit in Fig. 1 and the plate circuit of a vacuum tube. From previous study, we know that an opposition is offered to the passage of a DC current from the cathode to the plate inside the tube. This is known as the DC plate resistance. Starting from a high negative potential, if the grid is made less negative, or positive, the DC plate resistance is decreased and starting, from a high positive potential, if the grid is made less positive, or negative, the DC plate resistance is increased.

If a rapidly changing AC voltage is applied to the grid of the tube, the current through the entire plate circuit will be varied in accordance. An audio-frequency voltage applied to the grid produces audio-frequency changes in plate current and a radio-frequency voltage causes the plate current to vary at a radio-frequency rate. As these current changes pass from cathode to plate inside the tube, the opposition offered is less than the value calculated under static conditions (when a DC voltage is supplied to the grid) and is known as the "*plate resistance*"[1] of the tube. In Fig. 2, the action of the vacuum tube is the sole source of the current changes in the plate circuit. The plate supply voltage E is producing only the steady DC current. Of course, it would be impossible for the vacuum tube to function at all unless the voltage source E was present and the entire plate circuit complete.

Fig.2 Illustrating the similarity of a vacuum tube plate circuit to Fig.1. Varying the grid potential changes the resistance of Rp, which creates current changes in the plate circuit.



The voltage *variations* created across resistance R_L are due entirely to the current changes passing through it. It is only these voltage *variations* which can be passed on to the grid circuit of a succeeding amplifier, because the DC voltage drop across R_L, produced when the plate current is steady, is not effective in varying the grid potential. From this it is apparent that the constant current supplied by the voltage source E is of no consequence insofar as the actual amplification is concerned, being necessary only from the standpoint of securing correct operation of the vacuum tube. Since the vacuum tube is the sole source of current changes in the plate circuit, it is generally represented with a symbol such as shown in Fig. 3. The plate current changes must pass through the load resistance R_L and the plate resistance of the tube R_P in order to complete their circuit. The internal resistance of the plate voltage source E is neglected when it is properly by-passed by a large condenser. This is always done in actual amplifying circuits.

The amplitude of the changing current passing through the plate circuit depends upon the total impedance of the plate circuit and the amplitude of the voltage variations created across the vacuum

[1] The plate resistance of a tube is often called the "AC plate resistance" or "plate impedance".

tube from plate to cathode. In Figs. 2 and 3, the impedance of the plate circuit consists of the resistance R_L plus the plate resistance of the tube R_P. The voltage variations created across the tube depend upon two factors, namely: the grid voltage excitation[1] and the mu (μ) of the tube. The amplification factor or mu of a tube has previously been defined as the ability of a tube to amplify a voltage. If an AC voltage having an R.M.S. value of 10

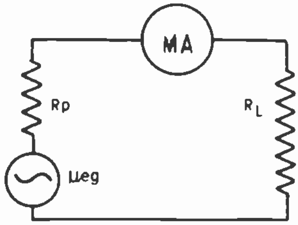


Fig.3 Equivalent electrical circuit for the plate circuit of a vacuum tube.

volts is applied to the grid circuit of a vacuum tube whose μ is 5, then the R.M.S. value of the AC voltage developed across the vacuum tube from plate to cathode will be the product of the grid exciting voltage and the mu of the tube. This is expressed by the following formula:[2]

$$\Delta E_P = E_G \times \mu \qquad (1)$$

Where:
- ΔE_P is the varying AC signal voltage developed across the tube from plate to cathode;
- E_G is the R.M.S. value of the signal voltage applied to the grid circuit;
- μ is the amplification factor of the tube.

Knowing the total impedance of the plate circuit and the R.M.S. value of the AC voltage developed across the tube, Ohm's Law may be applied directly to the plate circuit in order to determine the amplitude of the changing current which will flow. The form of Ohm's Law necessary for this application is:

$$I = \frac{E}{Z}$$

The E in Ohm's Law may be replaced with the product, $\mu \times E_G$. This is permissible because $\mu \times E_G$ as found from formula (1) is actually the AC voltage developed across the plate circuit due to the grid excitation. Then, the Z in Ohm's Law may be replaced by $R_P + R_L$, because this sum is the total opposition to the changing current through the plate circuit. Thus, we have:

---

[1] "Grid excitation" is an expression used to describe the AC signal voltage applied to the grid.

[2] The triangle, Δ, is the capital Greek letter for delta. Lower case delta is δ. Delta is commonly used in radio and electrical formulas to denote a variation.

$$\Delta I_P = \frac{\mu \times E_G}{R_L + R_P} \qquad (2)$$

Where:
ΔI_P is the R.M.S. value of the changing current through the plate circuit;
$\mu \times E_G$ is the R.M.S. voltage changes across the vacuum tube;
$R_P + R_L$ is the total impedance of the plate circuit.

From this formula, it can be seen that the amplitude of the varying plate current (signal current) will be increased by:

1. Increasing the mu of the tube.
2. Increasing the amplitude of the grid exciting voltage.
3. Decreasing the plate resistance of the tube (R_P).
4. Decreasing the load impedance in the plate circuit (R_L).

When discussing the action of a vacuum tube as an amplifier, it was stated that the actual voltage amplification is equal to the ratio of the voltage variations across the load resistance R_L to the voltage variations applied to the grid circuit of the tube. The higher the voltage variations across the load resistance R_L relative to the voltage variations applied to the grid, the greater is the amplification produced. The voltage variations produced across the load resistance R_L can be found by use of the following formula:

$$\Delta E_L = \Delta I_P \times R_L \qquad (3)$$

Where:
ΔE_L is the amplitude of the voltage changes across the load resistance R_L;
ΔI_P is the amplitude of the plate current changes as found by formula (2);
R_L is the resistance of the load impedance in ohms.

From formula (3), it can be seen that larger voltage variations will be created across the plate circuit load resistance, when:

1. The amplitude of the plate current change is high.
2. The load resistance is high.

In all types of voltage amplifiers we are primarily interested in securing as much voltage change across the plate circuit as possible; hence, the circuit should be designed so as to secure a high amplitude of plate current change and to accommodate a large plate load resistor. But, from formula (2), it can be seen that the use of a high plate load resistor tends to decrease the amplitude of the plate current changes. In view of this conflict, proper design of the entire circuit consists of obtaining the most satisfactory compromise between all factors involved.

This discussion on the action of a vacuum tube as a generator can be concluded by again referring to Fig. 3. This diagram shows the conventional method of illustrating the plate circuit of any vacuum tube. Notice that the DC voltage supply has been excluded.

This is done because the DC voltage supply has nothing to do with the amount of voltage or power amplification secured from a vacuum tube except to supply the initial DC power which enables the vacuum tube to function correctly as an AC generator. Beyond this necessity for correct operation of the tube, the DC power is not effective in producing amplification. The single cycle in the center of the circle indicates that the vacuum tube produces an AC voltage insofar as the plate circuit is concerned and is equal to the product of μ and E_G. These voltage variations increase and decrease in one direction only; that is, they actually consist of an AC superimposed on DC. The resistance, R_P, above the symbol represents the plate resistance of the tube.

In all vacuum tube applications, regardless of whether the tube is being used as a detector, an amplifier, or as an oscillator, it can be considered to perform the same as any other AC generator. The application of this principle to all types of vacuum tube circuits (except diodes) should be sufficient to impress its importance.

3. **TRANSFORMER-COUPLED, AUDIO-FREQUENCY AMPLIFIERS.** Audio-frequency amplifiers are required to amplify audio-frequency voltages ranging from 16 to 16,000 cycles. Whether or not the amplifier is capable of producing even amplification of all these frequencies will determine its usefulness for certain purposes. Audio-frequency amplifiers should also produce a minimum of distortion of the input signal voltage. This means that the waveform of the output voltage from the amplifier should be the same as the input waveform (except that it is amplified) as closely as possible. With the facts in mind that all audio-frequency amplifiers should amplify a wide band of audio frequencies and produce no distortion of the waveform, let us proceed to investigate the transformer method of coupling such amplifiers.

A typical transformer-coupled, audio-frequency amplifier is shown in Fig. 4. In this circuit, the plate voltage is being secured from a vacuum tube rectifier circuit and the grid bias is being supplied by C batteries connected in the individual grid circuits. The heater voltage is secured for the three tubes by connecting across the secondary winding marked X-X on the power transformer. Since three vacuum tubes are used in this amplifier, it is known as a three-stage transformer-coupled audio amplifier. A stage of amplification consists of a vacuum tube and a coupling device.

A coupling device is necessary in multi-stage amplifiers in order to transfer the amplified output of one tube into the grid circuit of the following tube. In Fig. 4, this coupling is secured with iron-core transformers and, for this reason, the name "transformer-coupled amplifier" is given to a circuit of this kind.

The coupling device employed between the plate circuit of one tube and the grid circuit of the succeeding tube must be capable of not only transferring the signal properly, but must also isolate the respective plate and grid circuits so as to prevent the high positive plate voltage from affecting the fixed grid bias on the succeeding stage. In a transformer-coupled amplifier, this is done

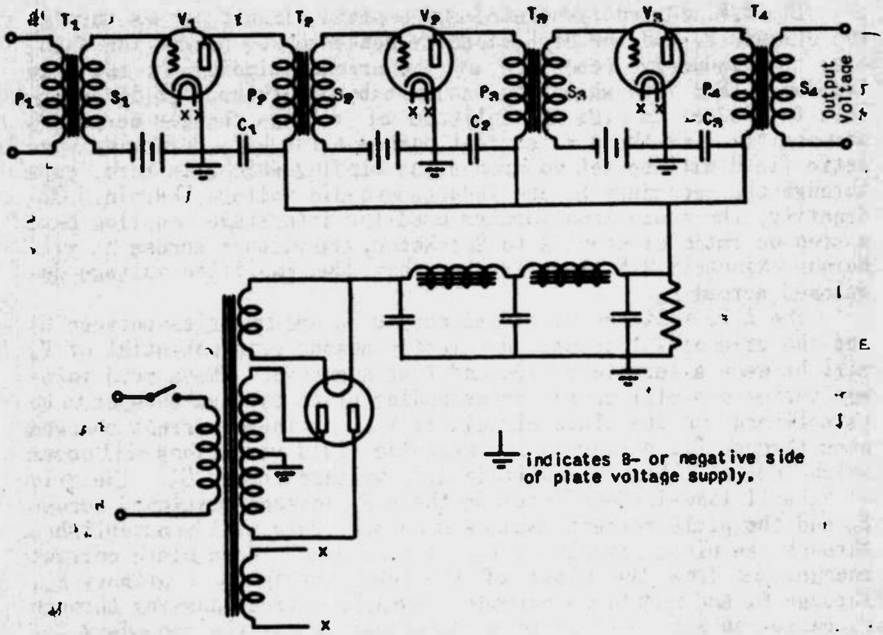


Fig.8 Transformer-coupled A.F. amplifier with vacuum tube rectifier circuit for plate voltage.

by feeding the positive plate voltage through the primary of the transformer and the negative bias for the grid of the following amplifier tube through the secondary. Since there is no direct electrical connection between the primary and secondary, these two circuits are isolated from each other insofar as the DC potentials are concerned.

The weak audio-frequency voltage to be amplified is fed to the primary of the input transformer T_1. This A.F. voltage causes a corresponding current to pass through the primary winding which sets up magnetic field variations. The magnetic field changes cut through the secondary winding and induce the audio-frequency voltage therein. Nearly all A.F. transformers are of the step-up type which means that the audio voltage induced in the secondary will be higher in amplitude than the voltage applied to the primary.

The A.F. voltage developed across the secondary is alternating in character and is in series between C- and the grid of the amplifier tube V_1. The instantaneous grid potential of V_1 will alternately be made more and less negative.[1] The A.F. voltage applied to the grid circuit between grid and cathode will cause corresponding voltage variations to be produced across the tube from plate to cathode and A.F. current changes to flow through the plate circuit. The amplitude of the audio voltages between plate and cathode will be equal to the μ of the tube times the A.F. grid exciting voltage (Ec).

[1] Refer to Section 12, Lesson 12, Unit 1.

The A.F. current generated in the plate circuit passes through the primary P_2 and the high-capacity condenser C_1 back to the cathode. The inductive reactance of the primary winding is the load impedance (R_L) into which the vacuum tube is working. It is desirable to produce as high an amplitude of voltage changes across P_2 as possible. As the A.F. current passes through P_2, a varying magnetic field will be set up around the winding which, in turn, cuts through the secondary S_2 and induces an audio voltage therein. Ordinarily, the audio transformers used for interstage coupling have a step-up ratio of about 1 to 3½; hence, the voltage across S_2 will be approximately 3.5 times greater than the amplified voltage developed across P_2.

The A.F. voltages developed across S_2 are in series between C- and the grid of V_2; hence, the instantaneous grid potential of V_2 will be made alternately more and less negative. These grid voltage variations will cause corresponding plate current changes to be established in the plate circuit of V_2. As these current changes pass through P_3, corresponding magnetic field variations will occur which induce a higher amplitude A.F. voltage across S_3. The grid of V_3 will likewise be affected by the A.F. voltage developed across S_3 and the plate current changes at an A.F. rate will be established through the plate circuit of V_3. The path of these plate current changes is from the plate of the tube, through the primary P_4, through C_3 and back to the cathode. The A.F. current passing through P_4 causes an A.F. voltage to be developed across the secondary S_4. Since the secondary S_4 is the output circuit of the amplifier, the last transformer T_4 is commonly known as an "output transformer".

The A.F. voltage developed across the secondary of the output transformer T_4 should be higher in amplitude, but *exactly the same in waveform* as the input voltage applied to the primary of the input transformer T_1. All audio frequencies fed into P_1 should be present across S_4; otherwise, "frequency distortion" exists in the amplifier and the tone quality is inferior.

The total voltage amplification of the amplifier may be calculated by finding the product of the voltage amplification produced by each tube and the step-up in voltage secured through each transformer. In Fig. 5, the same amplifier circuit is shown as in Fig. 4 (excepting the plate power supply) with the mu of each tube and

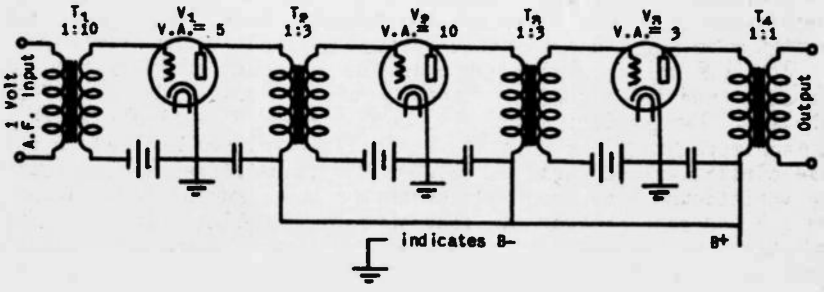


Fig.5 Illustrating the voltage gain in a three-stage transformer-coupled A.F. amplifier.

the turns ratio of each transformer indicated. To calculate the voltage gain, let us consider 1 volt A.F. input to the primary of T_1. Since T_1 has a turns ratio of 1:10, the voltage appearing across the secondary will be 10 volts (assuming no transformer losses). Since the voltage amplification of V_1 is 5, there will be 50 volts of A.F. voltage developed across the primary of T_2. The 1:3 turns ratio of T_2 steps the voltage up to 150 volts across the secondary. The voltage amplification produced by V_2 is 10; hence, there will be 1,500 volts across the primary of T_3. The voltage is stepped up 3 times through transformer T_3; so there will be 4,500 volts across the secondary of T_3. An A.F. potential of 13,500 volts appears across the primary of T_4, because the voltage amplification produced by V_3 is 3. The turns ratio of the output transformer T_4 is 1:1; hence, there will be no step-up or step-down in voltage. The output voltage from the three-stage amplifier will, therefore, be 13,500 times greater than the input voltage applied to the primary P_1, so it is said that the amplifier has amplified the voltage 13,500 times. In actual practice, an amplifier of this kind would have a voltage far less than 1 volt applied to its input.

Fig.6 Equivalent electrical circuit for the plate circuit of a transformer-coupled A.F. amplifier.

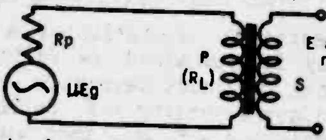


Fig. 6 shows the equivalent electrical circuit for the plate circuit of a transformer-coupled amplifier. The A.F. voltages applied to the grid causes a varying potential equal to μ times E_G to be developed across the plate circuit. The varying A.F. current in the plate circuit must pass through R_P (plate resistance of the tube) and R_L (primary of the transformer). Since the voltages developed across R_L are transferred to the next grid, it is desirable to make the impedance of R_L high to the current changes. This is done by winding as many turns as possible on the primary without causing excessive transformer losses. The actual voltage developed across R_L is equal to:

$$\Delta E_{RL} = \Delta I_P \times X_L$$

Where: ΔE_{RL} is the A.F. voltage across R_L
ΔI_P is the changing current through the plate circuit
X_L is the inductive reactance of the primary

There are several characteristics of a transformer-coupled amplifier which place it at an advantage or a disadvantage with respect to the other methods of coupling. These characteristics will be discussed in conjunction with those of other amplifiers in a subsequent section of this lesson.

4. RESISTANCE-CAPACITY COUPLED AMPLIFIERS. This type of A.F. amplifier has a theoretical operation somewhat different from that of the transformer-coupled type. The coupling device consists of two resistors and a condenser. The resistance-capacity arrangement serves to transfer the A.F. voltage from the output of one stage into the grid circuit of the succeeding stage and, at the same time, isolate the respective plate and grid circuits. The necessary circuit connections for a two-stage resistance-capacity coupled amplifier are shown in Fig. 7. In a resistance-capacity coupled amplifier, there is no step-up in voltage from the plate circuit of V_1 to the grid circuit of V_2 as was secured when a transformer was used. For this reason, all of the voltage gain secured in a resistance-capacity coupled amplifier must be produced by the tubes themselves.

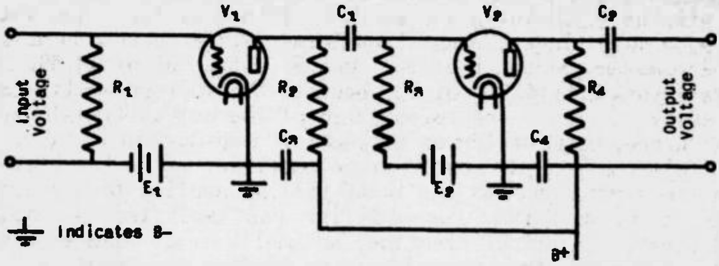


Fig.7 Two-stage resistance-coupled A.F. amplifier.

The theoretical operation of a resistance-capacity coupled amplifier may be explained as follows. When an A.F. voltage is applied across the input terminals (refer to Fig. 7), this voltage will cause a corresponding A.F. current to flow through resistance R_1, thus developing A.F. voltages across it. These audio voltages are in series between the negative terminal of the grid biasing battery E_1 and the grid of V_1; hence, the instantaneous grid potential will be made alternately more and less negative by the A.F. voltages. This application of an A.F. voltage to the grid of the tube will result in the development of A.F. voltages across the tube's plate circuit from plate to cathode. The path for the A.F. currents generated in the plate circuit will be through R_2 and C_3. The value of the A.F. voltages developed across the plate resistance R_2 relative to the input A.F. voltage developed across grid resistance R_1 is the amount of voltage amplification produced by V_1.

The amplitude of the voltage variations produced across the plate resistance R_2 will be equal to the product of the changing signal current through the plate circuit and the size of R_2 in ohms. Therefore, to secure high voltage variations across R_2, it is desirable to have the current changes high in amplitude and to use a value for R_2 as high as possible. From preceding discussions, it is apparent that it will be impossible to secure an exceedingly high amplitude of plate current changes when R_2 has a high value, because an increase in R_2 tends to reduce the amplitude of the plate current changes by inserting additional opposition in their path. (Refer to formula [2].) Another factor entering into the selection of the size of R_2 is the amount of B supply voltage available. When no signal voltage is being applied to the grid of the tube, it is necessary for the normal DC plate current to pass through R_2 to complete its circuit. The DC voltage drop across R_2 subtracts from the plate voltage of the tube as measured from plate to cathode. Increasing the size of R_2 with the plate supply voltage remaining the same tends to decrease the plate voltage. If the static plate voltage applied to the tube is not of the proper value, it will be impossible to secure satisfactory dynamic operation from it. Ordinarily, the size of R_2 depends upon the type of tube being employed. For a three-element tube, R_2 will generally have a value from 30,000 to 50,000 ohms. When tubes employing more elements are used for A.F. amplification, such as screen-grid and pentode tubes, the value for R_2 may be as high as 500,000 ohms.

The A.F. voltage variations produced across the plate resistance R_2 are available for grid excitation to the following tube. The by-pass condenser C_3 is always made sufficiently high in capacity so that its reactance to the A.F. currents will be negligible. The alternating signal voltage developed across R_2 is imparted to the grid of V_2 through the coupling condenser C_1. Since the A.F. signal is being transferred through C_1, its value in microfarads must be sufficiently high so that its reactance to the low audio frequencies will be as low as practical. If the size of this condenser is not selected carefully when designing the amplifier, the low audio frequencies will not be amplified to the same extent as the higher audio frequencies.

The A.F. current effectively passing through coupling condenser C_1 develops A.F. voltages across the grid resistance R_3. Since these A.F. voltages are in series between the negative side of the grid battery E_2 and the grid of the tube, the instantaneous grid potential of V_2 will be made alternately more and less negative. This alternating signal potential on the grid will create corresponding changes through the plate circuit of V_2. The plate current changes through V_2 produce varying voltage drops across the plate resistance R_4 in direct accordance with the current changes. These varying voltage drops are, in turn, transferred through the coupling condenser C_2 to the output terminals of the resistance-capacity coupled amplifier.

From the foregoing description, it is evident that the selection of proper values for the components of the coupling circuit, R_2, C_1 and R_3 is of great importance. R_2 must be selected from the standpoint of both voltage amplification and the available plate supply voltage. (The same statement pertains to R_4.) The capacity of the coupling condenser C_1 must be large so as not to cause a loss of the low audio frequencies when its reactance becomes high. Its reactance should be low at the lowest audio frequency to be amplified. There are limitations, however, on increasing the size of condenser C_1. The most important is that due to the amount of leakage current which would result from the use of a high capacity condenser.

A slight amount of leakage current through C_1 will upset the operation of the amplifier entirely. This leakage current would pass through the grid resistor R_3 and develop a voltage across R_3 opposite to the voltage of the biasing battery E_2. This decreases the negative bias applied to the grid, causes improper operation, possibly a flow of grid current, abnormally high plate current and probable damage to numerous components throughout the circuit.

If the size of grid resistance R_3 is made high in comparison to the size of R_2, the capacity of C_1 need not be made so great in order to secure good low-frequency amplification. R_3 is commonly known as the "grid leak" because it performs a function similar to the grid leak in a grid-leak detector circuit. Electrons which may be accumulated on the grid of the tube when the signal voltage drives the grid to near zero potential must be allowed to leak out of the grid circuit through resistance R_3. For this reason, R_3 cannot be made excessively high because the grid will become blocked, resulting in a general instability of the entire amplifier. Generally, R_3 is between 100,000 and 1,000,000 ohms. If this value of grid-leak resistance is used, the capacity of the coupling condenser is from .01 to .25 mfd.

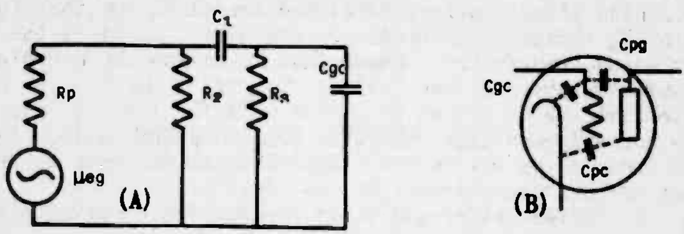


Fig.8 (Left) Equivalent electrical circuit for the plate circuit of a resistance-coupled A.F. amplifier.
(Right) Symbolic diagram to illustrate interelectrode capacities in a three-element tube.

The diagram shown at A, Fig. 8, illustrates the equivalent electrical circuit for a resistance-capacity coupled amplifier. The A.F. voltage generated by the vacuum tube is represented by the symbol marked μE_G, the plate resistance of the tube by R_P, the plate-coupling resistance by R_2, the coupling condenser by C_1 and the grid-leak resistance by R_3. When representing the equivalent circuit for this type of amplifier, it is also necessary to consider that capacity which is effectively across the grid leak resistance from grid to cathode inside of the tube. At A, Fig. 8, this interelectrode capacity of the tube is represented by the condenser C_{gc}. This is called the input capacity of the tube because it is directly across the input or grid circuit. There is, likewise, a similar capacity effect between each of the three elements within the tube, such as shown at B, Fig. 8. A more detailed discussion concerning the effects of these interelectrode capacities on the operation of a vacuum tube as an amplifier will be contained in Lesson 24. This interelectrode capacity between grid and cathode will not affect the low audio-frequency amplification; however, the high audio frequencies are apt to suffer considerable attenuation[1] due to its presence.

From the equivalent electrical circuit shown at A, Fig. 8, it is quite apparent that the grid-leak resistance R_3 is in parallel with the plate resistance R_2, neglecting the small capacitive reactance of the coupling condenser C_1. Since two resistors in paral-

[1] "Attenuation" means a reduction, or loss.

lel will have an effective resistance less than the value of the smallest, R_3 must be comparatively high in value to prevent a serious reduction of the load into which the tube is working. The actual load on the tube consists of not only R_2, but also R_3, so both of these resistors must be considered when determining the number of ohms into which the vacuum tube is working. If C_1 is sufficiently high in capacity, it can be seen that the same A.F. voltages will be developed across R_3 as are developed across R_2, because they form a parallel circuit. The audio voltages developed across R_3 in turn serve as grid excitation for the following amplifier tube.

The selection of the values for the components of the coupling circuit in a resistance-capacity coupled amplifier has quite an effect on the stability, voltage amplification and the possible frequency range of audio amplification. These will be discussed in a subsequent paragraph where a comparison is made between all types of audio-frequency amplifiers.

5. **IMPEDANCE-CAPACITY COUPLED AUDIO-FREQUENCY AMPLIFIERS.** The theoretical operation of an impedance-coupled A.F. amplifier is practically the same as that of the resistance-capacity coupled type, the only major difference being the manner in which the A.F. voltage drops are secured in the plate circuit.

The circuit diagram of a typical impedance-capacity coupled amplifier is shown in Fig. 9. It will be noticed that this circuit is the same as that in Fig. 7 with the exception that the plate résistances R_2 and R_4 have been replaced by the inductances L_1 and L_2 respectively. The use of an inductance as the plate load impedance prevents a high DC voltage drop due to the normal no-signal DC plate current. This eliminates the necessity for using a high B supply voltage to obtain plate voltage for the tube.

In Fig. 9, the input A.F. voltage will develop a corresponding potential difference between grid and cathode of V_1 by the voltages it produces across the input resistance R_1. The audio frequency voltages applied to the grid of V_1 generate corresponding A.F. currents in the plate circuit which pass through L_1 and C_3. As these A.F. currents flow through the inductance L_1, varying voltage drops are developed across it due to its inductive reactance. The A.F. voltage variations across L_1 divided by the input voltage across R_1 is the voltage amplification secured through the first stage of the impedance-coupled amplifier.

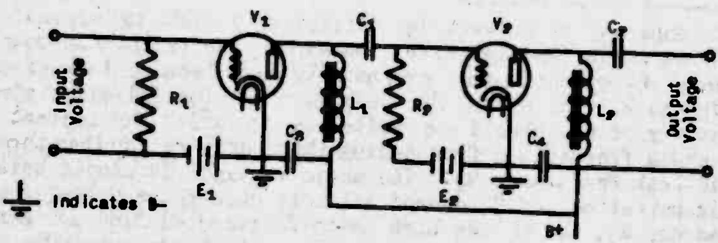


Fig.9 Two-stage impedance-coupled A.F. amplifier.

When a pure DC current passes through the inductance L_1, the voltage drop across it will be due only to its DC or ohmic resistance. The changing A.F. current in the plate circuit, however, generated by the action of the tube, will encounter not only ohmic resistance, but also inductive reactance. Ohmic resistance and reactance combined is called impedance; hence, the plate coil is often called an "impedance coil". From this, the name of the amplifier has been derived.

The varying voltage drops produced across L_1 are due entirely to the A.F. component of the plate current. These voltage drops will be equal in magnitude to the changing currents in the plate circuit times the impedance of L_1. This is expressed in the following formula:

$$\Delta E_L = \Delta I_P \times Z$$

Where:
- ΔE_L is the varying voltages across the impedance coil L_1
- ΔI_P is the changing current flowing through the plate circuit (refer to formula [2])
- Z is the impedance of the coil L_1 (neglecting the parallel effect of R_2)

The equivalent electrical plate circuit for an impedance coupled amplifier is shown in Fig. 10. Comparison with Fig. 8 reveals that the only difference between the impedance and the resistance-coupled amplifier is the use of an inductance instead of a resistance as the plate load. The function of the coupling condenser C_1, the grid-leak resistance R_2 and the effect of the interelectrode capacity from grid to cathode is the same in the impedance-coupled circuit as in resistance coupling. Again, it must be remembered that the grid-leak resistance R_2 is in parallel with the impedance of L_1; hence, the actual load into which the tube is working depends upon the effective impedance of this parallel circuit. As long as the resistance of the grid-leak R_2 is made sufficiently high, its shunting (parallel) effect toward decreasing the actual plate load can be neglected.

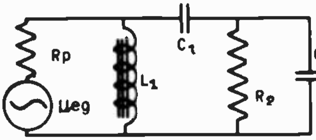


Fig.10 Equivalent electrical circuit for the plate circuit of an impedance-coupled amplifier.

The capacity of C_1 must be sufficiently high to prevent the loss of low audio frequencies the same as in the resistance-coupled amplifier. C_1 cannot be made excessively high because leakage current through R_2 will upset the operation of the following stage. The capacity of C_{gc} should be quite low in order to prevent the higher audio frequencies from taking this path, rather than through the grid-leak resistance R_2. The audio voltages developed between the grid and cathode of V_2 depend entirely upon those voltages produced across R_2; so if the high audio frequencies find an easier path (lower reactance) through the interelectrode capacity from grid to cathode, they will not pass through and develop voltages across R_2; hence, will be lost and will not be present in the output of the amplifier. This is an example of "frequency distortion".

Actual tests have shown that an average impedance-coupled amplifier will give a voltage gain slightly higher than a resistance coupled amplifier. This is due to the higher load impedance (R_L) offered by the inductance coil L_1, because of its high inductive reactance to the A.F. signal current. The inductance of L_1 is generally around 200 or 300 henries. Inductance values this high can be obtained by winding thousands of turns of fine wire on a well-designed iron core. It is not necessary for the wire on the coil to carry much DC plate current (plate current in a voltage amplifier is generally quite low); hence, small wire may be used. By calculating the inductive reactance of a 200-henry coil to an average audio frequency, say 1,000 cycles, it is found that the load impedance is much greater than could be economically inserted in a resistance-coupled A.F. amplifier.

Additional information on the stability, voltage amplification and frequency response of an impedance-coupled amplifier will be given later.

6. **DIRECT-COUPLED AMPLIFIERS.** The direct-coupled A.F. amplifier is often called the Loftin-White amplifier, in honor of E. H. Loftin and S. Y. White, who adapted this system for practical AC operation. A fundamental circuit diagram illustrating this method of coupling A.F. amplifiers is shown in Fig. 11. In the diagram, batteries are being used for plate and grid bias supply; however, if a vacuum tube rectifier circuit with a sufficiently high voltage output is available, both plate and bias voltages may be secured from it.

In the direct-coupled system, the plate of the first stage is connected directly to the grid of the next, with the coupling resistance R_2 common to both circuits. At first glance, this may appear somewhat unconventional, but, by tracing the path of the DC plate current through the entire circuit, it can be seen that the plate voltage for V_1 and the grid bias voltage for V_2 are applied in the proper manner. Starting from the negative terminal of the 500-volt plate supply battery, the DC plate current flows from the cathode to the plate of V_1. Upon passing through the plate resistance of V_1, a voltage drop is produced, this voltage drop being measured by M_3. Assuming that this drop is 200 volts, the plate voltage on V_1 from plate to cathode will be 200 volts. From the plate of V_1, the DC plate current passes through the coupling resistance R_2 from

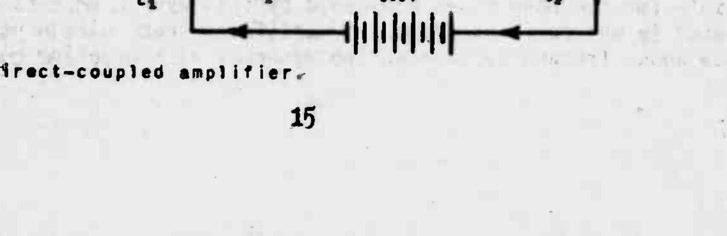


Fig.11 Direct-coupled amplifier.

3 to 4. Passing through this resistance, a voltage drop is produced with 3 negative and 4 positive. Let us assume that this voltage drop is 50 volts as read on meter M_2. The grid of V_2 is connected to point 3 and the cathode of V_2 is connected to point 4. Since point 3 is negative with respect to point 4, this means that V_2 will have 50 volts negative bias applied to its grid. From point 4, the DC plate current flows to the cathode of V_2, then through the plate resistance of the tube to point 6. Upon passing from cathode to plate through V_2, let us assume that the voltage drop produced is 250 volts; hence, the plate voltage as measured by M_1 will be 250 volts. From point 6, the DC plate current flows through the primary of the output transformer, then back to the positive terminal of the battery.

Careful consideration of this DC circuit will reveal that the supply battery is furnishing plate voltage to V_1 and V_2 and is also furnishing the negative grid bias on V_2. Adding the voltage drops produced across the three main parts of the circuit, they will be found to equal the plate supply voltage. The three main resistances consist of the plate resistance of V_1, the coupling resistance R_2 and the plate resistance of V_2. As indicated in Fig. 11, there is a 200-volt drop across V_1, 50 volts across R_2 and 250 volts across V_2. The sum of these three voltages equals the supply voltage.

The theoretical operation of the direct-coupled amplifier is as follows: The input A.F. voltage developed across R_1 will cause the instantaneous grid potential of V_1 to be varied accordingly. As the potential of the grid is made alternately more and less negative, corresponding plate current changes will be created. These plate current changes, as generated by the action of the tube, will pass through the resistance R_2 and the by-pass condenser C_1 in returning back to the cathode. As the A.F. current changes pass through R_2, corresponding voltage variations will be developed across it. These voltage variations are directly in series between the grid and cathode of V_2; hence, the instantaneous grid potential of V_2 will change in exact accordance with the voltage variations across R_2. As the grid of V_2 is changed in potential with respect to its cathode, the plate current will be varied. The A.F. plate current changes through the plate circuit of V_2 will pass through the primary of the output transformer and through the capacity C_2 back to the cathode. As the A.F. currents pass through the primary, a corresponding magnetic field will be established around the primary which induces the output A.F. voltage in the secondary. The purpose of C_2 is to offer a path of low opposition to the generated current changes for their return to the cathode of the tube.

From the foregoing explanation, it is apparent that the voltage variations developed across R_2 are common to both the plate circuit of V_1 and the grid circuit of V_2. This single resistance is therefore serving as the coupling circuit. The simplicity of a single resistance serving as the coupling device is largely responsible for the advantages possessed by this type of amplifier. Compared to the resistance-coupled amplifier, there will be no loss of low audio frequencies due to the presence of a coupling condenser;

the grid-leak resistance necessary in the coupling circuit of a resistance-coupled amplifier is also eliminated, so the shunting effect of the grid leak on the plate load resistance is absent. In Fig. 11, R_2 constitutes the entire load resistance into which the vacuum tube V_1 is working.

One defect present in the direct-coupled amplifier which is also true of the resistance-coupled type is that the grid-to-cathode capacity is in parallel with the A.F. voltage output of the preceding tube. This is shown in Fig. 12 by the equivalent electrical circuit representing the plate circuit of a direct-coupled audio amplifier. In Fig. 12, it can be seen that R_2 is the only load on the vacuum tube generator V_1 except the grid-to-cathode capacity of V_2. The shunting effect of this small capacity is negligible except at the higher audio frequencies.

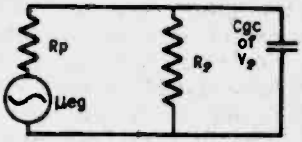


Fig.12 Equivalent electrical circuit for the plate circuit of a direct-coupled amplifier.

Considering the simplicity of construction and the exceptionally good low-frequency response possible from a direct-coupled circuit, it is rather surprising that this type of amplifier has not come into more common usage. The main objection, however, is the necessity for such a high plate supply voltage. In a two-stage amplifier, the voltage source must produce sufficient DC potential to supply plate voltage to the two tubes and grid bias for the second stage. This requires a supply of at least 400 to 500 volts; often higher. These voltages cannot ordinarily be secured from the smaller power supplies as used in radio receivers.

It is possible to secure a higher voltage gain from a two-stage direct coupled A.F. amplifier than from a two-stage resistance-coupled A.F. amplifier. The absence of a complicated coupling circuit is largely responsible for the higher efficiency of the direct-coupled amplifier in this respect. In most commercial circuits, a screen grid (four-element) vacuum tube is used as the first stage in a direct-coupled amplifier.

As well as the necessity for employing a high plate supply voltage, it is also necessary to use a separate filament transformer for the second tube unless it is of the indirectly heated cathode type. The addition of this extra winding means additional expense in commercial production. Another point against the direct coupled amplifier is the difficulty in adjustment. To secure the correct distribution of voltage in the plate circuits of the two tubes and in the grid circuit of the second tube, it is necessary that care be exercised in the selection of tubes as well as the size of the coupling resistance. The size of the coupling resistance is very critical and under no circumstances should it be changed when servicing an amplifier circuit which was known to give satisfactory operation.

A direct-coupled amplifier is sometimes called a "direct current amplifier" because it is capable of amplifying a DC as well as an AC input signal voltage. While these amplifiers are not extremely important for use in radio receivers, they are very popular for public address systems and in amplifiers for television work. We shall not discuss the use of this amplifier in television circuits at the present time; however, the student should bear in mind that it will be of great importance in future study.

7. **FREQUENCY RESPONSE OF AUDIO AMPLIFIERS.** A perfect audio frequency amplifier is one which gives the same amplification to all audio frequencies applied to its input and does not produce any distortion of the original waveform. This means that when a frequency of 16 cycles, 100 cycles, 1,000 cycles, 10,000 cycles, 16,000 cycles, or any intermediate frequency is fed to the input of the amplifier, it will amplify each of these frequencies the same amount and the output waveform will be exactly the same as the input waveform except that it is higher in amplitude.

So far it has been practically impossible to construct a perfect A.F. amplifier such as the one just mentioned. All methods of A.F. amplification will produce some waveform distortion and will amplify some frequencies to a greater extent than others.

A graph which shows the relative degree of amplification at different frequencies is known as the "frequency response curve" of an amplifier. For example, let us refer to the frequency response curve shown in Fig. 13. This graph shows four curves, illustrating the frequency response of typical transformer, impedance resistance and direct-coupled A.F. amplifiers. Inspecting the curve for a transformer-coupled amplifier, it can be seen that the amplification is approximately 4 when a frequency of 10 cycles per second is fed to the input. Without changing any part of the amplifier circuit, if a frequency of 100 cycles is fed to the input, the amplification obtained is nearly six times greater. The maximum amplification obtained from a transformer-coupled amplifier is in the vicinity of 2,000 cycles, after which the response at higher frequencies falls off rapidly. At 15,000 cycles, the voltage amplification through the transformer-coupled amplifier is zero. This means that an A.F. signal of this frequency will not appear

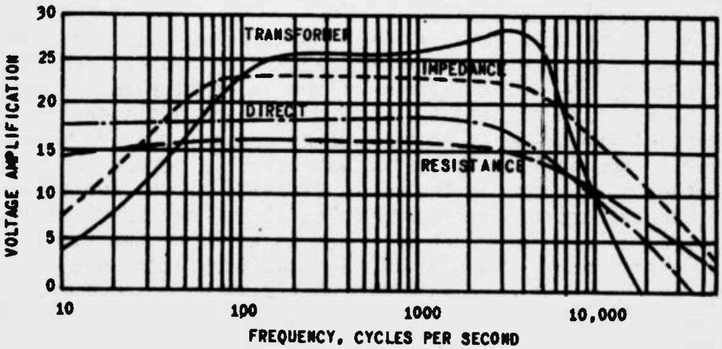


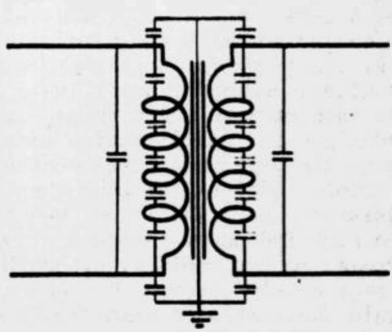
Fig.13 Curves illustrating the variation in amplification with frequency of typical transformer, impedance, resistance and direct-coupled amplifiers.

in the output even though it is applied to the input with the same strength as the other frequencies.

There are various reasons why a transformer-coupled amplifier will not amplify all audio frequencies to the same degree. At the lower frequencies, the decreased amplification is due mainly to the decreased load on the tube. The load (R_L) into which a tube employed in a transformer-coupled amplifier is working consists of the impedance of the transformer primary winding. Since the impedance increases as the frequency increases and decreases as the frequency decreases, it is apparent that at the lower audio frequencies, the value of the load impedance (R_L) will be quite low. Reference to formula (9) shows that the voltage amplification is decreased considerably when the tube is working into a small load impedance.

In Fig. 13, it is also noticed that the voltage amplification in a transformer-coupled amplifier decreases considerably at the higher audio frequencies. This can be accounted for by reference to Fig. 14. The individual turns on the primary and secondary windings are conductors and are separated from each other by an insulating material; hence, they form a multitude of very small condensers. Each turn possesses a small condenser effect with all those turns surrounding it. This capacity effect formed by each turn adds to that formed by all the other turns on the winding, resulting in a relatively high capacity which is, in effect, across the entire winding. This is true of both the primary and secondary. Likewise, each of these windings has an effective capacity to the iron core and since the iron core of the transformer is generally grounded, this means that there is a capacity between the transformer windings and ground. There is also a small capacity effect directly between the primary and secondary windings which serves to influence the operation of the amplifier. Obviously, the more turns on the primary and the more turns on the secondary, the greater this overall "distributed capacity" will be.

Fig.14 Illustrating the distributed capacity in a two-winding iron-core transformer.



At the lower audio frequencies, the reactance of the transformer's distributed capacity is sufficiently high that the voltage amplification of the amplifier is not altered to an appreciable extent. However, in the region of higher audio frequencies, the reactance of this distributed capacity becomes sufficiently low that a large portion of the signal voltage will be by-passed through the capacity effect rather than passing through the primary winding of the transformer. In effect, the distributed capacity of the primary is "short circuiting" the inductive reactance load on the tube because the reactance of the distributed capacity is low in comparison to the primary's high inductive reactance. Thus, the load impedance into which the tube is working (R_L) becomes decreased to a very low value and the A.F. voltage developed across the secondary terminals decreases as the input frequency is raised.

The frequency response curve for a typical resistance-coupled amplifier, as shown in Fig. 13, is a great improvement over the transformer-coupled method. The low audio frequencies are amplified practically the same as all other frequencies up to approximately 4,000 cycles. To obtain this good low-frequency amplification, it is necessary to use the proper size coupling condenser and the correct value for the grid-leak resistance as explained in a previous portion of this lesson. The high-frequency response of a resistance-coupled amplifier is affected mostly by the grid to cathode interelectrode capacity of the tube. The by-passing effect of the tube's interelectrode capacity is similar to that caused by the distributed transformer capacity. Since internal tube capacities are generally quite low, the frequency response is not affected to any great extent except at the extremely high end of the audio-frequency spectrum. The tube's capacity between plate and cathode will also be responsible for decreased high-frequency amplification to a certain extent. This plate-to-cathode capacity is of no outstanding importance unless it is desired to obtain an exceptionally good high-frequency response from the amplifier. All of the interelectrode capacities for the various tubes are given in the manufacturer's tube manual.

The impedance-coupled amplifier possesses a frequency response curve somewhat intermediate between the resistance and transformer-coupled type. Its response is better than the transformer-coupled type near the low-frequency end of the audio range. This is due to the higher inductance of the impedance coil used for the plate load in comparison with the permissible primary inductance of an average A.F. transformer. The higher load at the lower frequencies naturally results in a greater amplification of these frequencies. Throughout the intermediate audio range the impedance-coupled amplifier produces greater amplification than the resistance-coupled type, because the high inductive reactance of the impedance coil supplies a greater load on the tube than the highest value of plate coupling resistance permissible to use in a resistance-coupled amplifier. The high-frequency response of an impedance-coupled amplifier decreases rather rapidly, although not quite so much as the transformer-coupled type. The decrease in high-frequency response is again due mostly to distributed capacity in the inductive winding. The grid-to-cathode capacity of the following tube will also be effective in reducing the high-frequency response. Even though there are many more turns on an impedance coil than on the primary of an average A.F. transformer, the distributed capacity will generally be less, because smaller wire is used on the impedance winding. Then, too, there is only one winding on the impedance coil, whereas a transformer has two windings, each of which has distributed capacity.

From Fig. 13, it can be seen that the low-frequency response of a direct-coupled amplifier is practically perfect, at least being much better than any of the other three types. The gradual decrease in voltage amplification toward the higher frequencies is due to:

(1) The distributed capacity throughout the amplifier circuit.
(2) The plate-to-cathode capacity of the first tube.
(3) The interelectrode capacity between the grid and cathode of the second tube.
(4) The capacity between the cathode of the second tube and ground.
(5) The small capacities due to the wiring.

Comparison of the typical curves reveals that for best overall (low and high) frequency response, the resistance-coupled amplifier surpasses all others. If an exceptionally good low-frequency response is desired, the direct-coupled amplifier is best; and for maximum response throughout the intermediate range of audio frequencies, the transformer-coupled amplifier surpasses all others.

Fig. 13 can also be used to illustrate the relative amplification secured from each type of amplifier, considering an equivalent number of stages. Due to the step-up in voltage secured through the coupling transformers, the voltage amplification produced by a transformer-coupled amplifier is much greater than that of any other type. The impedance-coupled amplifier gives higher amplification throughout the intermediate audio - frequency range than a direct or resistance-coupled type. The resistance-coupled amplifier is the least efficient insofar as voltage amplification per stage is concerned, this being due mostly to the limited size permitted for the plate-coupling resistance and the shunting effect on the plate load by the grid-leak resistance in the grid circuit of the next stage. The exceptionally good overall frequency response and the relatively low cost of construction are the outstanding characteristics of a resistance-coupled amplifier and are responsible for its popular use in modern audio amplifiers.

8. WAVEFORM OR HARMONIC DISTORTION IN A.F. AMPLIFIERS. In Lesson 12, it was stated that an A.F. amplifier tube must be operated on the straight portion of its grid voltage - plate current characteristic curve. The importance of this fact necessitates additional discussion at this time.

If the waveform of the plate current changes (or the voltages across the plate load impedance) does not coincide with the waveform of the input voltage applied to the grid circuit, it is said that *distortion* has been introduced. This distortion may result from a number of sources, the most important of which are those pertaining to improper operation of the tube. Improper conditions under which the tube may be operated to cause a distortion of the plate current waveform are:

1. Insufficient grid bias
2. Excessive grid bias
3. Input signal too strong
4. Dynamic E_g-I_p characteristic not linear due to insufficient load impedance

Waveform distortion is often called "amplitude" or "harmonic" distortion. The justification for the expression "harmonic distortion" may be easily shown by considering the combination of a fundamental frequency and one of its harmonics as shown in Fig. 15. At A, a pure sine wave represents one cycle of an alternating current having a certain frequency; and at B, two cycles of an alternating current having a frequency twice as great are illustrated. For example, assume that the frequency at A is 1 cycle per second and at B the frequency is 2 cycles per second. *A harmonic frequency is defined as one having a frequency which is an exact multiple of a given frequency.* Since the frequency of B is exactly twice that of A, B is called the "second harmonic" of A. The third harmonic of A would be an alternating current having a frequency of 3 c.p.s., the fourth harmonic would be a frequency of 4 c.p.s., etc.

If the second harmonic as shown at B is combined with the fundamental frequency, A, the waveform of the resultant voltage will not be a pure sine wave. This is illustrated graphically at C in Fig. 15. At C, the fundamental frequency A and the second harmonic B are combined by adding the instantaneous values. The resultant wave C is obtained. This resultant waveform is shown separately at D in Fig. 15. By this graphical method of wave combination, it can be seen that when the second harmonic is combined with the fundamental frequency (both frequencies pure sine waves), the waveform of the resultant will not be a pure sine wave. In other words, the waveform will be distorted.

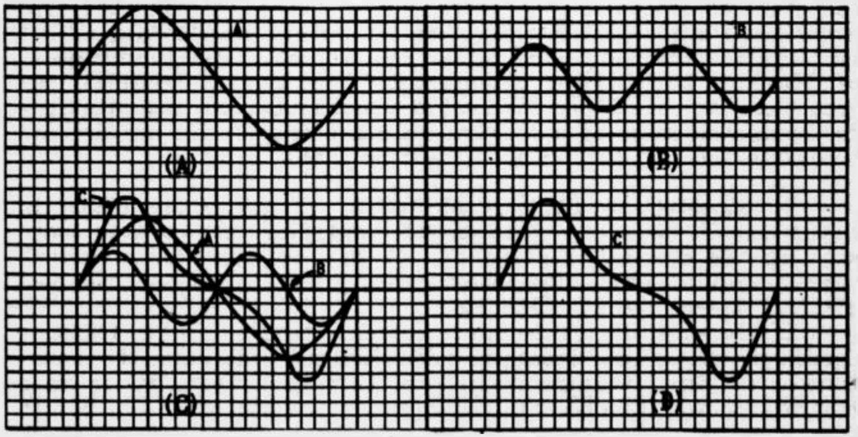


Fig.15 Curves to illustrate that a distorted waveform consists of a combined fundamental and harmonic frequency. In this case, the second harmonic (B) is combined with the fundamental (A) to obtain the distorted waveform (D).

The preceding example illustrates the combination of the second harmonic with the fundamental. If the third harmonic were combined with the fundamental, the fourth harmonic, or any higher harmonic, the waveform of the resultant curve would be considerably different from that shown at D in Fig. 15, but in all cases it would be far removed from a pure sine wave.

The resultant waveform becomes quite complicated when the fundamental is combined with its second, third, fourth, etc., harmonic frequencies. It is virtually impossible to graphically illustrate the combination of several harmonics with the fundamental to any degree of satisfaction. In all cases, however, *whenever one or more harmonic frequencies are combined with the fundamental frequency, a distorted waveform will result.*

It is also true that *any distorted waveform consists of a fundamental frequency combined with one or more harmonic frequencies, all of which are pure sine waves.* Thus, if a pure sine wave, such as shown at A in Fig. 15 were applied to the grid circuit of a vacuum tube and the waveform of the plate current changes appeared as shown at D in Fig. 15, it would be apparent that second harmonic frequencies were generated during the process of signal amplification.

If third harmonics were generated (due to improper operation), the waveform of the plate current change would be considerably different from that shown at D. If fourth harmonics were generated, the plate current would appear entirely different, etc. Regardless of what waveform the plate current changes may have and assuming that the input voltage applied to the grid circuit is a pure sine wave, the distorted waveform of the plate current changes can be considered to consist of the pure sine wave fundamental frequency and one or more sine wave harmonic frequencies, all combined together. An attempt will not be made to illustrate by diagram the exact appearance of a resultant waveform when more than one harmonic frequency is involved; however, it should be understood that any distorted waveform can be resolved into its component frequencies by this method.[1]

Various tube operating conditions which tend to cause waveform distortion are illustrated in Fig. 16. The diagram at A illustrates the tube's operation when the grid bias voltage and the plate voltage are too low. The operating point is high up on the static characteristic curve and when the grid signal voltage is applied, it is impossible for the plate current to properly increase above its normal value due to the curve at the upper end of the E_g–I_p characteristic on the negative alternation of the grid signal; however, the plate current decrease will be normal because the tube is operating over a fairly straight portion of the characteristic.

The effect of increasing the negative bias to an abnormally high value is shown at B in Fig. 16. In this case, the plate current will increase properly above its normal value when the grid is made less negative, but on the negative alternation of the grid signal, the plate current will not decrease in the proper manner due to the

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[1] Additional information on harmonics is contained in Lesson 26, Unit 1.

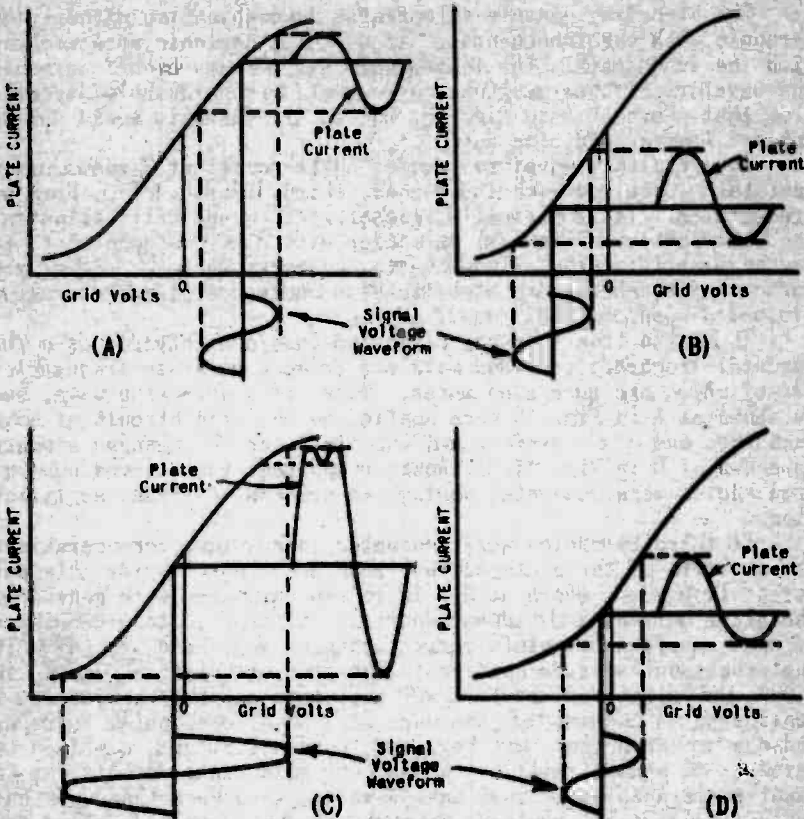


Fig.16 Illustrating improper vacuum tube operation
(A) Insufficient bias.
(B) Excessive bias.
(C) Excessive input signal.
(D) Insufficient plate load impedance.

curvature of the characteristic in this region. The resultant plate current changes indicate that the positive alternation of the output voltage from the amplifier will be of a higher amplitude than the negative alternation. This is the condition under which a grid bias detector is operated in order to secure rectification.

If the input signal voltage applied to the grid circuit is entirely too strong, the waveform of the resultant plate current changes will appear as shown at C, Fig. 15. On the positive alternation of the signal voltage, the plate current is driven into the upper curved region of its E_g-I_p characteristic and on the negative alternation, the plate current is driven down into the lower bend. During the time that the signal voltage is driving the grid potential positive, there will also be a flow of grid current through the grid circuit. As this grid current flows through the resistance or inductance contained in the grid circuit, it will produce a voltage drop in a direction opposite to the signal voltage, thus causing the actual voltage on the grid of the tube to be considerably different from the original applied voltage. For this reason, *grid current should never be allowed to flow in any voltage amplifier circuit.* The flow of grid current is prevented by applying the proper grid bias, then controlling the input signal voltage to make certain that it does not become excessive. If the input signal is too strong, it is called "overloading" the grid circuit.

The effect on the plate current waveform when insufficient load impedance is contained in the plate circuit is shown at D in Fig. 16.

Increasing the size of the load impedance in the plate circuit straightens out the dynamic E_g-I_p characteristic. Illustrations are shown in Fig. 17. These curves are typical of an amplifier tube when a pure resistance is contained in its plate circuit. The characteristic shown at A illustrates the appearance of the E_g-I_p curve when the load resistance in the plate circuit is zero. Notice that it is very curved. When the load impedance R_L is made equal to the plate resistance R_P of the tube, the characteristic approaches a straight line as shown by the curve B. Even a characteristic of this shape is not sufficient to entirely prevent the introduction of waveform distortion. To definitely assure that the plate current waveform will be similar to the grid signal waveform, *it is necessary that the load impedance R_L be equal to at least twice the plate resistance R_P of the tube.* The E_g-I_p characteristic becomes practically a straight line when R_L is equal to twice R_P. This is shown by curve C, Fig. 17. This means that if the plate resistance of the voltage amplifier tube is 10,000 ohms, the value of R_L should be at least 20,000 ohms to prevent waveform distortion.

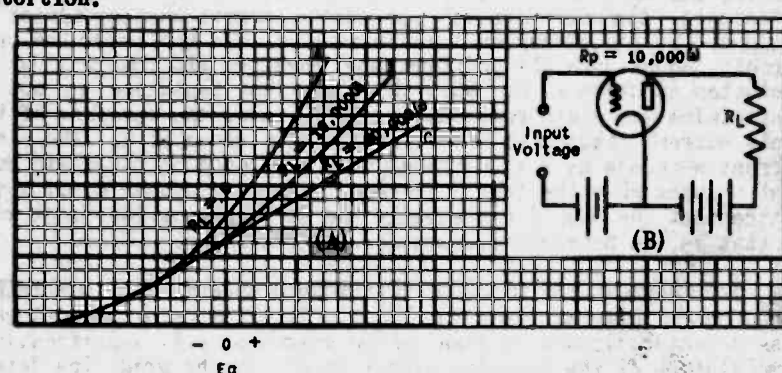


Fig.17 (A) Dynamic characteristics of a three-element tube, showing the effect of the load in the plate circuit upon the curvature of the characteristic.
(B) Typical triode vacuum tube circuit.

The load resistance is generally made higher, sometimes as much as five times the plate impedance of the tube. The use of a high plate load resistance assures that undistorted amplification will be obtained and that the voltage amplification of the stage will be high. The disadvantage of using such a large plate load

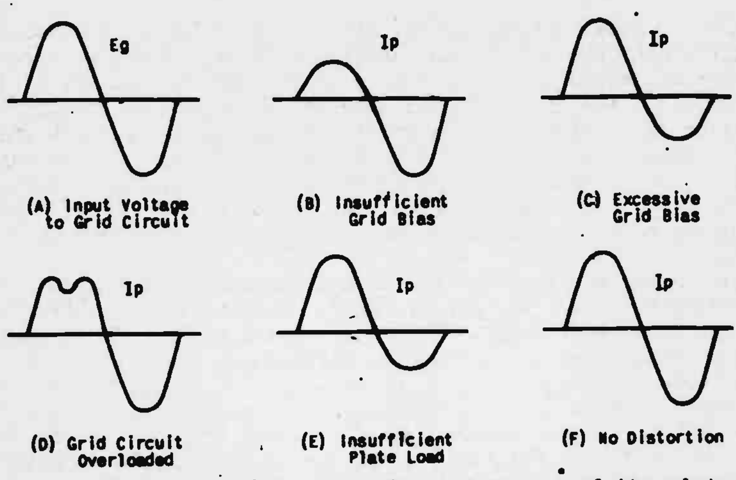


Fig.18 Diagrams to illustrate the appearance of the plate current variations when various forms of distortion exist.

resistance is the high B supply necessary to maintain the proper plate voltage.

The waveforms shown in Fig. 18 serve to summarize the foregoing information. At A, the pure sine wave voltage as applied to the grid circuit is shown. If insufficient bias is applied to the grid, the resultant waveform of the plate current changes will appear as shown at B. If the negative bias is made excessively high, causing the tube to operate on the lower bend of its E_g–I_p characteristic, the waveform of the plate current changes appear as shown at C. Too strong an input signal voltage applied to the grid circuit causes both the positive and negative alternations to be distorted as shown at D. When the plate load impedance is not at least twice the plate resistance of the tube, the waveform of the plate current changes will be distorted as shown at E. The plate current waveform at F illustrates the appearance of the plate current changes when the tube is operated under the proper conditions. Notice that the wave F has exactly the same shape as the input wave A; that is, no harmonic frequencies are generated.

9. CHARACTERISTICS OF A TRANSFORMER-COUPLED A.F. AMPLIFIER. The circuit diagram shown in Fig. 19 illustrates a typical grid bias detector circuit followed by two stages of A.F. amplification. Demodulation of the incoming signal occurs in the grid bias detector circuit and A.F. currents pass through the primary P_1 of the A.F. transformer T_1. The secondary voltage induced in S_1 excites the grid of V_2, which is the first A.F. amplifier. The A.F. output of V_2 is transformer-coupled into the grid circuit of V_3 which operates the loudspeaker. The last stage in an A.F. amplifier is commonly called the "power stage" and the tube employed in this stage is known as a power tube. Power tubes possess different characteristics than voltage amplifier tubes and Lesson 28 will be devoted to a detailed study of power amplifier circuits.

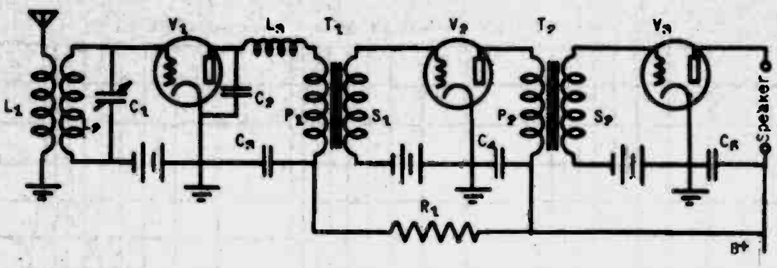


Fig.19 Grid-bias detector followed by a two-stage transformer-coupled A.F. amplifier.

The resistance R_1 in series with the B plus output of the vacuum tube rectifier circuit serves to decrease the plate voltage on the detector so as to operate it under the proper conditions for grid bias detection. The voltage amplifier tube V_2 and the power amplifier tube V_3 both require a higher plate voltage than the detector stage, so no resistance is included in their plate circuits. The heater of each tube in this circuit may be connected across a secondary winding on the power transformer which supplies the proper voltage. The grid bias for each tube is being secured from a C battery. In the following lesson, it will be shown how grid bias may be secured by the use of a resistance in the cathode circuit of the tube instead of with a C battery.

The characteristics of the transformer used for inter-stage coupling in a transformer-coupled amplifier governs, to a large extent, the total voltage amplification secured and the frequency response of the amplifier circuit.

Curves 1, 2, 3, and 4 in Fig. 20 show the variation of amplification with frequency for several different types of transformers. Curve 1 is a graph showing the characteristics of a small audio transformer commonly used in radio receiving sets around 1926. Since the primary inductance of these transformers was only about 15 henries, the response of the amplifier decreased considerably at the low frequencies. The frequency response for larger transformers typical of the design a few years later is shown by curves 2 and 3. In these transformers, the primary inductance has been increased, thus giving a better low-frequency response. On each of the characteristic curves, it will be noticed that the voltage amplification rises to a high value in the neighborhood of 6,000 to 9,000 cycles. This high amplification is caused by resonance being established in the transformer windings, due to their inductance and distributed capacity. At the resonant frequency of the transformer primary, the plate circuit of the tube is working into a parallel tuned circuit. Since a tuned circuit of this type possesses a very high impedance at the resonant frequency, the result is an abnormal amplification of this frequency. These peaks are undesirable because when these frequencies are passed through the amplifier, they will be reproduced from the loud speaker with exceptionally loud volume. The height of the resonant peak may be materially reduced by increasing the secondary resistance. In modern transformers, this is done by winding the secondary coil with very small wire,

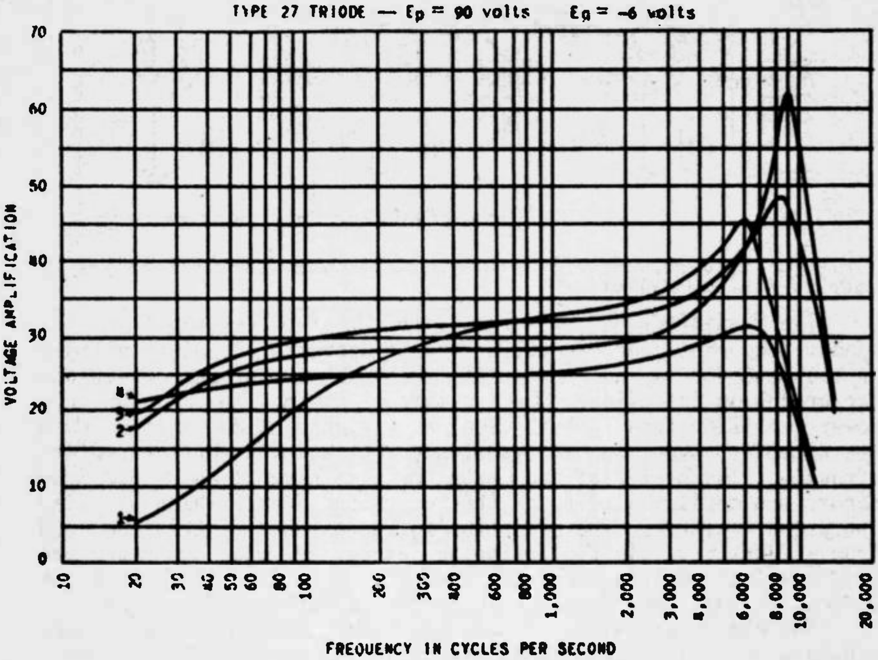


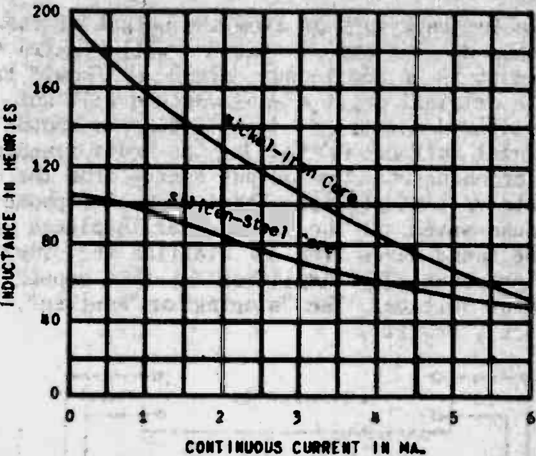
Fig.20 Voltage amplification per stage of a transformer-coupled amplifier for various types of transformers.

generally No. 40. Also, by connecting a high resistance of .5 to 1 megohm directly across the secondary winding, this resonant peak is effectively removed from the characteristic. A resistance across the secondary causes the overall voltage amplification to be less; however, the frequency response will be more constant over the entire audible range.

Curve 4 on Fig. 20 is representative of the modern design of good quality audio-frequency transformers. The primary inductance of modern transformers is made high by the use of an alloy core. When no DC current is passed through the primary winding, the average audio transformer has a primary inductance in the neighborhood of 150 henries. As the DC plate current passes through the primary, the inductance in henries is reduced. The curves shown in Fig. 21 illustrate the extent of this reduction for a transformer possessing a nickel-iron core and for a silicon-steel core. From Fig. 21, it is apparent that the DC plate current through the primary winding should be kept as low as possible in order to secure good low-frequency response from the amplifier. The use of a sizeable air gap in the iron core of the transformer is also effective in preventing the inductance reduction caused by the DC current.

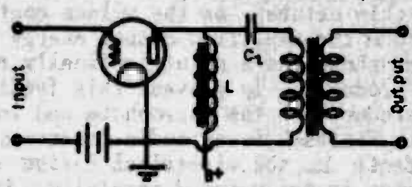
The undesirable effect of DC current through the primary may be avoided by the use of a circuit such as shown in Fig. 22. The

Fig.21 Variation in primary inductance from an audio-frequency transformer due to DC current through the primary.



DC current is supplied to the plate through the high inductance coil L; however, the A.F. current in the plate circuit takes the path through capacity C_1 and the primary of the transformer. This is commonly known as a "shunt feed plate circuit" because the AC signal current path is in parallel with the DC plate current path.

Fig.22 Transformer-coupled A.F. amplifier with shunt feed plate circuit.



In A.F. transformers, the size of the wire on the secondary is made as small as practical considerations will permit. Assuming the winding space and core size to be fixed, if it is desired to increase the turns ratio of the transformer, the only way in which this can be accomplished is to reduce the number of turns on the primary. This will reduce the primary inductance and impair the performance of the amplifier at low frequencies. A turns ratio from primary to secondary of greater than 1:4 is rather difficult to secure without some sacrifice in performance. For this reason, nearly all A.F. transformers have a turns ratio of about 1:3.

10. **FEEDBACK IN AUDIO AMPLIFIERS.** If a portion of the amplified output energy of a vacuum tube is fed back to the input circuit so as to reinforce the input voltage, the gain of the amplifier will be greatly increased. This is commonly known as "regeneration".[1] If the amount of feedback energy is sufficient, the amplifier will be capable of supplying its own input signal voltage. When in this condition, the original input signal voltage to the amplifier will no longer be amplified, but, rather, the effect of

---

[1] Regeneration is thoroughly discussed in Lesson 23, Unit 1.

the feedback voltage from the output of the amplifier will predominate to the extent that it will receive the amplification. The result is a continuous "sing" or "howl" from the loudspeaker and the original input signal voltage will not be heard. This can be readily demonstrated by the diagram shown in Fig. 23. The input signal voltage is fed to the audio-frequency amplifier from the microphone and the output energy from the amplifier is delivered into a loudspeaker. Since the microphone is responsive to all sound waves, if the loudspeaker is placed in such a position that the sound waves from it override the original sound waves at the microphone, the amplifier is then capable of supplying its own input voltage. The "singing" or "howling", commonly known as "feedback", results.

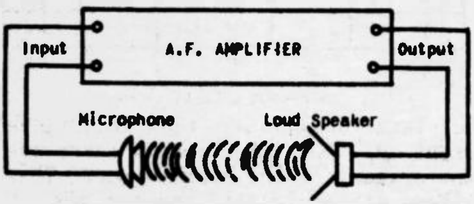


Fig.23 Block diagram to illustrate how the feedback of energy may occur from output to input in an A.F. amplifier.

Public address installations are often troubled with feedback of this nature. As the volume control of the amplifier is advanced, more of the amplified output energy from the loudspeaker enters the microphone and a point is finally reached where a continuous howl is produced. To prevent this feeding back, the gain control must be reduced or the microphone and loudspeaker relocated.

Feedback in an audio-frequency amplifier can also result from defects in the electrical design of the circuit. If the circuit design is not watched carefully, it is possible that some of the signal energy from the output stage of the amplifier will find its way to the input circuit in sufficient amounts so as to cause feedback. A resistance or impedance of any kind may be common to the input and output stages and cause this to occur. In A.F. amplifiers, the chief source of such common coupling is the plate supply voltage. Both sources of plate supply (batteries and vacuum tube rectifier circuits), possess a certain number of ohms of internal impedance. The signal current in each stage must pass through this internal impedance, and the resulting voltage drops produced at the output of the voltage supply source will be common to each plate circuit in the entire amplifier. Hence, it is possible for the plate voltage on the first stage of the amplifier to be varied in accordance to the current changes taking place in the final stage. This is the same as though a portion of the output energy were fed back to the input of the amplifier. If the feedback is sufficient in strength, the characteristic "howl" will result. If the feedback is too weak to produce a howl, serious frequency distortion will be produced and the loudspeaker reproduction is very unnatural.

In all audio amplifiers, it is necessary to take the essential precautions so as to prevent an instability of the circuit that would cause feedback. Fortunately, the transfer of energy from the plate circuit of the last tube to that of the first tube is usually all that need be considered since the differences in energy levels between any other pair of tubes is small compared with that between the first and last. Fig. 24 illustrates a method of stabilizing a transformer-coupled A.F. amplifier so as to minimize the unstable effects produced by common coupling through the plate supply voltage. Stabilization of the amplifier is accomplished by the use of the by-pass condenser C and the series resistance R in the plate circuit of each stage. The use of condenser C from the bottom of the primary winding to the cathode confines the varying signal cur-

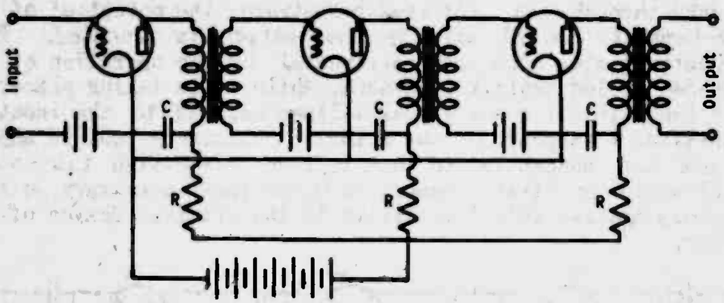


Fig.24 Three-stage transformer-coupled A.F. amplifier with plate circuit filters to prevent excessive feedback and instability.

rent in each stage to its own plate circuit; hence, it is not necessary for this changing signal current to pass through the common impedance of the plate voltage supply in order to return back to the cathode. These stabilizing condensers were shown in some of the previous diagrams in this lesson. The series resistors are generally not used unless the amplifier has an abnormal tendency toward instability. Their purpose is to prevent the signal current in the plate circuit from reaching the voltage supply and to compel the variations to return through the by-pass condenser C to the cathode. The size of resistance R is determined more or less by the size of the by-pass condenser. If the by-pass condenser C is very large (5 to 6 mfd.), the series resistance R can be made from 10,000 to 20,000 ohms. If, however, the size of the by-pass condenser is around .25 mfd., it is necessary to use a series resistor in the neighborhood of 100,000 to 250,000 ohms. The reason for this relationship between capacity and resistance is evident when we consider that the current changes will take the path of least opposition.

Impedance-coupled and resistance-coupled A.F. amplifiers have a similar tendency to become unstable due to an excessive feedback of energy, the same as the transformer-coupled type. An unstable impedance-coupled amplifier will produce the same "sing" or "howl" as a transformer-coupled amplifier when the feedback is excessive; a resistance-coupled amplifier, however, does not. In a resistance-coupled amplifier, feedback sufficient to cause instability manifests itself by "motorboating", a name given to it because of the similarity of sound produced in the loudspeaker to the exhaust of a motorboat. An unstable resistance-coupled amplifier supplies its own input voltage at the rate of about 1 c.p.s., the actual frequency being governed chiefly by the size of the grid-leak resistances and coupling condensers. The signal applied to the grid of one tube is amplified and fed back in the proper relationship so as to increase the strength of the original signal. This continues to increase in an abrupt fashion until one of the tubes in the amplifier accumulates sufficient negative charge on its grid to cut off the plate current. The amplifying action of the tube then stops and as the negative charge (electrons) accumulated on the grid leaks through the grid-leak resistance, the potential of the grid returns to normal and the same action is repeated. This "motorboating" action is very detrimental to the operation of any resistance-coupled amplifier because, while it is taking place, it will be impossible for any signal voltage applied to the input of the amplifier to appear in the output. Resistance-coupled amplifiers are more susceptive to this type of distortion than other types of audio amplifiers; hence, it is generally necessary to take precautions against this instability in the original design of the amplifier.

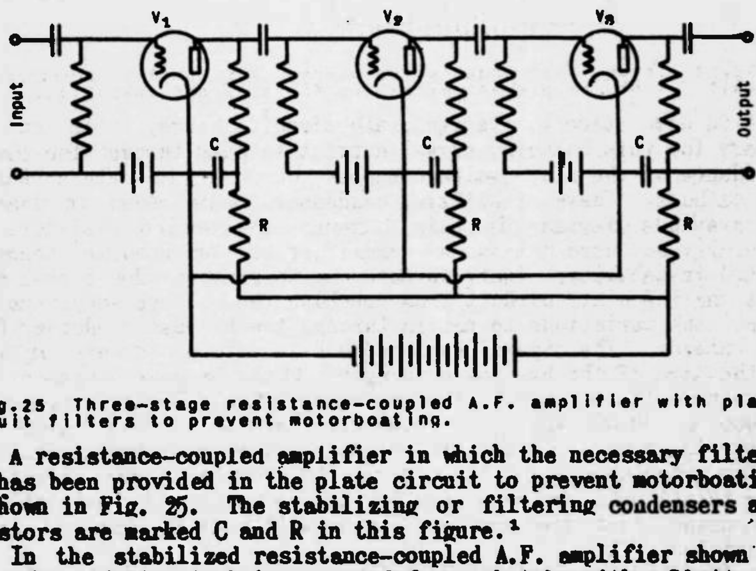


Fig.25 Three-stage resistance-coupled A.F. amplifier with plate circuit filters to prevent motorboating.

A resistance-coupled amplifier in which the necessary filtering has been provided in the plate circuit to prevent motorboating is shown in Fig. 25. The stabilizing or filtering condensers and resistors are marked C and R in this figure.[1]

In the stabilized resistance-coupled A.F. amplifier shown in Fig. 25, grid bias is being secured for each tube with a C battery. If a single C battery were used to supply grid bias for all three stages of the amplifier circuit, such as shown in Fig. 26, it is likely that there would be sufficient common coupling between the input and output stage through the common impedance of the biasing battery to cause motorboating to occur. In such a case, it is necessary to insert stabilizing resistors and condensers in each of the grid circuits. A single stage of a resistance-coupled A.F.

[1] These are sometimes called "decoupling" resistors and condensers.

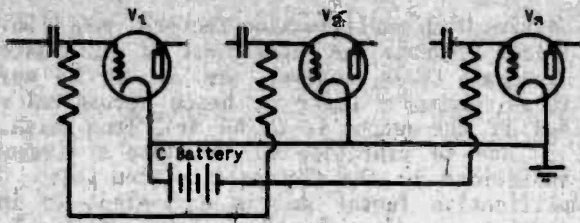
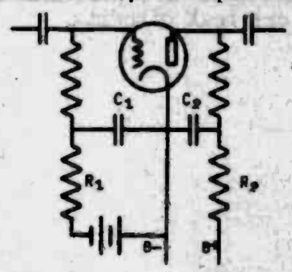


Fig.26 Circuit to illustrate how biasing battery may be used for several amplifier stages. Common coupling exists between the three grid circuits which may cause excessive feedback.

amplifier with the proper filtering in both grid and plate circuits to prevent motorboating is shown in Fig. 27. C_1 and R_1 constitute the grid filter and C_2 and R_2 constitute the plate filter. In the event of extreme instability in a resistance-coupled amplifier, it

Fig.27 Single stage of a resistance-coupled A.F. amplifier with grid and plate circuit filtering to prevent motorboating.



may be necessary to stabilize both the grid and plate circuits of each stage to prevent motorboating.

A plate-circuit stabilized impedance-coupled A.F. amplifier, preceded by a grid-bias detector, is shown in Fig. 28.

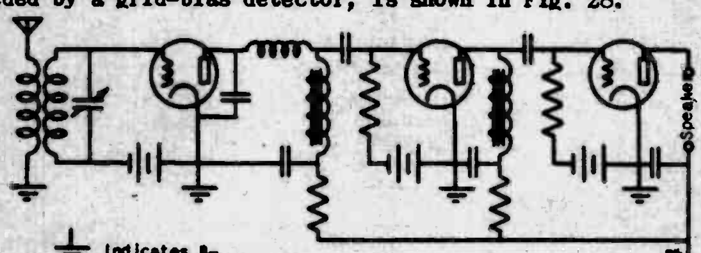


Fig.28 Grid-bias detector circuit followed by a two-stage impedance-coupled A.F. amplifier.

11. COMPARISON OF AMPLIFIERS. Transformer-coupled amplifiers are the most widely used type and can be designed to give fairly uniform amplification over the ordinary range of audio frequencies. They are capable of producing higher amplification per stage than the other types of amplifiers due to the voltage step-up through the coupling transformers.

A resistance-coupled amplifier is capable of constant voltage amplification over a wider frequency range than the other amplifiers. The resistance-coupled amplifier is cheaper to construct, lighter and more compact than the other types. With the advent of modern tubes having high amplification factors, the limited gain per stage no longer prevents the popular use of resistance-coupled amplifiers. High-gain tubes, however, are apt to be more microphonic than those having a lower μ; hence mechanical vibration must be avoided if the output is to be free from noise. Microphonic noise is due to vibration of the tube's elements which causes small variations in the distances between them. This affects the amplification factor and is equivalent to impressing small erratic voltages on the grid of the tube, which, when amplified, appear as noise.

The direct-coupled amplifier has been retarded from gaining extreme popularity primarily because of the expensive, high-voltage plate supply necessary for its operation. For television and oscilloscope circuits, their distortionless performance is far superior to their cost of construction, so they are used quite frequently in these critical circuits.

Notes

(These extra pages are provided for your use in taking special notes)

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UNIT NO. 1

GRID BIAS BY RESISTANCE

LESSON NO. 20

YOU WILL REAP ONLY AS YOU SOW

When a farmer plants a field of wheat, he will, if he is a good farmer, carefully prepare the soil, select firm seed and labor continually to insure proper growth. He does this because he knows that the wheat will not "head out" full and rich unless it is properly cared for during the growing season. He also knows that his cash rewards will depend entirely upon the size of the head at the top of each stalk, for the larger it is, the greater will be his yield and the more wheat he will have to sell.

You can, in several ways, be compared to this farmer. He looks forward to the reaping of a big crop and the enjoyment of seeing his hopes and ambitions become reality. You, too, have hopes and ambitions. You want to be a success. You want to enjoy life's pleasures and provide for your loved ones in a substantial manner. But you must remember this. Your hopes won't "head out" unless you, like the farmer, carefully prepare the ground from which your hopes must grow.

Just as the foresighted farmer carefully selects his seed, you must be equally careful to select hours for study and experimentation that will insure your retaining the most knowledge. Just as the farmer toils patiently to prepare the soil for the seed, you must improve the most important thing upon which your future success will depend.....your brain. If you will do these things, as time progresses your efforts will be rewarded .....your hopes will "head out", and instead of having wheat for sale, you will have an abundance of valuable knowledge and experience. And remember, you will sell that knowledge and experience for cash, just as the farmer sells his wheat for cash.

Midland Training, Engineer-Instructors, Equipment and Policies have all been designed to help you bring your hopes and ambitions to a full realization. Take full advantage of the facilities that have been placed at your disposal.....look to your future.....stick to your studies and experiments TODAY, so that TOMORROW you may reap a golden harvest!

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Lesson Twenty

GRID BIAS by RESISTANCE

"In Lesson 16, I described to you Power Rectifier Supply Circuits. All of the circuits described in that lesson were designed for the sole purpose of eliminating the need for the 'A' and 'B' batteries, which had been used in the receivers previously discussed. Thus, there remains only the 'C' battery to be eliminated in order to produce an all-electric receiver.

"In this lesson, I am going to describe various circuits which will accomplish this result. Every one of the circuits discussed in this lesson is either being used in present-day receivers or has been used in the past. Since the large majority of receivers being manufactured at present are entirely AC operated, I suggest that you study this lesson very carefully. With this information, you will have a comprehensive knowledge of how radio receivers are completely operated from the alternating current line supplying your home."

1. INTRODUCTION. Grid bias has been defined as the voltage difference between the grid and the negative side of the filament, when no signal is being received. It was learned that the grid must be kept negative with respect to the negative side of the filament to prevent the flow of grid current. Grid current always produces distortion in an amplifier or detector stage. Up to this time, the grid bias has been supplied by a C battery connected in the grid circuit with the negative terminal of the battery toward the grid, and the positive terminal toward the negative side of the filament.

Whenever possible, it is desirable to eliminate batteries. In Lesson 16, methods were discussed for using the AC line voltage, after proper conversion and filtering, for plate voltage on the tubes, thereby eliminating the use of the B batteries. It was also seen that the introduction of the AC tube, which could use an alternating filament voltage, made the A battery obsolete in all cases where an AC lighting voltage was available. There now remains only the C battery to be eliminated in order to produce a completely AC operated receiver. In this lesson, methods for securing grid bias without the use of the C battery will be discussed.

2. CATHODE RESISTOR BIASING. We shall first consider the indirectly heated cathode type tube, then apply the same principles to the filament type tube. Fig. 1 illustrates a circuit somewhat different in appearance from any presented heretofore. The plate voltage is furnished by a power supply drawn as a block diagram, and the heater circuit has been omitted to simplify the figure. Notice that a resistor, marked R, is connected in the cathode circuit. Let us trace the path of the plate current. The heater increases the temperature of the cathode to a point sufficient to cause it to emit electrons. Since the plate is positive with respect to the cathode, plate current flows through the coil connected in the plate circuit to B plus, through the power supply to B minus, through the resistor R, from B to A, and then back to the cathode. The total plate current must flow through the resistor

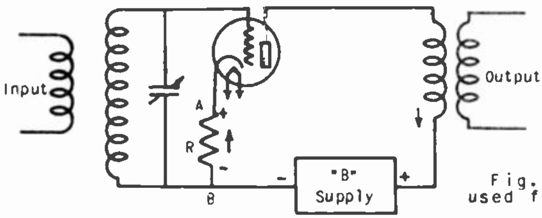


Fig.1 Fundamental circuit used for obtaining grid bias.

R, and in so doing, it produces a voltage drop across that resistor. Current, as we know, flows from negative to positive, and since the current flows through the resistor from B to A, point B must be negative with respect to point A. Point A is connected directly to the cathode, and point B directly to the grid. It is assumed that the resistance of the coil connected in the grid circuit is negligible. Since point A is positive with respect to point B, the cathode is positive with respect to the grid; or, conversely, the grid is negative with respect to the cathode. The voltage between the grid and the cathode is equal to the voltage drop across resistor R. This, then, would seem to be a good means of providing grid bias.

The size of the resistor to be used for a given value of grid bias can be found by applying Ohm's Law. For instance, in the case of the type 56 tube, we find upon reference to the tube manual that when the plate voltage is 100 volts, the correct grid bias for use as an amplifier is 5 volts; that is, the grid should be 5 volts negative with respect to the cathode when no signal is received. Therefore, the drop across resistor R must be 5 volts. With this particular tube, a plate voltage of 100 volts and a grid bias of -5 volts will produce a plate current of 2.5 ma. The resistor R must produce a voltage drop of 5 volts when 2.5 ma. flow through it. Therefore, its resistance is:

$$R = \frac{5}{.0025}$$

$$= 2,000 \text{ ohms.}$$

Let us work another example. This time we will use a type 45 tube. From the tube manual, it is found that when the plate voltage is 250 volts, the grid bias should be 50 volts and the plate current will be 34 ma. The voltage drop across the biasing resistor must be 50 volts; the amount of current which flows through it is 34 ma. To find the value of this resistor, we have:

$$R = \frac{E}{I}$$

$$= \frac{50}{.034}$$

$$= 1,470 \text{ ohms.}$$

Now let us investigate the difficulties encountered when using this type of grid bias. As long as no signal is being received, the plate current remains at a steady value. This constant or pure direct current flowing through the biasing resistor produces a constant bias voltage. When a station is tuned in, the signal voltage applied to the grid causes the instantaneous voltage of the grid to vary. The plate current varies in direct accordance with the variation of the grid voltage. The plate current becomes a pulsating direct current. This pulsating direct current in flowing through the biasing resistor produces a pulsating direct voltage; therefore, the bias voltage varies when a signal is applied to the grid. This is very undesirable. It produces a shift of the operating point of the vacuum tube and we know that for any given plate voltage, there is just one value of grid bias for the best operation.

Let us examine this action more thoroughly and determine just what occurs. During the alternation when the signal voltage is in such a direction as to buck against the grid bias, it drives the grid of the tube less negative. This results in an increase in plate current. Increased plate current flowing through the biasing resistor causes an increased voltage drop across it or an increased bias which tends to drive the grid more negative. Thus, the signal voltage, in driving the grid less negative, has produced another voltage which tends to prevent this action. On the other hand, at the instant when the signal voltage is in such a direction as to drive the grid more negative, the plate current correspondingly decreases. The decreased plate current in flowing through the biasing resistor produces a lower voltage or a lower grid bias. Obviously, a lower grid bias will tend to drive the grid less negative. Using this system of biasing, we do not obtain a constant bias voltage (a condition very necessary for proper operation) and also the variations in bias are such as to prevent the signal voltage from producing its maximum effect upon the plate current. This "opposing action" which the varying grid bias offers to the signal voltage is called "degeneration".

In order to produce a constant bias voltage, a pure direct current must flow through the biasing resistor. The varying plate current is a pulsating direct current. It was learned in Lesson 14 that a pulsating direct current is composed of a DC component and an AC component. If, therefore, we devise a simple low-pass filter circuit which will allow the DC component of the plate current to flow through the biasing resistor and, at the same time, prevent the passage of the AC component, we will have a constant voltage drop across the resistor and a constant grid bias.

In Fig. 2, the same circuit used in Fig. 1 is shown except that a condenser C is connected across the biasing resistor R. When no signal is received, the plate current is steady; this produces a steady voltage drop across the resistor and the condenser charges to this voltage. When the plate current increases, due to the application of a signal voltage, the current flowing through the resistor tends to increase. If, however, condenser C has sufficient capacity to make its capacitive reactance to the frequency of the signal voltage considerably less than the resistance of the biasing resistor, most of these extra electrons, which are flowing

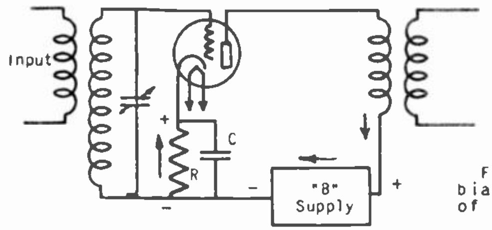


Fig.2 Illustrating how grid bias may be obtained by means of a resistor and a condenser.

around the circuit, will flow on to the bottom plate of condenser C. This will drive an equal number from the top plate, which then flow to the cathode to be emitted again. Thus, the current through the biasing resistor remains constant at the no-signal value. When the plate current decreases, there is a tendency for the current through the biasing resistor to decrease. However, those electrons which have collected upon the bottom plate of the condenser now flow through the resistor from bottom to top and on to the top plate of the condenser. In other words, the condenser discharges slightly. The total current through the resistor is the plate current plus this discharging current of the condenser. This again results in practically the same current flowing through resistor R.

Considering this action from a different viewpoint, we can say that, since the capacitive reactance of the condenser is much lower than the resistance of the resistor, the AC component of the plate current will prefer to flow effectively through the lower opposition path provided by the condenser and very little of this AC component will flow through the resistor. To the DC component, the condenser offers infinite capacitive reactance. Therefore, all the DC component of the plate current is forced to flow through the biasing resistor. This simple low-pass filter circuit is ordinarily sufficient to maintain the biasing voltage at a value which is, for all practical purposes, constant. By this method, degeneration is minimized.

The condenser is known as the cathode by-pass condenser. It effectively by-passes the AC component of the current and prevents it from flowing through the resistor. The value of capacity to be used depends upon the frequency being amplified. *The capacitive reactance of the condenser should not be greater than .1 of the resistance of the biasing resistor at the lowest frequency to be amplified.* Let us consider a stage of A.F. amplification which uses a type 56 tube. The correct biasing resistor was previously found to be 2,000 ohms. If the lowest frequency to be amplified is 100 cycles, the capacity of the by-pass condenser may be calculated in the following manner. One-tenth of 2,000 is 200. This is the maximum capacitive reactance permissible. The formula for capacitive reactance as given in Lesson 11 is:

$$X_c = \frac{1}{6.28 \times F \times C}$$

If this equation is solved for C, there is obtained:

$$C = \frac{1}{6.28 \times F \times X_c}$$

This formula may be used to find the capacity needed to produce a known capacitive reactance at a known frequency. By substitution in this formula, we obtain:

$$C = \frac{1}{6.28 \times 100 \times 200}$$

$$= .0000079 \text{ farad,}$$

$$= 7.9 \text{ mfd.}$$

From this calculation, it may be seen that a condenser whose capacity is approximately 8 mfd. should be used. Condensers having this large a capacity and being of small enough physical dimensions to be practical are available only in the electrolytic type. Therefore, many electrolytic condensers are used for cathode by-passing on A.F. amplifier stages. The voltage across the condenser is obviously equal to the grid bias which, in receiving tubes, is seldom greater than 60 volts. Thus, an electrolytic condenser to be used as a cathode by-pass for an audio stage need have a breakdown voltage of only 70 or 75 volts. Since the breakdown voltage is low, the dimensions of the condenser will be small enough to be convenient.

In R.F. amplifier stages, it has become common practice to use a .25 mfd. condenser for cathode by-passing. If the R.F. amplifier stage uses a type 56 tube which requires a biasing resistor of 2,000 ohms, the capacitive reactance of the condenser will be small compared to the value of the resistor at any frequency in the broadcast band. This may be checked by reference to the capacitive reactance table given in Lesson 11, which gives the reactance of a .25 mfd. condenser at 500 kilocycles as 1.28 ohms. Since 1.28 ohms is such a small part of 2,000 ohms, the by-passing action of the condenser will be very effective.

Another important problem arises when securing grid bias by resistance. Fig. 3 shows the essential parts of a typical amplifying circuit in a radio receiver. Let us assume the tube requires 250 volts on the plate and 50 volts grid bias. To produce this grid

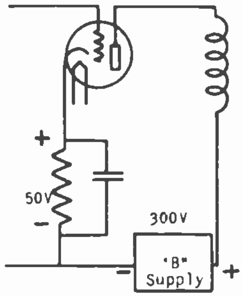


Fig.3 Illustrating the necessity of increasing the plate supply voltage when cathode bias is employed.

bias requires that the voltage drop across the resistor be 50 volts. The grid is 50 volts negative with respect to the cathode, or the cathode is 50 volts positive with respect to the grid. Notice that the bottom end of the biasing resistor is connected to B minus. This makes the cathode 50 volts positive with respect to the negative terminal of the power supply. The definition of the plate voltage of a vacuum tube is the voltage existing between the plate and the negative side of the filament; or, if the tube is of the cathode type, it is the voltage between the plate and the cathode. The plate voltage is to be 250 volts. This, in turn, means that B plus must be 250 volts positive with respect to the cathode. Notice that the voltage drop across resistor R bucks against the voltage of the power supply. For this reason, the difference in potential between B plus and the cathode is equal to the voltage of the power supply less the voltage drop across R. Since the drop across R is 50 volts, the voltage of the power supply must be 300 volts to produce a voltage of 250 volts between the plate and the cathode. In Fig. 4, a simplified diagram is shown illustrating the relationship between these voltages. It is seen that the biasing resistor and the cathode-to-plate resistance of the tube are in series. The sum of the voltage drop across a series circuit equals the applied voltage; therefore, the voltage drop across the tube (250 volts) plus the voltage drop across the resistor (50 volts) must equal the applied voltage (300 volts). From the foregoing, it is clear that the voltage output of the power supply must be equal to the plate voltage plus the grid bias when this type of biasing is used. In this case, where the plate voltage is 250 volts, and the grid bias 50 volts, it must have a voltage of 300 volts.

Often when the grid bias is small, it need not be taken into account. For example, the plate voltage of a type 56 tube is 100 volts and its grid bias 5 volts. Theoretically the output of the

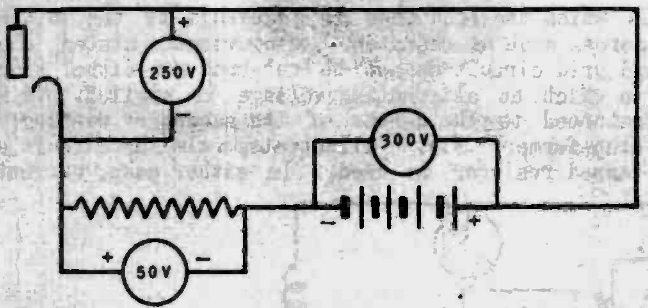


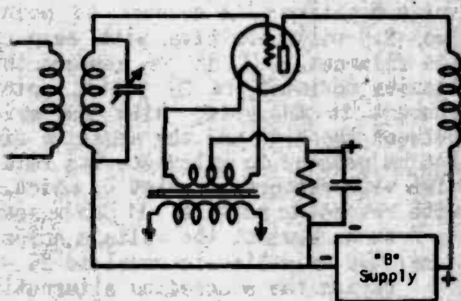
Fig.4 Showing how the voltage of the power supply divides between the tube and the cathode resistor.

power supply should be 105 volts; however, it is usual to make the voltage of the power supply equal to the rated plate voltage in such a case, since the grid bias is so small compared to the plate voltage. If this is done, the actual plate voltage is 95 volts, which produces little, if any, change in the operation of the tube.

Cathode-resistor biasing is often called "self bias" or "automatic bias" in contra-distinction to battery bias, which is known as "fixed bias". For any value of plate voltage, there is an optimum value of grid bias. The automatic feature of this method of biasing is manifested in its tendency to maintain the bias at the optimum value if the plate voltage changes, due to poor regulation of the power supply, or to variations of the line voltage. An increase in plate voltage produces an increase in plate current which, in turn, increases the voltage drop across the resistor and makes the grid bias enough greater to partially compensate for the change in plate voltage. In a like manner, a decrease in plate voltage is accompanied by a lowering of the grid bias. The automatic action of cathode-resistor biasing is by no means perfect; but it will prevent the flow of an excessive plate current which would damage the tube, if an excessive plate voltage is inadvertently applied.

It is also possible to use the resistor method of biasing with directly heated cathode or filament type tubes. Fig. 5 shows a

Fig.5 Using resistor bias with a filament type tube and a center-tapped transformer.



circuit in which the grid bias is furnished by the voltage drop produced across such a resistor. As previously stated, the plate circuit and grid circuit cannot be returned to either side of a filament to which an alternating voltage is applied. In Fig. 5, they are returned to the center of the secondary winding of the filament transformer. Fig. 6 illustrates a similar circuit in which a center-tapped resistor is used. In either case, current flows

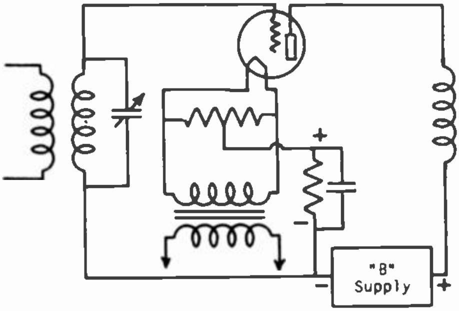


Fig.6 Using resistor bias with a filament type tube and a center-tapped resistor.

from the filament to the plate, through the plate circuit, through the power supply, up through the resistor to the center tap and then back both sides of the filament to the emission surface. The plate current in flowing through this resistor produces a voltage drop which causes the center tap of the filament to be positive with respect to the grid by the amount of voltage dropped across this resistor.

We are now ready to consider another problem which presents itself in the operation of directly heated cathode or filament type tubes. We know that all differences in potential in a vacuum tube are stated with respect to the negative side of the filament. As discussed in detail in Lesson 16, the grid and plate circuits must be returned to a point which does not change its potential as the filament voltage alternates. Either the center point of the filament secondary or the mid point of a center-tapped resistor satisfies this condition. Let us consider Fig. 7, which uses a center-tapped resistor across the filament circuit of a tube requiring 5 volts filament voltage. During one alternation, point C is 5 volts positive with respect to point A. This makes B (the center tap) 2.5 volts positive with respect to A, the negative side of the filament. If it is assumed that the voltage drop across the biasing resistor is 25 volts, point B is 25 volts positive with respect to the grid. With the grid bias defined as the voltage between the grid and the negative side of the filament (point A), let us proceed to calculate its value. The grid is 25 volts negative with respect to point B, which, in turn, is 2.5 volts positive with respect to point A. It can be seen that the voltage drop from A to B bucks against the voltage across the biasing resistor; therefore, the grid bias is equal to 25 - 2.5 = 22.5 volts.

During the succeeding alternation, point C becomes the negative side of the filament, and again the center tap (point B) is

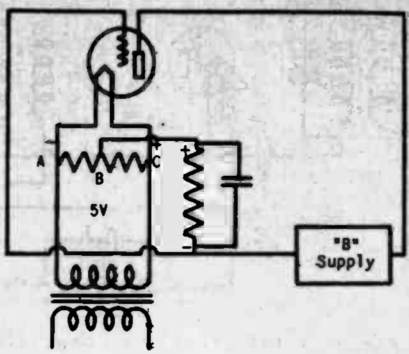


Fig.7 Showing why the actual grid bias measured from the grid to the negative side of the filament is equal to the voltage drop across the biasing resistor less one-half of the filament voltage.

2.5 volts positive with respect to the negative filament. The grid bias is, therefore, 22.5 volts as before. Perhaps the diagram shown in Fig. 8 will make this clear. The bottom line represents the potential of the grid or of B minus, to which the grid is connected. The upper line represents the potential of point B, which is 25 volts positive with respect to B minus and the grid. Point B, however, is 2.5 volts positive with respect to the negative side of the filament; therefore, the line which represents the potential of the negative side of the filament is drawn below the top line.

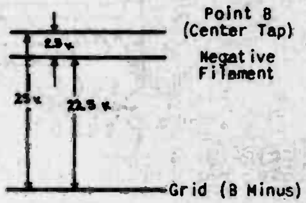


Fig.8 A potential diagram illustrating the voltages of the circuit of Fig. 7.

The grid bias is the voltage difference between the grid and the negative side of the filament and is, therefore, seen to be 22.5 volts.

From the foregoing, it is evident that the actual voltage drop across the biasing resistor, when used with AC filament type tubes, must be slightly greater than the grid bias required. The actual grid bias is equal to the voltage drop across the biasing resistor minus one-half of the filament voltage.

When two or more tubes require the same grid bias, it is possible to use one resistor to supply the bias for all. Fig. 9 illustrates a two-stage R.F. amplifier using cathode type tubes. Let us trace the path of the current. The plate current of VT-1 flows from the plate to the power supply, through the power supply, through the biasing resistor from right to left, and then back to the cathode of this tube. The plate current of VT-2 flows from its plate, through the power supply, through the biasing resistor from right to left, and back to the cathode of the second tube. Thus, the combined

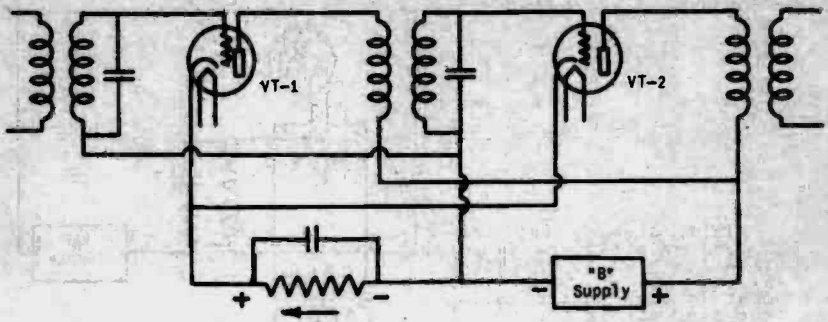


Fig. 9 A two-stage R.F. amplifier using one biasing resistor.

current of both tubes flows through the biasing resistor. In calculating the value of this resistor, this fact must be taken into account. If both tubes draw the same plate current, the biasing resistor must have a value just half as much as if it were used with one tube. Fig. 10 shows a three-stage amplifier using fila-

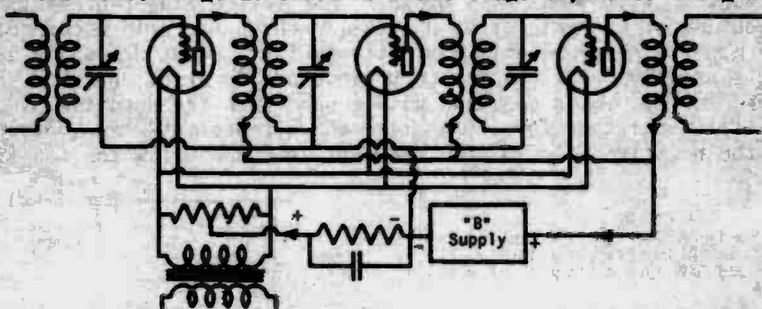


Fig. 10 A three-stage R.F. amplifier with filament type tubes using one biasing resistor for all the tubes.

ment type tubes. The bias for each of the three stages is provided by the voltage drop produced across one biasing resistor. This method may be used only when all of the tubes so connected require the same grid bias. In this case, the value of the biasing resistor is one-third of that used for one tube, since three times as much current flows through it.

Fig. 11 illustrates a three-stage amplifier in which the first two tubes are of the cathode type and the last is of the filament type. Notice, in this circuit, that the grid return is connected neither to B minus nor to the bottom end of the biasing resistor; it is grounded instead. The ground symbol signifies that the circuit is connected to the metal chassis on which the amplifier is built. Since this is common practice and since many illustrations are drawn in this manner, it is advisable for you to become familiar with this type of diagram. It is noticed that each of the filter condensers is grounded; this saves considerable wire. Let us trace the path of the plate current through the first or left-hand tube. From the plate, it flows down through the primary of an audio

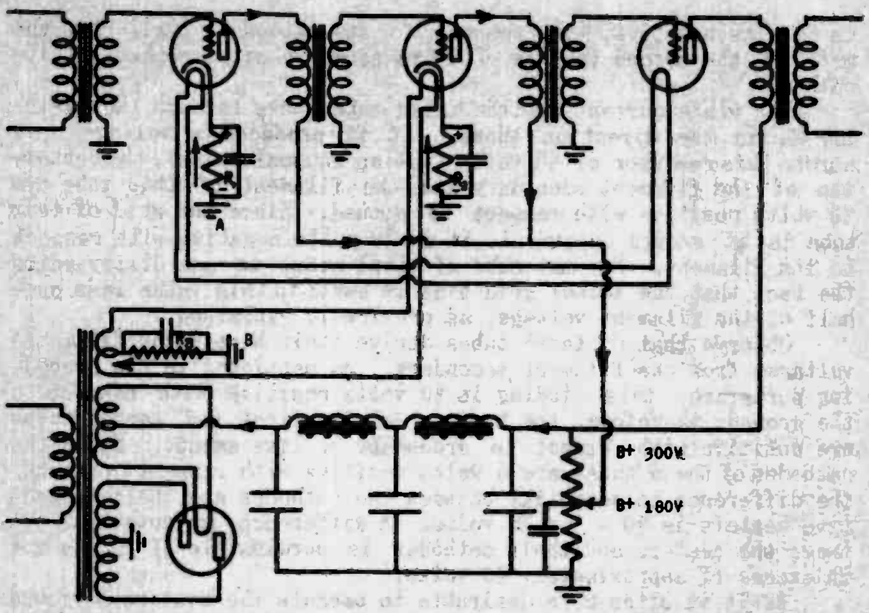


Fig.11 A three-stage A.F. amplifier using resistor bias. The grid returns, the cathodes, the center tap of the high-voltage secondary, and the filter condensers are grounded to the chassis in order to save wiring.

transformer to a point on the voltage divider marked B plus 180 volts. From there it flows through the upper section of the voltage divider to B plus, 300 volts. It now passes through the two chokes of the filter system to the filament of the rectifier; thence alternately to the plates of the rectifier tube, through the high-voltage secondary to its center tap which is grounded. From ground the plate current flows through the metal chassis to point A, which is also grounded. Point A is seen to be the lower end of the biasing resistor of the first tube. To complete its path, this current flows upward through the biasing resistor to the cathode. The plate current of the second tube may be traced in a similar manner.

Let us now pass to the third tube. Its plate current flows from its plate to the top end of the voltage divider, through the filter and rectifier to the center of the high-voltage winding, which is grounded. From ground it flows through the chassis to point B which is one end of the biasing resistor for the third tube. It then completes its circuit by flowing through this resistor to the center tap of the filament secondary, through both sides of the filament leads to the emission surface of the third tube's filament.

With the directions of the plate currents well fixed in mind, let us now determine how the tubes secure their bias. The plate current of the first tube flows through R_1 in the direction shown by the arrow, producing a voltage drop of, perhaps, 5 volts. The cathode of this tube is 5 volts positive with respect to ground; the grid is at ground potential; therefore, the grid of this tube is 5 volts negative, with respect to its cathode. Similarly, the grid of the second tube is 5 volts negative with respect to its cathode.

The plate current of the third tube flows through the resistor R_3 in the direction shown. If it produces a voltage drop across this resistor of 30 volts (not an unusual value), the center-tap of the filament secondary and the filament of this tube are 30 volts positive with respect to ground. Since the grid of this tube is at ground potential, it is 30 volts negative with respect to its filament. For the sake of simplicity, we are disregarding the fact that the actual grid bias is equal to this value less one-half of the filament voltage, as previously explained.

Observe that all three tubes derive their heater (or filament) voltages from one filament secondary. As mentioned in the preceding paragraph, this winding is 30 volts positive with respect to the ground; therefore, the heaters of the first and second tubes are positive with respect to ground by a like amount. Since the cathodes of these tubes are 5 volts positive with respect to ground, the difference in potential between the cathodes and their respective heaters is 30 - 5 = 25 volts. A difference in potential between the heaters and their cathodes is permissible if it is not in excess of approximately 40 volts.

As it is often more desirable to operate the heaters at ground potential, a separate heater winding is usually provided on the power transformer. When this is the case, the center tap of the winding is grounded, as shown in Fig. 12. This is done to prevent

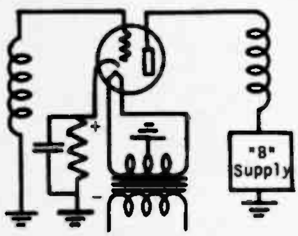


Fig.12 Showing how the center tap of the heater winding is grounded in cathode type tubes to prevent the accummulation of static charges.

the accumulation of static charges on the heater circuit which might cause the difference in potential between the cathode and the heater to rise to such a value as to break down the insulation resistance between them. Also, the grounding of the center tap balances the heater circuit; any stray voltages which might be induced in this circuit, either electro-magnetically or electrostatically, will be balanced with respect to ground and, therefore, cancelled.

The problem of degeneration at radio frequencies is not serious. It is simple enough to use a condenser for cathode by-passing whose capacitive reactance is so small compared to the resistance of the biasing resistor as to form an almost perfect low-pass filter. It is possible to select a condenser whose capacitive reactance at any radio frequency is less than .001 of the resistance of the biasing resistor. When such is the case, the alternating voltage between the grid and the cathode (due to the passage of the varying plate current through the biasing resistor) is only .001 as much as it would be if no condenser were used. This reduction is more than enough to produce efficient results.

In A.F. amplifiers, this problem is much more serious. It has been demonstrated that, if a type 56 tube is to amplify a frequency of 100 cycles without appreciable degeneration, the condenser must have a capacity of 8 mfd.; in which case, its capacitive reactance at this frequency is .1 of the value of the biasing resistor. If the A.F. amplifier is to be used in conjunction with other high-fidelity equipment, it should be capable of amplifying all frequencies ranging from 30 to 10,000 cycles. Assuming that the biasing resistor is 2,000 ohms, let us calculate the capacity of the by-pass condenser needed at 30 cycles:

$$.1 \times 2{,}000 = 200 \text{ ohms}$$

$$C = \frac{1}{6.28 \times F \times X_c}$$

$$= \frac{1}{6.28 \times 30 \times 200}$$

$$= .0000265 \text{ fd.}$$

$$= 26.5 \text{ mfd.}$$

It is at once seen that a very large capacity is required to effect a reduction of the AC voltage across the biasing resistor to .1 of its former value. While it is possible to procure electrolytic condensers of this capacity which are of convenient size, there is another method often used in A.F. amplifiers by which the reduction in the AC voltage can be made .001 or less of its original value and which does not require such a large capacity.

A circuit of this type is illustrated in Fig. 13. The condenser C_g is connected between the grid return and the cathode. Remembering that it is the AC voltage setup between the grid and the

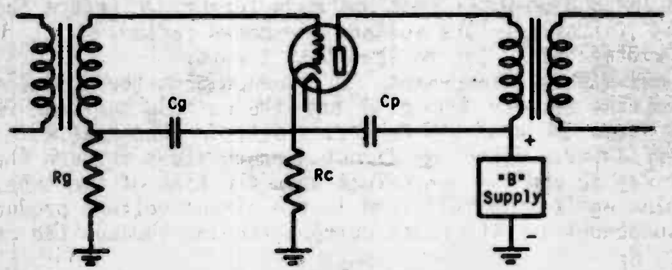


Fig.13 A method for securing a steady grid bias which does not require the use of a very large capacity.

cathode due to the varying plate current which causes degeneration, it is clear that the only voltage which can cause degeneration is that produced across C_g, C_p is called the plate filtering condenser, and it has a capacity of 1 mfd. or more. It is connected between the cathode and the lower end of the plate coil. Its purpose is to by-pass the AC component of the plate current around the power supply and the resistor R_c. R_g is the grid filtering resistor which helps to prevent degeneration.

To simplify the explanation of this circuit, it has been redrawn in Fig. 14. By close inspection we can see that this circuit is equivalent to that of Fig. 13. The power supply and R_c are connected in series, and across this combination is connected C_p. The condenser C_p reduces the AC voltage across the biasing resistor to perhaps .1 of the value it would have if no by-passing were

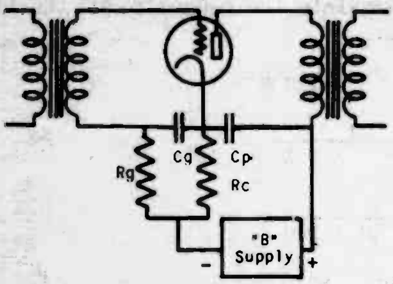


Fig. 14 The circuit of Fig. 13 redrawn to illustrate how this arrangement is able to minimize degeneration.

used. It is seen that R_g and C_g are in series and that their combination is in parallel with R_c; therefore, any AC voltage across R_c is also applied across the combination R_g and C_g. R_g has a resistance of 100,000 ohms and C_g a capacitive reactance of 1,000 ohms at 30 cycles. Together they form a voltage dividing circuit and, of the total voltage appearing across them, only one-one hundredth is across C_g, since its capacitive reactance is one-one hundredth of the resistance of R_g. As previously stated, it is this voltage across C_g which can cause degeneration. This voltage is only .001 of its former value, since C_p reduced it to .1 and R_g and C_g reduced it to .01 of .1, which is .001. A capacity of .5 to 2 mfds. is suitable for C_g, depending on the size of R_g. If R_g is ¼ to ½ megohm, C_g may be made around .5 mfd.; however, if R_g is 100,000 ohms, C_g must be made larger to secure the same degree of filtering. The voltage breakdown rating of C_g is low and the wattage of R_g can be less than 1 watt.

By using this arrangement, it is seen that the actual alternating voltage between the grid and the cathode has been reduced far more than is possible by using only a condenser across the biasing resistor. Since no direct current flows through the grid resistor R_g, it can have no effect upon the bias of the tube. The actual bias applied to this tube is the direct voltage produced by the DC component of the plate current flowing through the cathode resistor, R_c.

2. **VOLTAGE DIVIDER BIASING.** Since the plate voltages are obtained by a drop across the voltage divider, it would seem possible to use a part of this voltage as grid bias. Fig. 15 shows how this may be accomplished. The resistor in the diagram represents the voltage divider of a power supply; the filter and rectifier have been omitted to simplify the illustration. The negative

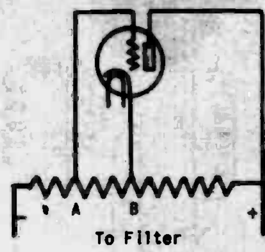
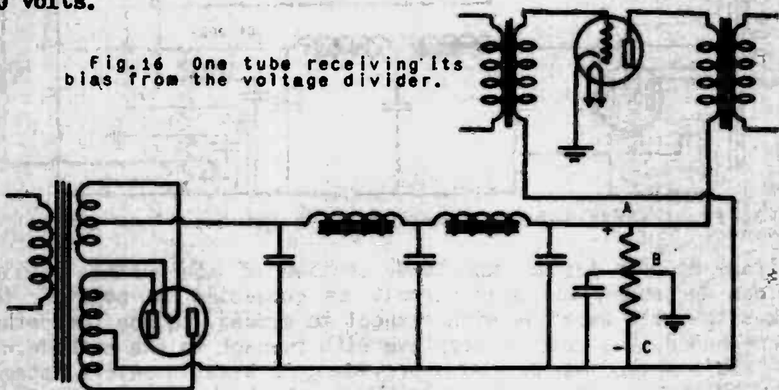


Fig.15 A fundamental circuit illustrating voltage divider biasing.

end of the voltage divider is not connected to ground as is usual; the positive end is connected to the plate. A point, (B), is then chosen, somewhere along the voltage divider so that the voltage between the positive end and this point is equal to the desired plate voltage. A second point, (A), is selected so that the voltage between it and point B is equal to the desired grid bias, and this point is then connected to the grid circuit. Since point A is negative with respect to point B, the grid bias is obtained by the voltage drop across this part of the voltage divider. If this tube requires 250 volts plate voltage and 50 volts grid bias, the total output voltage across the voltage divider would have to be at least 300 volts.

Fig.16 One tube receiving its bias from the voltage divider.



In commercial practice, this type of grid biasing appears as shown in Fig. 16. Let us trace the plate current through this circuit. The plate current flows from the plate of the tube to the positive end of the voltage divider, through the filter and rectifier to the center tap of the high-voltage secondary to the negative end of the voltage divider, point C. It then flows through the lower section of the voltage divider from point C to point B, which is grounded. From ground, it flows to the cathode of the tube, which is also grounded, and, thereby, completes its circuit. In addition to the plate current which flows through the lower section of the voltage divider, there is also a bleeder current which flows through the entire voltage divider. Since all of this current flows from the bottom toward the top of the voltage divider, the bottom end is negative with respect to the top. Also, the bottom, point C, is negative with respect to ground by the amount of

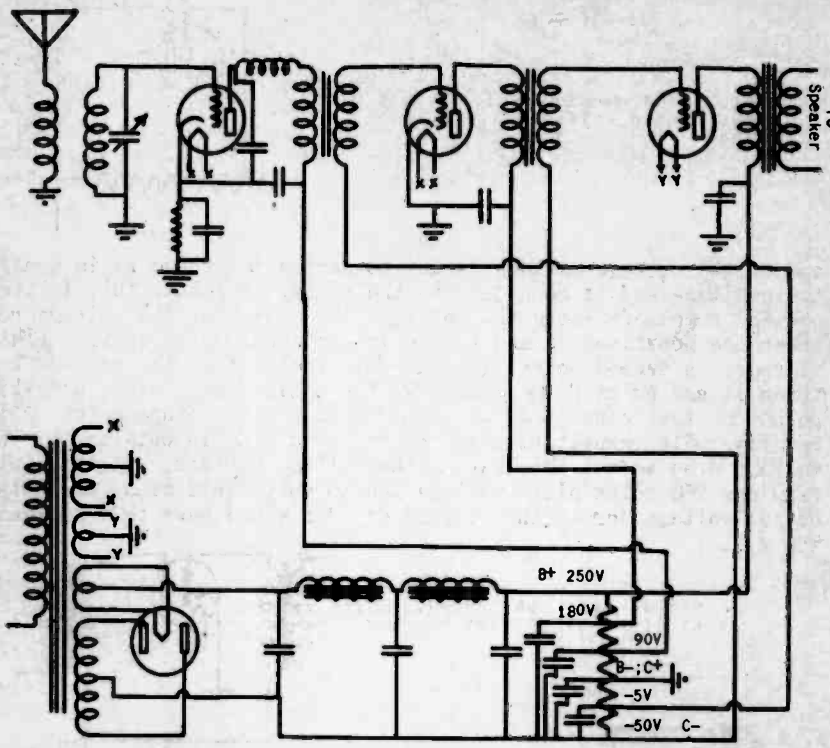


Fig.17 A three-tube receiver securing its bias from the voltage divider.

voltage dropped across the lower section of the voltage divider. As can be seen, the grid circuit is connected to point C; this makes the grid negative with respect to ground. Since the cathode is grounded, the grid is negative with respect to the cathode.

This method may be used to provide grid bias for several stages. Fig. 17 shows a three-tube receiver in which the first tube is the detector and the two remaining tubes are A.F. amplifiers. The bias for the detector tube is produced by the voltage drop across the cathode resistor. The two A.F. amplifier stages obtain their bias from the voltage divider. The top end of the voltage divider is 250 volts positive with respect to ground. A lead is taken off at this point to furnish plate voltage for the second A.F. amplifier. The first tap below this is at a voltage of 180 volts positive with respect to ground. This tap furnishes plate voltage for the first A.F. amplifier. The tap below this is 90 volts positive with respect to ground and it furnishes plate voltage for the detector stage. The next tap below this is grounded. It, therefore, is B minus, or, likewise, C plus. The first tap below this is 5 volts negative with respect to ground and is used to furnish grid bias for the first A.F. amplifier. Finally, the bottom end of the voltage divider is 50 volts negative with respect to ground and is used to supply bias to the second A.F. amplifier stage. Let us trace the paths of the plate currents. Current flows from negative to positive; therefore, we shall start at the most negative point in the circuit. This, obviously, is the negative end of the voltage divider. The plate currents of all of the tubes start from this point. The plate current of the detector flows from C minus, up through the voltage divider to the point which is grounded. Then, from ground it flows up through the biasing resistor in the cathode circuit of the detector to the cathode, through the tube to the 90-volt tap on the voltage divider, to the top end of the voltage divider, through the filter and rectifier, and back to C minus. The plate current of the first A.F. amplifier flows from C minus to C plus (which is grounded), to the cathode of the first A.F. amplifier, through the tube, to the 180-volt tap, to the top of the voltage divider, and through the remainder of the power supply to C minus. The plate current of the second A.F. tube flows from C minus to C plus, to ground, to the center tap of the filament winding marked YY and then up through the filament leads (not shown in the diagram) to the filament of the second A.F. amplifier, through the tube to the most positive end of the voltage divider, and through the rest of the power supply to C minus. It should be noticed that the plate current of all of the tubes flows through that part of the voltage divider connected between C minus and C plus or ground.

It is now necessary to learn the method of calculating the sizes of the resistors used in the construction of a voltage divider. The voltage desired at each of the taps and the current to be drawn from each must be known. Fig. 18 is an enlarged draw-

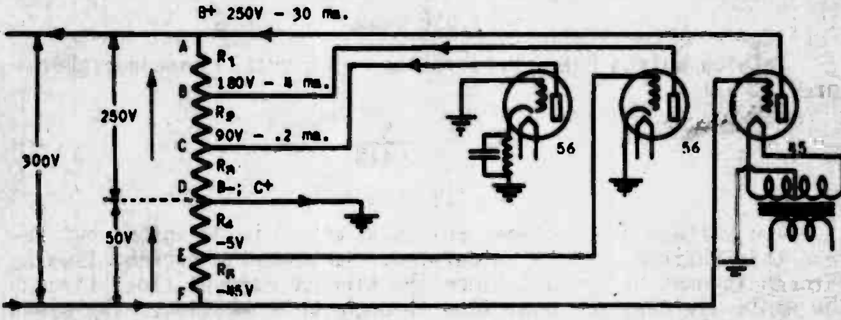


Fig.18 An enlarged drawing of the voltage divider used in the receiver of Fig.17. This figure is used to explain the calculation of the voltage divider.

ing of the voltage divider used in the receiver of Fig. 17. Only the parts essential to the explanation have been included in the diagram. We will assume that the second stage A.F. amplifier tube is a type 45, which requires 250 volts plate voltage, 50 volts grid bias, and draws 30 ma. of plate current; that the first A.F. amplifier stage uses a type 56 tube, which requires 180 volts plate voltage, 5 volts grid bias, and draws 4 ma. plate current; and that the detector tube is a type 56, which has 90 volts on its plate, 9 volts on its grid, and draws .2 ma. of plate current. The size of the detector biasing resistor is found by determining the resistance necessary to produce a voltage drop of 9 volts when the current is .2 ma. This is:

$$R = \frac{9}{.0002}$$

$$= 45{,}000 \text{ ohms.}$$

Before the voltage divider resistors can be calculated, the value of the bleeder current must be selected. This value is not critical, but should be enough to give the power supply good voltage regulation. If it is too low, the no-load voltage across the filter condensers may be great enough to cause them to break down. Let us assume that it is 10 ma. in this case. The total current flowing between points F and E in the voltage divider is, as previously explained, the sum of all of the plate currents plus the bleeder current. Current through:

$$R_5 = 30 + 4 + .2 + 10 = 44.2 \text{ ma.}$$

Between points F and E of the voltage divider, a voltage drop of from -50 to -5 volts, or 45 volts, is desired. Therefore, R_5 is:

$$R_5 = \frac{E}{I}$$

$$= \frac{45}{.0442}$$

$$= 1{,}018 \text{ ohms.}$$

Between points E and D, a voltage of 5 volts is needed; therefore, R_4 is:

$$R_4 = \frac{5}{.0442}$$

$$= 113 \text{ ohms.}$$

The voltage drop between points D and C is 90 volts, but before this resistor can be calculated, the amount of current flowing through it must be found. Since the bleeder current flows through the whole divider, it must flow through this section. The plate current of the second A.F. stage is returned to point A; that of the first A.F. stage to point B; and that of the detector to point C. From the points where these currents are returned, they flow upward to point A and then to the filament of the rectifier tube. It is then clear that none of these plate currents flows through R_3, and the only current in R_3 is the bleeder current; therefore, R_3 is:

$$R_3 = \frac{90}{.01}$$

$$= 9{,}000 \text{ ohms.}$$

From B to C, the voltage drop is from 180 to 90 volts or a drop of 90 volts. The currents flowing through this section are: the 10 ma. of bleeder current plus the .2 ma. of detector plate current, or a total of 10.2 ma. Therefore, R_2 is:

$$R_2 = \frac{90}{.0102}$$

$$= 8{,}823 \text{ ohms.}$$

From A to B, the voltage falls from 250 to 180 volts, a drop of 70 volts. Through this section there flows the 10 ma. of bleeder current, the .2 ma. of detector plate current, and the 4 ma. plate current of the first A.F. stage, a total of 14.2 ma. Therefore, R_1 is:

$$R_1 = \frac{70}{.0142}$$

$$= 4{,}929 \text{ ohms.}$$

The power dissipated in R_1 may be found by using the I^2R Law. It is:

$$I^2R = .0142^2 \times 4{,}929$$

$$= .99 \text{ watts}$$

In a similar manner, the power dissipated in R_2 is found to be .92 watt; in R_3, .9 watt; in R_4, .22 watt; and in R_5, 1.99 watts. If separate resistors are to be used for the various sections of the voltage divider, they should have wattage ratings of at least twice the actual power dissipated. Thus, all of the resistors except R_5 should be rated at 2 watts, while a 5-watt resistor should be used for R_5.

It is much safer to use resistors with a higher wattage rating than the actual power dissipated, since they will probably be placed where a free circulation of air is not available to carry off the heat produced.

The total power dissipated in the voltage divider is the sum of the powers used in the separate sections. It is found to be 5.02 watts. If one resistor with four taps is to be used for the voltage divider, it should have a wattage rating of at least 10 watts, and preferably somewhat higher. By the preceding method, any voltage divider may be calculated.

9. **SPEAKER FIELD BIASING.** There are many different methods of securing grid bias and we shall not, in this lesson, attempt to study the characteristics of every type. There is, however, another method which has been used extensively, especially as a means of providing grid bias for the power tube or tubes of the receiver.

After you have studied the lesson on loudspeakers, you will learn that dynamic speakers have what is known as a field winding. The field must be excited from a direct voltage source, and this is usually accomplished by using the speaker field in place of one of the filter chokes in the filter system of the power supply. By proper arrangement, it is possible to use the voltage drop across the speaker field as the grid bias for the power tube of the receiver. The average speaker field has a resistance of 2500 ohms; therefore, the voltage drop produced across it is sufficient to provide bias for the power tube.

Fig. 19 shows a method which may be used to supply bias for one or more tubes of the receiver. The center tap of the high-voltage winding is not grounded, but is connected to one terminal of the field of the dynamic speaker. The other connection to the field is then grounded. Naturally, whatever current flows through the rectifier system must also flow through the field windings. This serves to magnetize the speaker field and, at the same time, the voltage drop produced across the field by this current flowing through it can be used for grid bias. From the diagram, it can be seen that the center tap of the high-voltage secondary is not at ground potential, but is negative with respect to ground by an amount equal to the voltage drop across the speaker field. Therefore, a lead may be taken from the center tap of the high-voltage winding and the voltage between that point and ground used as grid bias. A filter system must be provided across the speaker field to insure that the bias voltage applied to the grid of the tube is

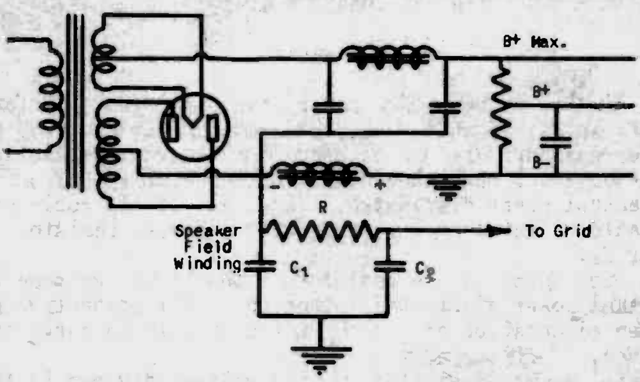


Fig.19 Illustrating how the voltage across the speaker field may be used for grid bias.

as pure a DC voltage as it is possible to obtain. This filter system consists of resistor R and the two condensers C_1 and C_2 shown in the figure; it is a low-pass filter. Notice, however, that a resistor is used instead of a choke. This is possible because no direct current flows through the resistor, since the grid is kept negative with respect to its cathode. Therefore, R can be very high in value. An ordinary value would be 500,000 ohms. C_1 should be about 8 mfd. with a fairly low breakdown voltage, and C_2 may be around .25 mfd. Remember that the actual DC voltage between the right end of resistor R and ground is equal to the DC voltage between the center tap of the high-voltage winding and ground. Since there is no direct current flowing through resistor R, there is no steady voltage drop across it. When the voltage input to this filter varies, the condensers C_1 and C_2 charge and discharge, and a small AC current flows through resistor R. The condensers serve to short the AC component of the varying voltage to ground, while the high resistance greatly reduces the AC component, due to the AC charging current which flows through it. This arrangement can produce a practically pure DC voltage at its output, thus assuring a pure DC bias supply.

RESISTOR COLOR CODE

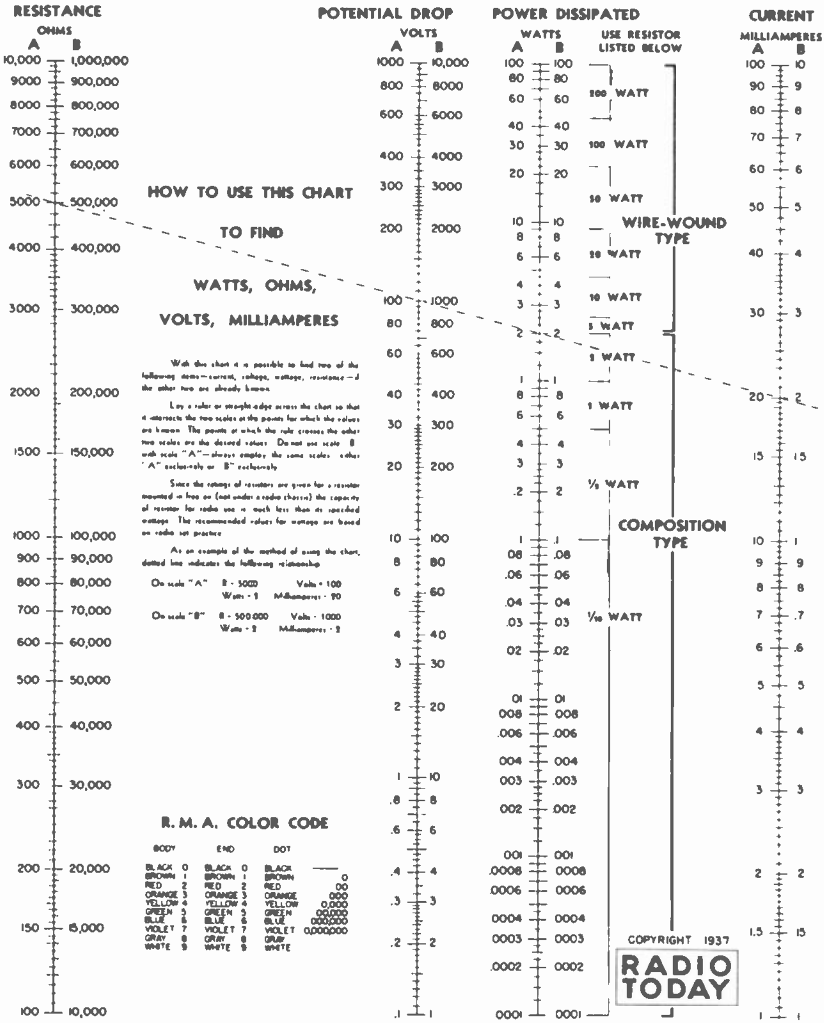
Body Color		End Color		Dot Color	
Black	0	Black	0		
Brown	1	Brown	1	Brown	0
Red	2	Red	2	Red	00
Orange	3	Orange	3	Orange	000
Yellow	4	Yellow	4	Yellow	0000
Green	5	Green	5	Green	00000
Blue	6	Blue	6	Blue	000000
Purple	7	Purple	7	Purple	0000000
Gray	8	Gray	8	Gray	00000000
White	9	White	9	White	000000000

The body color of a resistor denotes the first significant figure, the end color the second significant figure and the dot indicates the number of ciphers after the first two significant figures.

Example: A 350 ohm resistor has an Orange Body, Green End, and Brown Dot. First significant figure is 3 (Orange Body), second significant figure is 5 (Green End) and one cipher following (Brown Dot).

(Courtesy Hygrade Sylvania Corp.)

HOW TO TELL WHAT RESISTOR TO USE



HOW TO USE THIS CHART TO FIND WATTS, OHMS, VOLTS, MILLIAMPERES

With this chart it is possible to find two of the following items—current, voltage, wattage, resistance—if the other two are already known.

Lay a ruler or straight-edge across the chart so that it intersects the two scales at the points for which the values are known. The points at which the rule crosses the other two scales are the desired values. Do not use scale "B" with scale "A"—always employ the same scales, either "A" exclusively or "B" exclusively.

Since the ratings of resistors are given for a resistor mounted in free air (not under a radio chassis) the capacity of resistor for radio use is much less than its specified wattage. The recommended values for wattage are based on radio set practice.

As an example of the method of using the chart, dotted line indicates the following relationship:

On scale "A"	R - 5000	Volts - 100
	Watts - 2	Milliamperes - 20
On scale "B"	R - 500,000	Volts - 1000
	Watts - 2	Milliamperes - 2

R. M. A. COLOR CODE

BODY		END		DOT	
BLACK	0	BLACK	0	BLACK	—
BROWN	1	BROWN	1	BROWN	0
RED	2	RED	2	RED	00
ORANGE	3	ORANGE	3	ORANGE	000
YELLOW	4	YELLOW	4	YELLOW	0,000
GREEN	5	GREEN	5	GREEN	00,000
BLUE	6	BLUE	6	BLUE	000,000
VIOLET	7	VIOLET	7	VIOLET	0,000,000
GRAY	8	GRAY	8	GRAY	
WHITE	9	WHITE	9	WHITE	

RADIO TODAY

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UNIT NO. 1

EXPLANATION OF RATIO AND PROPORTION

LESSON NO. 21

LET'S LOOK AHEAD

.....YOUR BASIC FOUNDATION IS ALMOST COMPLETED.

As you begin the study of this, the twenty-first lesson, you have the deep satisfaction of knowing that the basic foundation of your future training is two-thirds completed.

Page by page, lesson by lesson, you have been building a foundation that is firm and strong. As you progress to the advanced portions of your training, you will naturally encounter problems that are more complex. But they need cause you no concern, for the knowledge you will secure from the first thirty lessons comprising Unit One will enable you to master them handily.

A building of only three or four stories does not require a foundation of exceptional strength. A man, whose ambitions are limited, may also "get by" with limited knowledge, or a weak foundation. But the higher the building and the ambitions of man soar, the stronger must be the foundation upon which that building and those ambitions must rest. You want to go as high in the radio industry as possible. That is why you are building a basic foundation of impregnable strength.

When you have completed Lesson Thirty, you will be ready to embark upon an interesting journey that will take you through Receiver Servicing, Transmitters, and other advanced subjects. But your journey should be both pleasant and rapid, for you will be in possession of a wealth of valuable information which will clear your path of technical obstacles.

You may look ahead to your future studies with the assurance that can only come through a thorough understanding of the fundamentals of electricity and radio. And.....when you have completed those advanced studies, you will be able to face the future, secure in the thought that your training is built upon a foundation whose strength is fully capable of supporting the loftiest ambitions.

Midland training is complete......it goes all the way through radio. Stick to it with determination so that you can climb to the top, safely beyond the reach of "failure" and blasted hopes.

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Lesson Twenty-One

EXPLANATION of RATIO and PROPORTION

"In keeping with the plan of making your course of study as complete as possible, I have included another lesson on mathematics. It may be that you did not study the subjects covered in this lesson while attending public school. Therefore, I suggest that you spend sufficient time on this material to master it completely and thoroughly.

"A complete comprehension of this lesson will, I am sure, assist you in learning many of the interesting things to come."

1. PERCENTAGE. The word "per cent" means "by the hundred". The symbol for per cent is %. 5% means 5 per cent or $\frac{5}{100}$ or .05! Percentage is merely a convenient means of representing a part of the whole when it is assumed that the whole is divided into 100 equal parts.

Since per cent does mean "by the hundred", you should notice carefully that the per cent sign stands for two decimal places. Thus, 10% is .10; .05% is .0005; 85% is .85; 200% is 2.00; etc. To reduce a fraction to the percentage notation, first change the fraction into a decimal and then multiply by 100.

Example: Change $\frac{3}{5}$ into an equivalent per cent.

$$\frac{3}{5} = \frac{6}{10} = .6 = 60\%$$

We know that 50% means 50 one-hundredths, or .50, or $\frac{1}{2}$. Therefore, 50% of 300 = $\frac{1}{2} \times 300 = 150$. The 300 is called the base, the 50% is called the rate, and the 150 is known as the percentage. Listed in tabular form, these definitions are:

(1) The base is the number of which the per cent is taken.
(2) The rate is the number of per cent taken.
(3) The percentage is that part of the base determined by the rate.

There are three types of examples to be considered in the solution of percentage problems. They are as follows:

Type 1. To find the percentage when the rate and base are known.
Type 2. To find the rate when the percentage and base are known.
Type 3. To find the base when the percentage and rate are known.

Let us first consider an example of Type 1.

Example 1: We know the base and rate and wish to find the percentage. Let us say that the base is 60 and the rate 5%. Or, in other words, we wish to find 5% of 60. First, the rate is changed into a decimal; 5% = .05! Next, the base is multiplied by the rate; .05 × 60 = 3. 3, therefore, is the percentage. From this example, we can formulate an equation which expresses the relation between these three terms. It is: Percentage equals base times rate (P = B × R). By using this form of the equation, any percentage problem of the first type may be solved. Or, to find the percentage, the base is multiplied by the rate. Remember to change the rate into a decimal fraction.

Example 2: What is 72% of 40? 72% = .72! 40 × .72 = 28.8! 28.8 is the percentage.

This general equation may, by transformation, be solved for the rate. After this has been done, it reads as follows: Rate equals percentage divided by base (R = P ÷ B). This form of the equation may be used to solve all percentage problems of the second type.

Example 3: Let us assume that the base is 150, and that the percentage is 30. To find the rate, 30 is divided by 150. $\frac{30}{150} = \frac{2}{10}$ = .2 = 20%.

Example 4: 20 is what per cent of 120? 20 is the percentage, and 120 is the base; we wish to find the rate. $\frac{20}{120} = \frac{1}{6} = .16\frac{2}{3} = 16\frac{2}{3}\%$.

If the general equation is solved for the base, it then reads: Base equals percentage divided by the rate (B = P ÷ R). This may be used to solve all percentage problems of the third type.

Example 5: Suppose that the percentage is 25, the rate is 5%, and it is desired to find the base. Changing the 5% into .05, we have: $\frac{25}{.05}$ = 500.

Example 6: 21 is 70% of what number? 21 is the percentage, 70% is the rate. The base equals $\frac{21}{.70}$ = 30.

Exercises

1. What is 32% of 76? *Answer:* 24.32

2. What is 97% of 18? *Answer:* 17.46
3. 27 is what per cent of 29? *Answer:* 93.1%
4. 3 is what percent of 270? *Answer:* 1.1%
5. 17 is 4% of what number? *Answer:* 425
6. 60% of what number is 12? *Answer:* 20

The problems heretofore considered have been of the very simplest type. In your future study, there may arise problems to which, at first sight, it may appear that the foregoing formulas do not apply. However, upon analyzing the problem, you will find that it is solvable by the application of one or more of these formulas.

Example 7: It is stated that a vacuum tube amplifies a voltage 18 times. The DC power applied to the tube is 8 watts; and of this power, 62% is lost in the dissipation of heat. A second vacuum tube of a different type will give 25% more amplification with 15% less loss. What are the amplification and the loss of the second tube, if the DC power applied to it is the same as that of the first tube?

First, to determine the amplification of the second tube, we have given 18 (the amplification of the first tube) and 25% (the increase in amplification of the second tube over the first). The 18 is the base and the 25% is the rate. The percentage is:

$$18 \times .25 = 4.5$$

The total amplification of the second tube is:

$$18 + 4.5 = 22.5$$

The last part of the problem states that 62% of the 8 watts of DC power is lost. The actual loss is:

$$8 \times .62 = 4.96 \text{ watts}$$

The loss of the second tube is 15% less than this:

$$4.96 \times .15 = .744 \text{ watts}$$

The .744 is the difference in power loss between first and second tubes. The total loss of the second tube is, therefore:

$$4.96 - .744 = 4.216 \text{ watts}$$

Per cents greater than 100% are sometimes used in percentage notation. Thus, 6, which is 2 times 3, is said to be 200% of 3. Likewise, 9 is 1½ times 6 or 150% of 6.

2. EFFICIENCY. Suppose that a certain machine delivers ¾ of the energy supplied to it as useful work. The remaining ¼ is consumed within the machine itself; that is, it is converted into

heat energy due to the friction of the moving parts. We do not actually know how much energy is being supplied to the machine nor how much can be taken from it, but we do know that for each 5 parts of energy supplied to it, 4 of them are useful and one is wasted. It is for problems such as these that the idea of percentage is particularly useful. It can be said that this machine wastes 20% of the energy supplied to it. We are now ready to define a new term; it is "efficiency". *Efficiency is the amount of useful work which can be taken from a machine, divided by the total energy or work, which is put into the machine.* It is ordinarily expressed as a per cent. Thus, we would say that the machine in the preceding example was 80% efficient, or had an efficiency of 80%. The power applied to a machine is known as the input and the power which may be taken from the machine is the output. The efficiency may be found by the formula:

$$\text{Efficiency (in \%)} = 100 \times \frac{\text{Output}}{\text{Input}}$$

The 100 is used in the above equation in order that the efficiency will be given directly in per cent instead of as a decimal.

Example 1: The DC power input to a vacuum tube is 54 watts. The available AC power output is 12 watts. What is the efficiency? Substituting in the formula, we have:

$$\text{Efficiency} = 100 \times \frac{12}{54} = 100 \times .22 = 22\%$$

The difference between the output and the input is the power loss.

Example 2: The efficiency of a tube is 30%. The output is 20 watts. What is the power loss?

The efficiency and output are known. Before the power loss may be found, the input must be calculated. This is accomplished by changing the formula to read:

$$\text{Input} = 100 \times \frac{\text{Output}}{\text{Efficiency (in \%)}}$$

Substituting in this formula, we have:

$$\text{Input} = 100 \times \frac{20}{30} = 66.6 \text{ watts}$$

The power loss is:

$$66.6 - 20 = 46.6 \text{ watts}$$

The power loss may also be calculated in another manner. The efficiency is 30%; this means that 30% of the input is available as the output. Therefore, the remaining 70% of the input is the power lost in the tube. Thus, the power loss may be determined by first subtracting the efficiency from 100%; then the number obtained is the per cent of the input which is lost.

$$\text{Power loss} = 70\% \text{ of } 66.6 = .70 \times 66.6 = 46.6 \text{ watts}$$

Example 3: The maximum power which may be dissipated in the form of heat in a particular tube is 15 watts. If the tube is operating at an efficiency of 40%, what is the permissible power input, and what output can be obtained?

Of the power input, 40% is available for output power. The remaining 60% is lost in the tube. There are two known quantities, the power loss (15 watts) and the per cent (60%). The 15 is the percentage and the 60% is the rate. The input power is the base which must be found. This is a type 3 percentage problem. The base (input power) is:

$$\frac{15}{.60} = 25 \text{ watts}$$

The output is 40% of the input; therefore:

$$\text{Output} = .40 \times 25 = 10 \text{ watts}$$

Notice that the sum of the output and the power loss is equal to the input (10 + 15 = 25).

We shall have occasion to use the idea of efficiency many times in the study of radio transmitting circuits.

3. RATIO. In many mathematical problems, it is necessary to compare one number with another. Considering the two numbers 20 and 30, we may say that 30 is $1\frac{1}{2}$ times as large as 20, or that 20 is $\frac{2}{3}$ as large as 30. We have then expressed the relation between the two numbers by means of fractions. This relation may also be expressed by means of the percentage notation. We may say that 30 is 150% of 20; or, as it would more likely be expressed, 20 is $66\frac{2}{3}\%$ of 30.

There is another method which is often used to express this relation between two numbers. It is known as "ratio". *Ratio may be defined as the relation between two numbers expressed by dividing the first by the second.* Thus, the ratio between the two numbers 20 and 30 is 20 divided by 30, or 2 divided by 3. This is often written 2:3, and read as the ratio of 2 to 3.

A ratio is nothing more than an indicated division. This is also the definition for a fraction, so all rules which apply to fractions, apply equally well to ratios. It is obvious that two things cannot be compared unless they are of like kind. Thus, a ratio between hours and inches would have no meaning, as the two units are in no way similar. Let us try another example. Express the relation between the two numbers 12 and 60. Written as a fraction, this would be 12 divided by 60, which, when reduced to lowest terms, becomes $\frac{1}{5}$, or it may be stated that these two numbers are in the ratio of 1:5.

The two numbers used in a ratio are called the *terms* of the ratio. The first number of the ratio is called the antecedent, the second number the consequent. The antecedent is the dividend and the consequent is the divisor. Let us solve a problem involving ratio.

Example 1: Suppose that $60.00 is to be divided into two parts. The amount of money in the two parts is to have the ratio of 2:3. This means that of each $5.00 of the $60.00, $2.00 will be placed in one pile and $3.00 in a second pile. From this, it is easy to see that $\frac{2}{5}$ of the $60.00 is to be placed in the first pile, and $\frac{3}{5}$ of the $60.00 is to be placed in the second pile. Or, the relation may be expressed as a percentage: 40% of the $60.00 is placed in the first pile, and 60% of the $60.00 is placed in the second pile. To solve such a problem by ratio, the two terms of the ratio are added together: $2 + 3 = 5$. The quantity involved is then divided by this sum: $60 \div 5 = 12$. To find the amount of money to be placed in the first pile, the first term of the ratio is multiplied by this quotient (12): $12 \times 2 =$ $24.00. To find the amount of money to be placed in the second pile, the second term of the ratio is multiplied by this same quotient: $3 \times 12 =$ $36.00. Notice that the two numbers, $24.00 and $36.00, are in the ratio of 2:3, since $\frac{24}{36} = \frac{2}{3}$.

Example 2: Suppose that 30 people are to be divided into two groups in the ratio of 3:7. How many people will there be in each group? The sum of the terms of the ratio is:

$$3 + 7 = 10$$

When the number of people is divided by the sum, there is obtained:

$$\frac{30}{10} = 3.$$

The number of people in the first group is:

$$3 \times 3 = 9$$

The number in the second group is:

$$3 \times 7 = 21$$

The ratio 3:2 is said to be the inverse of the ratio 2:3. The ratio of the two currents flowing through the two branches of a parallel circuit is equal to the inverse ratio of the two resistances. Fig. 1 shows a parallel circuit consisting of a 4 and a

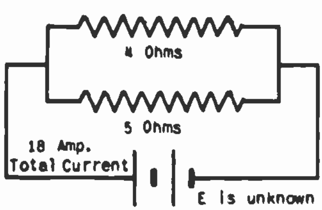

Fig. 1 Illustrating the application of ratio to electrical circuits.

5-ohm resistor. The voltage of the battery is not known, but the total current drawn from it is 18 amperes.

The ratio of the resistances is 4:5, and the ratio of the two currents flowing through them is the inverse of this, or 5:4.

The sum of the terms of this ratio is:

$$5 + 4 = 9$$

The number of amperes (18) when divided by this sum gives:

$$\frac{18}{9} = 2$$

Therefore, the current through the 4-ohm resistor is this quotient multiplied by 5, since the ratio must now be used in the inverse order.

$$2 \times 5 = 10 \text{ amp. (through 4-ohm resistor)}$$

The current through the 5-ohm resistor is the quotient multiplied by 4:

$$2 \times 4 = 8 \text{ amp. (through 5-ohm resistor)}$$

Thus, while the resistors are in the ratio of 4:5, the corresponding currents are in the ratio of $\frac{10}{8}$, or $\frac{5}{4}$, or 5:4.

While many problems may be solved by means of ratio, it is sometimes simpler to employ the method of proportion, which we shall now discuss.

4. **PROPORTION.** A proportion is a statement which expresses the equality of two ratios. For example: The ratio 1:3 and the ratio 3:9 are equal, since when written in fractional form, both can be reduced to $\frac{1}{3}$. When the relation is expressed as 1:3 = 3:9, it is called a proportion. This is read: 1 is to 3 as 3 is to 9, and it is sometimes written 1:3::3:9. It may also be written in fractional form as: $\frac{1}{3} = \frac{3}{9}$. As previously stated, both terms of a ratio must refer to like things. In a proportion, however, the two terms which constitute the first ratio do not have to refer to the same two things to which the terms of the second ratio refer. For example: 2 hours:3 hours = \$6.00:\$9.00. Both terms of the first ratio are hours, while both terms of the second ratio are dollars. This is also a proportion and is correctly stated.

The first and last terms of a proportion are called the "extremes", the second and third terms are known as the "means". In the preceding proportion, the 2 and 9 are the extremes, and the 3 and 6 are the means. This proportion may also be written:

$$\frac{2 \text{ hours}}{3 \text{ hours}} = \frac{\$6.00}{\$9.00}$$

In which case the extremes and means are the same as before. When written in this form, it may or may not be considered as a proportion. If it is, it should be read: 2 hours is to 3 hours as $6.00 is to $9.00.

There are three fundamental principles which must be learned in order to solve proportional problems. They are:

1. In any proportion, the product of the means is equal to the product of the extremes.
2. The product of the means divided by either extreme gives the other extreme.
3. The product of the extremes divided by either mean gives the other mean.

To prove these principles, let us use the proportion 3:5 = 6:10. The extremes are 3 and 10; the means are 5 and 6. The product of the extremes is 3 × 10 = 30; the product of the means is 5 × 6 = 30. This proves the first principle. The product of the means divided by one extreme gives the other extreme:

$$\frac{5 \times 6}{3} = \frac{30}{3} = 10 \text{ (the second extreme)}$$

or,

$$\frac{5 \times 6}{10} = \frac{30}{10} = 3 \text{ (the first extreme)}$$

This proves the second principle. The product of the extremes divided by either mean gives the other mean:

$$\frac{3 \times 10}{5} = \frac{30}{5} = 6 \text{ (the second mean)}$$

or,

$$\frac{3 \times 10}{6} = \frac{30}{6} = 5 \text{ (the first mean)}$$

Thus, the third principle is proved. If upon applying any of these principles, results are obtained which are known to be untrue, the original expression was not a true proportion. Several examples involving the use of proportion will now be discussed.

Example 1: If 18 condensers cost $2.16, how much will 5 condensers cost?

The ratio of the number of condensers in the first instance to that in the second is 18:5. If we are to have a proportion, another ratio must be found. The cost of the first lot of condensers is in the same ratio to the cost of the second lot as the preceding ratio, 18:5. Therefore, the proportion is:

18:5 = $2.16:X

Where X is the cost of 5 condensers, the unknown X is an extreme and, by the second principle, it is equal to the product of the means divided by the other extreme:

$$X = \frac{5 \times 2.16}{18} = \frac{10.80}{18} = \$.60 \text{ (Ans.)}$$

Notice that the first two terms of the proportion refer to number of condensers, while the last two terms refer to money.

Example 2: If 4 vacuum tubes cost $1.80, how many vacuum tubes can be bought for $3.15?

The ratio of the costs is 1.80:3.15! The ratio of the number of tubes is 4:X, where X is the number of tubes that can be bought for $3.15. These two ratios must be equal and the proportion is:

$$4:X = 1.80:3.15$$

By the third principle:

$$X = \frac{4 \times 3.15}{1.80} = \frac{12.60}{1.80} = 7 \text{ (Ans.)}$$

The relation between two variable quantities is often expressed by stating that one is proportional to the other. For example, the current flowing through a circuit is proportional to the applied voltage. The actual voltage and current are not known, but, whatever the voltage may be, the current will be such that the ratio of the voltage to the current is always the same constant value as long as the circuit is not changed. When one quantity is directly proportional to another, doubling the value of the first quantity doubles the value of the second; and likewise, halving the value of the first halves the value of the second. Thus, the ratio of the first quantity to the second is a constant value.

The word "directly" must be included in the preceding definition, since there are other relationships between variable quantities for which the above conditions do not hold. For example, we know that there is some relation between the amount of resistance in a circuit and the amount of current that flows, assuming that the applied voltage remains constant. However, as the resistance is increased, the current is decreased; therefore, the two quantities are not directly proportional to each other. Instead, it is stated that the current is inversely proportional to the resistance. This means that if the resistance is doubled, the current is halved; and if the resistance is halved, the current is doubled. When two quantities are so related that as one of them increases, the other decreases at the same rate, the first is said to be inversely proportional to the second.

Example 3: Fig. 2 illustrates a circuit containing a 20-ohm and a 40-ohm resistor in parallel. The applied voltage is 120 volts. By using Ohm's Law, it is found that the current flowing

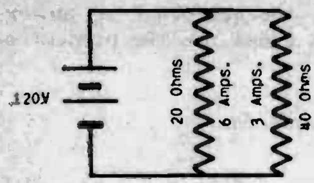

Fig. 2 Circuit used in Example 3.

through the 20-ohm resistor is 6 amperes and that through the 40-ohm resistor, 3 amperes. There is evidently some relation between the currents flowing through these resistors and the values of the resistors. Let us see what it is. The ratio of the two resistors is 20:40. The ratio of the currents is 6:3. These two ratios are evidently not equal, since 20 divided by 40 is ½ and 6 divided by 3 is 2. However, we have said that the current which flows is *inversely* proportional to the resistance, and so before a proportion can be formed, the current ratio must be inverted. The proportion then reads 20 ohms : 40 ohms = 3 amperes:6 amperes. This is an example of an inverse proportion.

Example 4: A voltage of 120 volts is applied across a parallel circuit containing a 3,000 and a 4,000-ohm resistor. If 40 ma. flow through the 3,000-ohm resistor, how much will flow through the 4,000-ohm resistor?

The resistance ratio is 3,000:4,000. The current ratio is 40 ma.:X ma. The inverse of the current ratio is X ma.:40 ma. The proportion should state that the resistance ratio is equal to the inverse of the current ratio, or 3,000:4,000 = X:40.

$$X = \frac{40 \times 3{,}000}{4{,}000} = 30 \text{ ma. (By principle 3)}$$

In addition to direct and inverse proportion, there are other types in which one quantity varies as the square of the other. A familiar example is the relation between the current flowing in a circuit and the power dissipated as heat (I^2R).

If the resistance is kept constant and the current is doubled, the power will increase four-fold. Thus, the power is not directly proportional to the current, since they do not increase at the same rate. The power is directly proportional to the square of the current. In a like manner, the area of a circle is proportional to the square of the diameter.

Still another type of proportion is the one which relates the diameter of a wire to the resistance of a given length of the wire. If the diameter of a wire is increased and the length is held constant, the resistance is decreased, due to the larger cross section of the wire. There is obviously an inverse relation between these two quantities, since one increases as the other decreases. When the diameter is doubled, is the resistance halved? By reference to any copper wire table, we will find that doubling the diameter reduces the resistance to one-fourth of its original value. Therefore, the resistance is not inversely proportional to the diameter, but is inversely proportional to the *square* of the diameter.

These are the simpler types of proportions and they by no means include all of the ways in which one variable quantity may be related to another; in fact, the number of kinds of proportions is unlimited.

5. **POSITIVE AND NEGATIVE NUMBERS.** Most of us are familiar with at least one application of negative numbers; this is their use to indicate temperatures below zero. We know, for instance, that a temperature of 15 degrees F below zero is written -15° F. This is just one use, and throughout your study of Radio and Television, you will encounter negative numbers several times. For this reason, it is thought advisable to discuss the fundamental mathematical operations involving negative numbers at this time. Positive numbers are preceded by a plus (+) sign and negative numbers by a minus (-) sign. In ordinary mathematical work, however, when negative numbers are not used, the plus sign is omitted from the positive numbers since there is no chance of confusion.

Both positive and negative numbers may be represented by points on a line, as shown in Fig. 3. Any point on this line is selected

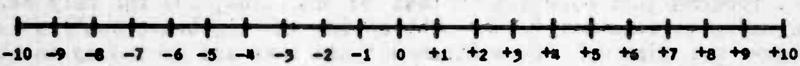

Fig. 3 Chart showing the significance of negative numbers.

and designated as zero; then, all positive numbers will lie to the right of this point and all negative numbers to the left, as shown in the diagram.

All the positive numbers, and all the negative numbers, together with zero, form a system known as *algebraic numbers*. The absolute or numerical value of a number is the value of that number without regard to its sign. Thus, -3 and +3 have the same absolute value. We are now ready to consider the operation of adding both positive and negative numbers. Referring to Fig. 3, suppose that we wish to add 2 to 6. Starting from 6, we count two places to the right and arrive at 8. So we say 6 + 2 = 8. To add +3 to -2, start at -2 and count three places to the right, arriving at +1. We, therefore, say that -2 + (+3) = +1. To add +3 to -7, start at -7 and count 3 places to the right, arriving at -4. We, therefore, say that -7 + (+3) = -4. To add a positive number, we count to the right; to add a negative number, we must count to the left. For example, add -5 to +3. Starting at +3, count 5 places to the left, arriving at -2. We, therefore, say that 3 + (-5) = -2. To add a -3 to a -2, start at -2 and count 3 places to the left, arriving at -5. Therefore, -3 + (-2) = -5. The general rules for the addition of algebraic numbers is as follows:

1. The algebraic sum of two numbers having like signs is equal to the sum of their absolute values with the common sign prefixed.

2. The algebraic sum of two numbers having unlike signs is equal to the difference between their absolute values with the sign of the greater in absolute value prefixed.

Let us try a few examples using the above rules. To add a +5 to a +3, add their absolute values, which is 8, and prefix a (+) sign (+8). To add a -4 to a -7, add their absolute values, obtaining 11, and prefix a (-) sign (-11). To add a -7 to a +3, take their difference (4), and prefix a (-) sign (-4), since the -7, which has the greater absolute value, is a negative number.

Exercises

Add the following:

1.	-9234 and +3461	*Answer:*	-5773
2.	+8263 and -7432	*Answer:*	+831
3.	-561 and -221	*Answer:*	-782
4.	+387 and +422	*Answer:*	+809

The subtraction of algebraic numbers will be very easy if you have learned the rules for adding algebraic numbers. Subtraction is a process just opposite to that of addition, and the only rule one needs to remember in the subtraction of algebraic numbers is: Change the sign of the subtrahend[1] and then add according to the rules for the addition of algebraic numbers. Let us see how this works out. Subtract +3 from +8. Changing the sign of the subtrahend, we have a -3. To add a -3 and a +8, we find their difference (5) and prefix the sign of the +8, since it has the greater absolute value (+5). Therefore:

$$(+8) - (+3) = +5$$

To subtract -4 from -11, change -4 to +4; find the difference (7); prefix the (-) sign (-7).

$$(-11) - (-4) = -7$$

To subtract -5 from +8, change -5 to +5, and add algebraically:

$$(+5) + (+8) = +13$$

To subtract +3 from -11, change +3 to -3; since -11 and -3 now have like signs, find their sum (14) and prefix the common sign (-14).

$$(-11) - (+3) = -14$$

In all the subtractions so far given, the absolute value of the subtrahend has been less than the absolute value of the minuend.

[1] The "subtrahend" is defined in Lesson 4, Unit 1.

This, however, is not always the case. For example, +8 may be subtracted from +5. Changing the sign of the +8, we obtain -8, which, when added algebraically to +5, gives -3. To subtract -9 from +2, change the -9 to +9 and then add to obtain +11. These examples should serve to illustrate the applications of the foregoing rule.

Exercises

1. Take -21 from +36	*Answer:*	+57
2. Take +34 from +12	*Answer:*	-22
3. Take +13 from -20	*Answer:*	-33
4. Take -18 from -5	*Answer:*	+13

Multiplication of algebraic numbers involves no great difficulty. There are just two simple rules to remember. They are: *The product of two numbers having like signs is a positive number. The product of two numbers having unlike signs is a negative number.* For example, +3 × +4 = +12; -7 × -3 = +21; +8 × -4 = -32.

The rules which apply to the multiplication of algebraic numbers also apply to their division. They are: *The quotient of two numbers having like signs is a positive number. The quotient of two numbers having unlike signs is a negative number.*

Example: +12 ÷ +3 = +4; -18 ÷ -9 = +2; -36 ÷ +6 = -6.

Exercises

1. -23 × +17	*Answer:*	-391
2. -14 × -12	*Answer:*	+168
3. -128 ÷ +32	*Answer:*	-4
4. -256 ÷ -64	*Answer:*	+4

Resistance of Insulating Materials

Material	Resistivity, megohms* per square inch-mil.
Asbestos	7
Asbestos and muslin, oiled	850
Cotton, single covering	10
Cotton, single covering, soaked in paraffin	11,800,000
Cotton, double covering	10
Cotton, double covering, shellacked	25
Fiber, red, vulcanized	470
Mica	33,000
Micanite cloth, flexible	440,000
Micanite paper, flexible	500,000
Micanite plate, flexible	320,000
Oiled cloth	650
Oiled paper, double coat	1,600
Brown paper	2
Paraffined paper	11,800,000
Rubber sheet	3,000,000
Shellacked cloth	30
Silk, single covering	50
Silk, single covering, shellacked	75
Silk, double covering	50
Silk, double covering, shellacked	75

*A megohm = 1,000,000 ohms. This column gives resistances in megohms for a square inch of material $\frac{1}{1000}$ in. in thickness.

Notes

(These extra pages are provided for your use in taking special notes)

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POWER & LIGHT BUILDING, KANSAS CITY, MISSOURI

UNIT NO. 1

TUNING CIRCUITS

LESSON NO. 22

AUGUST, 1877

.......A REVOLVING PIECE OF TIN FOIL SPEAKS!

One August day in 1877, John Kreusi, the man who made the first model of Edison's talking machine from a crude sketch, was so startled at hearing a human voice speak, "Mary Had A Little Lamb", that he excitedly exclaimed, "Mein Gott in Himmel!"

And little wonder that he was so startled, for this voice came, not from a human throat, but from a tiny horn. It had been recorded on a piece of tin foil, and represented the first successful recording and reproduction of sound.

John Kreusi and thousands of other people were amazed. To know that the human voice could be recorded on a piece of tin foil, and then be reproduced at will, seemed beyond belief. But today, people are not surprised at machines that talk and sing. They accept, without thought, the wonderful accomplishments which make it possible for them to turn a tiny switch and listen to marvelous electrical recordings of great orchestras and prominent people.

The very fact that most of us are inclined to calmly accept the wonders created through the inventive mind of man is largely responsible for our lack of foresight in taking advantage of the opportunities created by those wonders. We fail to appreciate the comforts and higher living standards they have made possible. And we also fail to appreciate the actual money-making opportunities placed within our reach.

Perhaps we should say, "SOME of us fail to appreciate the money-making opportunities". YOU realize that such opportunities exist, for you are preparing yourself to take advantage of them. Other ambitious and foresighted men are doing the same. However, you should guard yourself carefully against the advice of well-meaning but poorly informed people, who, because they know very little about the vastness and future possibilities of the Radio-Television industry, may be inclined to discourage you. Remember this always........

IT'S YOUR FUTURE THAT IS AT STAKE! INSURE IT BY STICKING AND STUDYING!

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Lesson Twenty-Two

TUNING CIRCUITS

"Of course, you have undoubtedly tuned a radio receiver many times, but when tuning that receiver, did you not wonder why it was possible to turn a knob and thereby select the station that you desired to receive?

"The subject of Tuning Circuits is both important and interesting. I am sure you will derive a lot of pleasure in understanding how it is possible to tune from one station to another."

1. **A BRIEF REVIEW OF SERIES AND PARALLEL RESONANCE.** A complete discussion of series and parallel resonance was given in Lesson 14 and it is not our purpose to repeat that material here. Rather, we shall briefly review the most important properties of each type of resonant circuit.

A resonant circuit is one that contains inductive reactance and capacitive reactance. At the resonant frequency, the two reactances are exactly equal and, having opposite effects upon the phase angle, they balance each other. In this case, the only opposition to the flow of the current is that offered by the total resistance of the circuit which, ordinarily, is quite low. These are the conditions necessary for series resonance. Since the opposition to the flow of current at the resonant frequency is limited only by the resistance of the circuit, the flow of current will ordinarily be very great at resonance. At frequencies lower than or greater than resonance, a smaller value of current (higher impedance) will flow. It may, therefore, be stated that one of the most important properties of a series resonant circuit is that it allows a maximum current to flow through it at the resonant frequency.

The voltage developed across either the coil or the condenser is equal to the current flowing through that element times its reactance. Since the current at resonance is very large, the voltage developed across the coil or condenser is high and may exceed the applied voltage many times. This may be said to be the second important property of a series resonant circuit.

In a parallel resonant circuit, the current flowing through the coil is 180° out of phase with the current flowing through the condenser, provided that the resistance in the circuit is negligible. The line current, or current flowing from the voltage source, is equal to the difference between the coil current and condenser current. Therefore, at resonance, it would be zero if the coil current and condenser current were *exactly* equal and *exactly* 180° out of phase. Since the presence of resistance in the circuit, due to the conducting wires, the turns of the coil, condenser plates, etc., precludes the possibility of attaining this phase difference, there will always be some line current flowing. However, at the resonant frequency, this line current will be minimum and the smaller the total resistance of the circuit, the lower this minimum will become. This is one of the important properties of a parallel resonant circuit.

At the resonant frequency, the current flowing through the coil and condenser is rather large, perhaps many times as great as the actual line current itself. This may be said to be the second important property of a parallel resonant circuit.

2. CALCULATION OF THE RESONANT FREQUENCY.[1] At resonance, the inductive reactance of a circuit is equal to the capacitive reactance. The inductive reactance is 6.28 × F × L and the capacitive reactance is 1 ÷ (6.28 × F × C). In accordance with this necessary condition, these two expressions may be equated as follows:

$$6.28 \times F \times L = \frac{1}{6.28 \times F \times C} \qquad (1)$$

It is a well-known fact that if both sides of an equation are multiplied by the same thing, the balance of the equation is not destroyed. Let equation (1) be multiplied by F; it will then read:

$$6.28 \times F \times F \times L = \frac{F}{6.28 \times F \times C} \qquad (2)$$

The two F's in the right member of equation (2) will cancel, leaving:

$$6.28 \times F^2 \times L = \frac{1}{6.28 \times C} \qquad (3)$$

Let both members of equation (3) be divided by 6.28 × L; it then reads:

$$\frac{\cancel{6.28} \times F^2 \times \cancel{L}}{\cancel{6.28} \times \cancel{L}} = \frac{1}{6.28 \times C} \times \frac{1}{6.28 \times L}$$

[1] While several formulas are given in the presentation of this subject, it is not necessary to memorize all of these. However, you must be sure that you understand how to use them.

Or:

$$F^2 = \frac{1}{(6.28)^2 \times L \times C} \qquad (4)$$

Taking the square root of both sides of the equation, we obtain:

$$F = \frac{1}{6.28 \times \sqrt{L \times C}} \qquad (5)$$

By dividing 1 by 6.28, we obtain .159, and equation (5) becomes:

$$F = \frac{.159}{\sqrt{L \times C}} \qquad (6)$$

This equation gives the frequency in cycles, at which the inductive reactance of the circuit is equal to the capacitive reactance, when L is expressed in henries and C in farads. Since it is much more convenient to use a formula expressing the frequency in kilocycles, the inductance in microhenries, and the capacitance in microfarads, the preceding equation is usually transformed to make this possible. It then becomes:

$$F = \frac{159}{\sqrt{L \times C}} \qquad (7)$$

Where: F is in kilocycles
L is in microhenries
C is in microfarads

Before proceeding further, let us demonstrate the use of this equation by a few examples.

Example 1: At what frequency will a circuit be resonant if it contains an inductance of 100 microhenries and a capacitance of 100 micromicrofarads?

Solution: Before substitution can be made in the formula, the 100 micromicrofarads must be converted into microfarads. This is accomplished by dividing it by 1,000,000, thereby obtaining .0001 microfarad. Substituting these values in equation (7), there is obtained:

$$F = \frac{159}{\sqrt{100 \times .0001}}$$

$$= \frac{159}{\sqrt{.01}}$$

$$= \frac{159}{.1}$$

$$= 1590 \text{ Kc.} \quad \textit{(Answer)}$$

Example 2: At what frequency will a circuit containing a 3-henry coil and a 3-microfarad condenser be resonant?

Solution: Since the inductance is given in henries and the capacitance in microfarads, it would be easier to use formula (6). This may be done if the 3 microfarads are converted into farads. Dividing 3 microfarads by 1,000,000, there is obtained .000003 farad. Then, by substitution in this formula, we have:

$$F = \frac{.159}{\sqrt{3 \times .000003}}$$

$$= \frac{.159}{\sqrt{.000009}}$$

$$= \frac{.159}{.003}$$

$$= 53 \text{ cycles } \textit{(Answer)}$$

It is often desirable to know what particular value of capacitance should be used with a given value of inductance to produce resonance at a given frequency. A formula for the easy determination of this may be derived by the following method:

If equation (4) is multiplied by C, it becomes:

$$F^2 \times C = \frac{\cancel{C}}{(6.28)^2 \times L \times \cancel{C}}$$

$$= \frac{1}{(6.28)^2 \times L}$$

By dividing this last equation by F^2, we arrive at this expression:

$$\frac{\cancel{F^2} \times C}{\cancel{F^2}} = \frac{1}{(6.28)^2 \times L \times F^2}$$

Or:

$$C = \frac{1}{(6.28)^2 \times F^2 \times L}$$

$$= \frac{1}{39.44 \times F^2 \times L}$$

Or:

$$C = \frac{.0253}{F^2 \times L} \qquad (8)$$

Where: C is in farads
F is in cycles
L is in henries

Equation (8) may be converted to a more convenient form such as:

$$C = \frac{25,300}{F^2 \times L} \qquad (9)$$

Where: C is in microfarads
F is in kilocycles
L is in microhenries

By a similar method, the following equation, which is often useful, may be derived:

$$L = \frac{25,300}{F^2 \times C} \qquad (10)$$

Where: L is in microhenries
F is in kilocycles
C is in microfarads

By use of equations (7), (9) and (10), almost any problem concerning resonance may be solved.

Example 3: If a circuit contains 200 microhenries of inductance, how much capacity needs to be added to make the circuit resonant at a frequency of 1,000 kilocycles?

Solution: To solve this example, we shall use formula (9).

$$C = \frac{25,300}{1000^2 \times 200}$$

$$= \frac{25,300}{200,000,000}$$

$$= .0001265 \text{ mfd., or } 126.5 \text{ mmfd.}$$

Example 4: If a 300-micromicrofarad condenser is to produce resonance at a frequency of 500 kilocycles, what inductance must the circuit contain?

Solution: Before substitution in this formula is possible, the 300 micromicrofarads must be changed to .0003 microfarads.

$$L = \frac{25,300}{500^2 \times .0003}$$

$$= \frac{25,300}{75}$$

$$= 337 \text{ microhenries}$$

3. OSCILLATORY ACTION OF A RESONANT CIRCUIT. A resonant cir-

cuit is often called a tuned circuit. If its capacity is variable, it may be made resonant at different frequencies by changing the amount of capacity in the circuit. Since the term "tuned circuit" is somewhat more common than "resonant circuit", it shall be used in the future.

A tuned circuit is shown in Fig. 1. It consists of a conden-

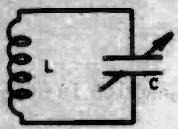


Fig.1 A simple oscillatory circuit.

ser connected across a coil. Whether this circuit shown in Fig. 1 is a series or a parallel tuned circuit will depend, of course, upon how the voltage is applied to it. In a following paragraph, the exact distinction between parallel and series tuned circuits will be given. Before discussing the oscillatory action of a tuned circuit, it is advisable to obtain a general idea of oscillation and oscillatory action as applied to mechanical systems.

The word "oscillate" means to swing back and forth in a regular periodic motion. Undoubtedly the most familiar example of an oscillation is the swinging of a clock pendulum. Let us tie a piece of string to a plum bob and make our own pendulum, as shown in Fig. 2. When undisturbed, the pendulum hangs vertically, as shown at A

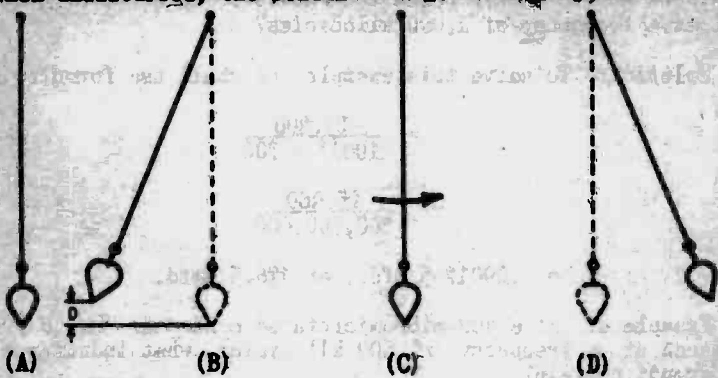


Fig.2 An oscillating pendulum.
(A) Pendulum at rest.
(B) Pendulum displaced to one side. In this position, its energy is potential.
(C) Pendulum passing through its rest position. Its energy is now kinetic.
(D) Pendulum at its extreme right position. Its energy is again all potential.

in the figure. Suppose that the pendulum is now displaced to the left and held in this position as shown at B. When so placed, the pendulum possesses potential energy for, if allowed to fall, it would do work. It possesses potential energy due to the fact that it has been raised above its normal level, as shown by the distance (D) in the diagram.

If the pendulum is now allowed to fall, it will start to return to its normal position and will increase its velocity as it travels. Since its level is being lowered, it is losing its potential energy, but is acquiring kinetic energy as its velocity is increased. At the instant the pendulum reaches its normal position, as shown at C in the figure, it possesses no potential energy; it is still traveling at a rapid rate, however, and therefore possesses considerable kinetic energy. In fact, the kinetic energy that it possesses at this point is very nearly equal to the potential energy it had at B. The kinetic energy will carry it on past its normal position and cause it to rise on the opposite side. As it begins to rise, it gains potential energy; and, since its velocity is decreasing, it loses kinetic energy. Finally, it reaches the point shown at D in the figure. Here all of its energy is potential and is very nearly equal to the original potential energy given to it. This is not strictly true, because a small amount of the energy must have been dissipated as heat in overcoming the friction of the air, when the pendulum bob passed through it.

The pendulum continues to swing back and forth, or to oscillate, changing its energy from potential to kinetic and back to potential, etc. During each swing, a small amount of this energy is converted into heat as the pendulum bob overcomes the friction of the air and so, during any given swing, the total energy possessed by the pendulum is very slightly less than that of the preceding swing. Finally, all the energy originally imparted to the pendulum is dissipated in the form of heat and the pendulum comes to a rest. Electrical oscillations in a tuned circuit or oscillatory circuit are very similar to the mechanical oscillations of a pendulum.

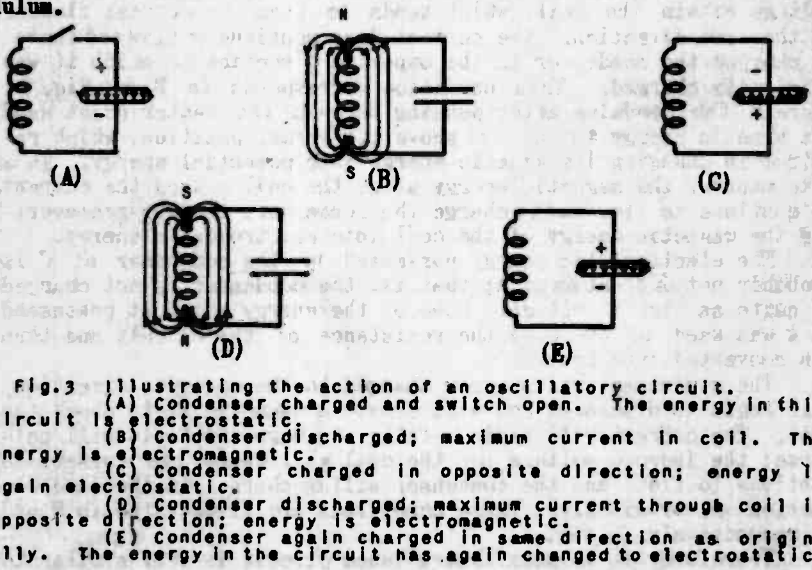


Fig.3 Illustrating the action of an oscillatory circuit.
(A) Condenser charged and switch open. The energy in this circuit is electrostatic.
(B) Condenser discharged; maximum current in coil. The energy is electromagnetic.
(C) Condenser charged in opposite direction; energy is again electrostatic.
(D) Condenser discharged; maximum current through coil in opposite direction; energy is electromagnetic.
(E) Condenser again charged in same direction as originally. The energy in the circuit has again changed to electrostatic.

Let us suppose that by some means, a condenser is charged and is connected across a coil, as shown at A in Fig. 3. The switch in the circuit is open; the condenser cannot discharge; the energy possessed by the tuned circuit is wholly electrostatic. This would correspond to holding a pendulum over to one side of its swing and not allowing it to fall. The charged state of the condenser is indicated by the electrostatic field around it; the lines drawn between its plates are electric lines of force.

The switch is now closed. Immediately the condenser begins to discharge; a current flows from one plate of the condenser, around through the coil to the opposite plate. This current creates a magnetic field around the coil which is accompanied by a self-induced voltage within the coil tending to prevent the rise of the current. The current, therefore, rises slowly and reaches its maximum value just at the instant when the condenser is completely discharged. This condition is illustrated at B in the figure. Since the condenser is completely discharged, its electrostatic field has disappeared. The current, however, is maximum and the magnetic field surrounding the coil has attained its greatest strength. This point of the oscillation is analogous to C, Fig. 2. wherein the pendulum was at the center of its swing and possessed no potential energy, but did possess considerable kinetic energy due to its motion. Likewise, the energy of the tuned circuit is no longer electrostatic, because the condenser is not charged, but is wholly electromagnetic since a strong magnetic field is present about the coil.

As the condenser is now completely discharged, this large value of current will begin to fall. As it decreases in value, the magnetic field about the coil collapses; in so doing, it induces a voltage within the coil, which tends to keep the current flowing in the same direction. The current does continue to flow and thereby charges the condenser in the opposite direction to which it was originally charged. This condition corresponds to D in Fig. 2, wherein the pendulum after passing through its center point used its kinetic energy to carry it above its normal position, which resulted in changing its kinetic energy into potential energy. In a like manner, the magnetic energy about the coil caused the current to continue to flow and to charge the condenser, thereby reconverting the magnetic energy of the coil into electrostatic energy.

The electrostatic energy possessed by the condenser at C is probably not as great as at A; that is, the condenser is not charged to quite as high a voltage. Some of the energy which it possessed at A was used to overcome the resistance of the circuit and thus was converted into heat.

The condenser, which is now charged in the opposite direction, will begin to discharge and will create a magnetic field about the coil. The current will begin to fall; the magnetic field will collapse; the induced voltage in the coil will cause the current to continue to flow, and the condenser will be charged in the same direction as originally. These conditions are illustrated in D and E, respectively, in Fig. 3.

Therefore, it is seen that a tuned circuit is very similar to a pendulum. Current oscillates back and forth between the coil and the condenser and the energy is periodically changed from electrostatic (in the charged condenser) to electromagnetic (in the magnetic field about the coil). The oscillations continue until all of the energy originally bestowed upon the condenser has been converted into heat by the ohmic resistance of the circuit. The oscillating current is, of course, an alternating current, since it reverses its direction. The frequency of this alternating current depends upon two things: the inductance of the coil and the capacitance of the condenser. Its frequency will be the one to which this tuned circuit is resonant and may be determined by formula (7).

If either the inductance of the coil or the capacitance of the condenser is increased, the frequency of this oscillating current becomes lower. With a larger inductance, the tendency of the induced voltage to prevent the current from increasing will be even more effective and it will take it a longer time to rise to its maximum value. Likewise, it will require a longer time to charge a larger capacitance, and, therefore, increasing the size of either element will lower the frequency of this oscillating current.

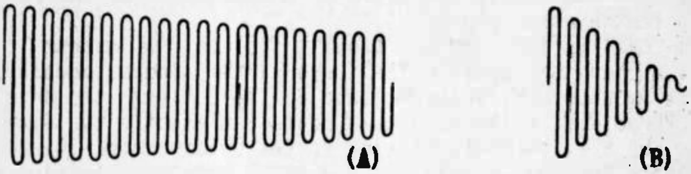


Fig. 4 (A) Waveform of the oscillating current in a circuit containing but little resistance.
(B) Waveform of the oscillating current in a circuit containing considerable resistance. This wave is more "damped".

The waveform of the oscillating current is shown at A in Fig. 4. In this case, the resistance of the circuit was made as low as possible and it is seen that the current oscillates through many cycles before it finally dies down. At B in the same figure is shown the effect of adding a small amount of resistance to the tuned circuit. It is at once noticed that the presence of this resistance causes the oscillating current to decrease very rapidly. When each peak is slightly smaller than the preceding one, the current is said to be a "damped oscillation". Thus, A is slightly damped, while B is highly damped.

A tuned circuit is often called a "tank" circuit, since it has the ability to store energy through one part of the cycle and release it during the following part.

It should be noted that any disturbance which causes the condenser of the tuned circuit to become charged will set up these oscillations in the tuned circuit at the frequency found by formula (7). This frequency is called the natural frequency of the circuit and the oscillations produced are known as free oscillations.

Let us now investigate the use of a tuned circuit in receiving radio signals. Fig. 5 shows a circuit in which the antenna is coupled to a tuned circuit, which in turn is connected between the grid and cathode of a vacuum tube. This could be either a detector or an R.F. amplifier circuit.

The electromagnetic wave in the ether will strike the antenna and induce therein R.F. voltages which are exact reproductions of the R.F. current produced by the station in its broadcasting antenna. These R.F. voltages produce an R.F. current flow from the anten-

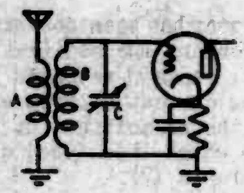


Fig.5 A circuit used to receive radio signals.

na, through the antenna coil to ground, and then in the reverse order as the current reverses direction.

The antenna circuit is, itself, a tuned circuit. It contains inductance both in the antenna coil and in the antenna wire as all conductors possess some inductance. The capacitance of the antenna circuit is that which exists between the antenna wire and the earth; that is, the antenna is one plate of a condenser and the earth, or ground, is the other plate.

The oscillating current flowing through the antenna circuit creates a changing magnetic field around the antenna coupling coil A. This induces R.F. voltages into B, the coil of the tuned circuit. These R.F. voltages are, of course, of exactly the same waveform as the R.F. currents flowing in the antenna circuit.

Before continuing this discussion, we must now determine whether the tuned circuit in this figure is a series or a parallel tuned circuit. The following rules should enable you to very easily distinguish the two types.

1. In a series tuned circuit, the voltage source is in series with the coil and with the condenser. Any current that flows from the voltage source must flow through both the coil and the condenser.

2. In a parallel tuned circuit, the tuned circuit, as a unit, is in series with the applied voltage. The current that flows through the coil and the current that flows through the condenser are not necessarily of the same value as that which is forced to flow by the voltage source.

It might be thought that the tuned circuit shown in Fig. 5 is a parallel tuned circuit; this, however, is untrue. The voltage source in this case is the voltage induced directly into the turns of coil B. Whatever current flows through coil B must also flow through the tuning condenser C. The application of the voltage to this circuit may be represented by the circuit shown in Fig. 6. The coil has been divided into two sections and an AC alternator connected between them; it is, thus, easy to see that this is a series tuned circuit. Actually, a voltage is induced in each turn of the coil and a true representation would show an alternator between each two turns.

An example of a parallel tuned circuit is shown in Fig. 7. The voltage source may be considered to be within the tube and it is evident that the value of the current flowing through the tube

Fig.6 A circuit equivalent to the tuned circuit of Fig. 5. The alternator represents the total voltage induced from A into B in Fig. 5.

is not necessarily the same as that which flows through the coil or through the condenser. Also, the tuned circuit, as a unit, is in series with the voltage source. This, therefore, is a parallel tuned circuit. As a general rule, those used in the grid circuits of vacuum tubes are series tuned, while those used in the plate circuits are parallel tuned circuits.

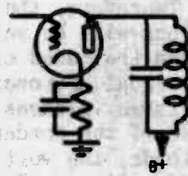


Fig.7 Showing how a parallel tuned circuit may be used with a vacuum tube.

Having satisfied ourselves that the circuit shown in Fig. 5 is a series tuned circuit, we shall continue the discussion of how its oscillatory action may be applied to receiving radio signals. The R.F. voltages induced in the coil B charge the condenser C, thus starting oscillations in the tuned circuit; the current surges back and forth between the coil and condenser. If the resonant frequency or natural frequency of the tuned circuit is equal to the frequency of the incoming radio signal, the R.F. voltages induced in the coil B will be timed correctly to reinforce the oscillating current of the tuned circuit.

Again the pendulum analogy may be used to advantage. The oscillating pendulum of a clock would soon dissipate all its energy and would come to rest in a vertical position were it not for the fact that in swinging back and forth, it is given a push during each of its swings by the escapement wheel of the clock's movement. These energy pulses are so spaced as to produce a maximum effect and are sufficient in amount to compensate for the loss of energy due to friction.

In a like manner, the R.F. voltages induced in coil B occur at such intervals as to add energy to the tuned circuit, and if this energy is enough to counterbalance that lost in the resistance of the circuit, the oscillations will not be damped or die out, but each peak of the oscillating current will have an amplitude equal to the preceding one (assuming that the R.F. signal is unmodulated). When such is the case, the current in the tuned circuit is said to be producing sustained oscillations and the waveform of the current will be that shown in Fig. 8.

A 100% modulated R.F. voltage will vary in amplitude from zero to twice its unmodulated value and thus the energy applied to the tuned circuit will vary similarly. This causes the amplitudes of the oscillating current to fluctuate in direct accordance with the variations of the modulated R.F. signal.

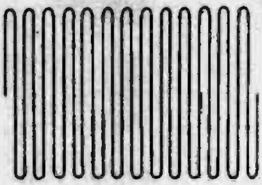


Fig.8 Waveform of a current when the circuit is producing sustained oscillations. All peaks are of the same amplitude.

If the resonant frequency of the tuned circuit is not equal to the frequency of the incoming signal, the voltages induced in the coil B will not be timed correctly to reinforce the oscillations occurring in the tuned circuit and may, in fact, even interfere with them. Therefore, the value of the oscillating current under these conditions will be very, very low.

When the tuned circuit is resonant to the frequency of the incoming signal, the oscillating current in flowing through it produces fairly large voltages across both the coil and the condenser. Since one side of the condenser is connected to the grid and the other to the cathode, the voltage across the condenser may be used to vary the grid voltage. This is a modulated R.F. voltage and must be detected before being applied to a loudspeaker or a pair of headphones.

4. **GAIN OF A TUNED CIRCUIT.** As was explained in Lesson 14, the voltage across the coil or the condenser of a series tuned circuit at resonance may be much larger than the applied voltage. The ratio of the voltage across the coil or the condenser to the applied voltage at resonance is called the "gain" of the tuned circuit. The calculation of this gain will now be considered.

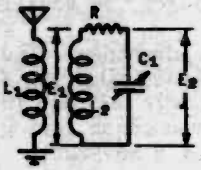


Fig.9 Diagram to illustrate the gain of a tuned circuit. E_2 is the voltage developed across the condenser; E_1 is the voltage induced into L_2.

In Fig. 9, the applied voltage is E_1; it is the voltage induced in L_2 from L_1. At resonance, the inductive reactance of the coil is equal to the capacitive reactance of the condenser and the only opposition to the current flow is that due to the resistance of the circuit which is designated by R in the figure. The oscillating current is, therefore:

$$I = \frac{E_1}{R} \qquad (11)$$

This current flows through the capacitive reactance of the condenser and produces the voltage drop E_2. This is:

$$E_2 = I \times X_c \qquad (12)$$

When the value for I in equation (11) is substituted in equation (12), the following results:

$$E_2 = \frac{E_1}{R} \times X_c \qquad (13)$$

The ratio of the voltage across the condenser (E_2) to the input voltage (E_1) is the gain of the tuned circuit. This is found by dividing equation (13) by E_1:

$$\frac{E_2}{E_1} = \frac{E_1 \times X_c}{R} \times \frac{1}{E_1}$$

Or:

$$\frac{E_2}{E_1} = \frac{X_c}{R} = \text{gain} \qquad (14)$$

Since $X_c = X_L$ at resonance:

$$\frac{X_L}{R} = \text{gain}$$

From the foregoing, it is seen that the gain of the circuit is equal to the reactance of either the coil or the condenser (since they are equal at resonance), divided by the resistance. Thus, the greater the reactance or the smaller the ohmic resistance of the circuit, the greater will be the gain of the tuned circuit.

Example 5: Suppose that the voltage induced in the coil is 1 millivolt (.001). It is assumed that the reactance of either the coil or the condenser at the frequency under consideration is 1,000 ohms and that the total resistance of the tuned circuit is 10 ohms. What is the gain of the tuned circuit and how much voltage is developed across the condenser?

Solution: The gain is found by using formula (14). It is:

$$\text{Gain} = \frac{1000}{10} = 100$$

Since the gain is 100, the voltage developed across the condenser must be equal to the applied voltage multiplied by the gain, or:

$$.001 \times 100 = .1 \text{ volt}$$

From the foregoing example, it is evident that the tuned circuit greatly increases the signal voltage before it is applied to the grid of the tube. This, of course, is very desirable since the strength of the signal induced in the antenna is very low, sometimes not more than a few microvolts.

5. **SELECTIVITY OF A TUNED CIRCUIT.** A series resonant circuit has a preference for current of the resonant frequency, and currents of frequencies either higher or lower than this will encounter a greater opposition in flowing through the tuned circuit.

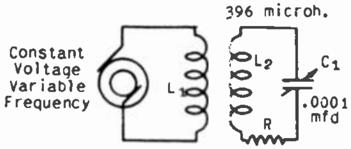


Fig.10 Circuit used to obtain the graph shown in Fig.11.

Fig. 10 shows a tuned circuit coupled to the output of a voltage source which has a constant voltage and a variable frequency. Since the voltage induced in the tuned circuit is in series with the coil and with the condenser, it is a series tuned circuit. The coil has an inductance of 396 microhenries and the condenser a capacity of .0001 microfarad; the total resistance is 10 ohms. By formula (7), the resonant frequency of the tuned circuit is found to be 800 kilocycles. At frequencies lower than resonance, the capacitive reactance will be greater than the inductive reactance and the net reactance will not be zero. Likewise, at frequencies higher than resonance, the inductive reactance will be greater than the capacitive reactance and, again, the net reactance will not be zero.

Fig. 11 shows how the inductive, the capacitive and the net reactance of this circuit vary as the frequency is changed from a value below to a value above resonance. The heavy vertical line through the center of the graph indicates the resonant frequency, 800 kilocycles. It is noticed that the scale along the vertical or Y axis is in two parts and extends from zero to several thousand in either direction. Values below the zero line represent capacitive reactance, while those above represent inductive reactance. From the graph, it is evident that at 800 kilocycles (the resonant frequency), the two reactances are equal and the solid line, which represents the net reactance, is zero at this point, since it crosses the zero axis. The inductive reactance increases in a uniform manner as the frequency is raised; its graph is a straight line. The graph of the capacity reactance, however, is not a straight line. At very low frequencies, the capacitive reactance is quite high and as the frequency is raised, the reactance decreases rapidly at first and then at a slower rate. The net reactance is, of course, the difference between the inductive and capacitive reactance at any particular frequency.

It would be instructive to plot a graph showing how the current in the tuned circuit varies in value as the frequency of the applied voltage is changed. Before constructing such a graph, let us compose a table listing the values of the several elements of the circuit shown in Fig. 10 at various frequencies. We shall as-

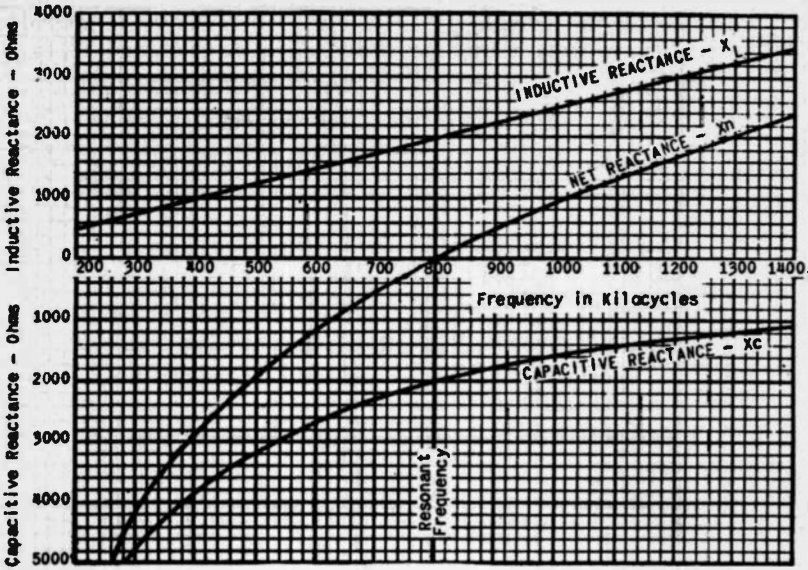


Fig.11 Illustrating how the inductive reactance, the capacitive reactance, and the net reactance of the circuit of Fig. 10 vary as the frequency of the applied voltage is changed from 200 to 1400 kc.

sume that a constant voltage of one millivolt (.001 volt) is induced into the coil L at any frequency at which the voltage source might be set. The following table will furnish material for the construction of the graph.

Frequency KC.	Inductive Reactance (X_L) Ohms	Capacitive Reactance (Xc) Ohms	Net Reactance (Xn) Ohms	Impedance (Z) Ohms	Current Microamps.	Voltage Across Condenser (IxXc) Volts
750	1865	2123	258	258.2	3.9	.008
760	1890	2095	205	205.2	4.9	.010
770	1915	2068	153	153.3	6.5	.013
780	1940	2041	101	101.5	9.9	.020
785	1952	2029	77	77.6	12.9	.026
790	1965	2016	51	52.	19.2	.039
795	1977	2003	26	27.9	35.8	.072
800	1990	1990	0	10.0	100.0	.199
805	2002	1978	24	26.	38.5	.076
810	2014	1966	48	49.	20.4	.040
815	2027	1954	73	73.7	13.6	.027
820	2039	1942	97	97.5	10.3	.020
830	2064	1919	145	145.3	6.9	.013
840	2089	1896	193	193.3	5.2	.010
850	2114	1873	241	241.2	4.1	.008

From the information contained in this table, the current flowing in the tuned circuit is plotted along the Y axis and the frequency along the X axis. The resulting curve is shown at A, Fig. 12. From this curve, it is plainly evident that the amount of oscillating current is low except at the resonant frequency.

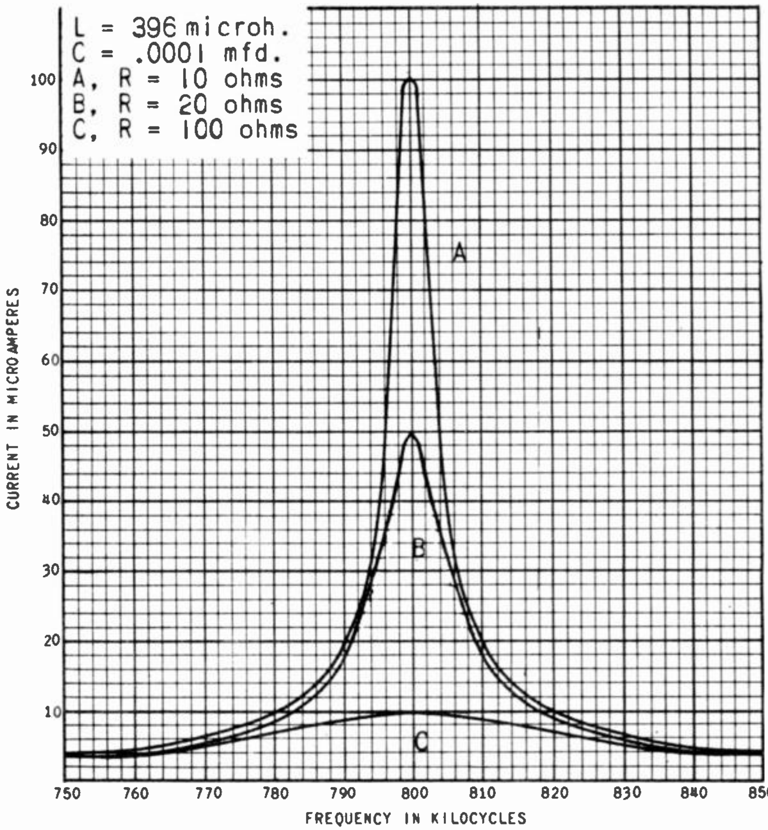


Fig.12 Plot of current flowing in the tuned circuit of Fig. 10, with a constant voltage of .001 volt and a variable frequency applied. Curve A is for 10 ohms resistance, and curves B and C are for 20 and 100 ohms, respectively.

At 800 kilocycles, the current is 100 microamperes and at 805 kilocycles, it has dropped to 38.5 microamperes. And it is 35.8 microamperes at 795 kilocycles. Now notice the last column in the table. This gives the voltage developed across the condenser or the voltage which serves to vary the grid voltage of the tube at the various frequencies. At the resonant frequency, 800 kilocycles, the voltage applied to the tube is .199 volts. At either 795 kilocycles, or 805 kilocycles, this voltage has dropped to .07+ volts; or at 5 kilocycles either side of resonance, the voltage applied to the tube is only 35% of that applied at the resonant frequency. It is noticed that at frequencies farther from resonance, the voltage across the condenser C becomes increasingly smaller and finally reaches a value of 8 millivolts at 750 kc. and 8 millivolts at

850 kc. If it were not for the principles involved in this graph and table, it would be impossible to have more than one station on the air at a time in any one vicinity. Otherwise, the radio receiver would receive the signals of all the local stations equally well, would amplify them equally well, and the output from the loudspeaker would be a conglomeration, unintelligible to any one.

The use of tuned circuits, however, makes the simultaneous operation of many stations in the same locality possible. Although the stations may produce equivalent voltages in the receiving antenna, only that station whose frequency is equal to the resonant frequency of the tuned circuit will build up sufficient voltage across the condenser to produce appreciable amplification. This ability of a tuned circuit to allow the easy passage of one frequency and to tend to reject all others is known as its "selectivity".

The process of tuning consists of varying the capacity of the tuning condenser until its capacitive reactance at the frequency of the desired station is equal to the inductive reactance of the coil at that frequency. When the stage is correctly tuned to the desired frequency, a maximum signal voltage will be applied to the tube and maximum amplification will be obtained at that frequency. Likewise, frequencies greater than or less than the desired frequency will suffer discrimination.

6. **EFFECT OF RESISTANCE UPON SELECTIVITY.** The effect of resistance in a series tuned circuit is to decrease the amount of current flowing at the resonant frequency in a greater proportion than it decreases the current flowing at other frequencies. At the resonant frequency, the only opposition to the current flow is the ohmic resistance of the circuit. Naturally, if this ohmic resistance is made larger, the amount of current flowing at the resonant frequency will be reduced. At frequencies slightly off resonance, the opposition to the flow of current consists of the ohmic resistance and the net reactance, which together make up the impedance of the circuit at that frequency. An increase in the resistance of the tuned circuit does not affect the net reactance and changes the impedance only slightly; therefore, the percentage of reduction in the current at frequencies slightly off resonance is much less than the reduction at the resonant frequency.

This fact is illustrated in the curve of Fig. 12. Notice that when the resistance is 10 ohms, the current that flows at 800 kilocycles, the resonant frequency, is 100 microamperes. Increasing the resistance to 20 ohms (curve B) produces a current flow at this frequency of 50 microamperes; thus doubling the resistance in the circuit has reduced the current flow at the resonant frequency by one-half. Now, consider a frequency of 805 kilocycles. When the resistance in the circuit is 10 ohms, the current is 38.5 microamperes. Increasing the resistance in the circuit to 20 ohms reduces the current flow at 805 kilocycles to 32.1 microamperes. This constitutes a reduction of about 16% compared to a 50% reduction in the current flow at the resonant frequency.

Thus, the effect of resistance in the tuned circuit is to flat-ten out the resonance curve, making it less sharp and, in consequence thereof, less selective. Its ability to discriminate between the resonant frequency and all other frequencies is greatly reduced.

The idea of selectivity may be viewed in two different lights. One may consider that a voltage slightly different from the resonant frequency will produce a lesser effect, since at this frequency the inductive reactance and the capacitive reactance do not balance and the impedance of the tuned circuit is greater than at the resonant frequency; therefore, the amount of current which may flow in the tuned circuit is less and the voltage developed across the condenser smaller. On the other hand, one may consider that the application of a voltage to the tuned circuit of any frequency would tend to set up an oscillating current as previously explained, in the tuned circuit. This oscillating current would, if no further energy were added to the tuned circuit, soon die out, since the oscillating current would expend energy in overcoming the resistance of the circuit. If there were no resistance in the circuit (a theoretical case), the oscillating current would continue to flow at its same amplitude for an indefinite period. This condition may be realized by supplying enough energy to the tuned circuit to offset that which it loses in overcoming the resistance. This energy which is to be added to produce sustained oscillations must be correctly timed; otherwise, it would hinder, rather than aid the maintenance of the oscillations at their maximum value. Only a signal of the resonant frequency would have its energy pulses so timed as to maintain continuous oscillations at a maximum value. Signals other than the resonant frequency might produce feeble oscillations at their own frequency, but such oscillations are relatively small. When a circuit is caused to oscillate at a frequency not its resonant frequency, it is said to be producing "forced oscillations. Such oscillations are very small compared to those produced at the resonant frequency (free oscillations).

7. SIDEBAND FREQUENCIES. Before it is possible to discuss selectivity further, it will be necessary to investigate another phenomenon with which selectivity is closely associated. As explained in Lesson 18, a modulated radio-frequency wave varies in amplitude at an audio-frequency rate as shown at A, Fig. 13. In an earlier lesson, it was shown how a pulsating direct current waveform could be resolved into its AC and DC components. In a like manner, a modulated R.F. wave may be resolved into its several constituents. It does not have a DC component, but is composed of three separate AC components.

The proof underlying this theory will not be given, since it involves mathematics beyond the scope of this course.

Let us assume that the modulated R.F. wave of A, Fig. 13, has a frequency of 1,000 kilocycles, or 1,000,000 cycles and that its amplitude is varying at a rate of 2,000 cycles per second. Such a wave would be produced by a station operating upon an assigned frequency of 1,000 kilocycles, if a tuning fork of a 2,000-cycle frequency were struck in front of one of the station's microphones. The first of the three AC components of such a waveform is an un-

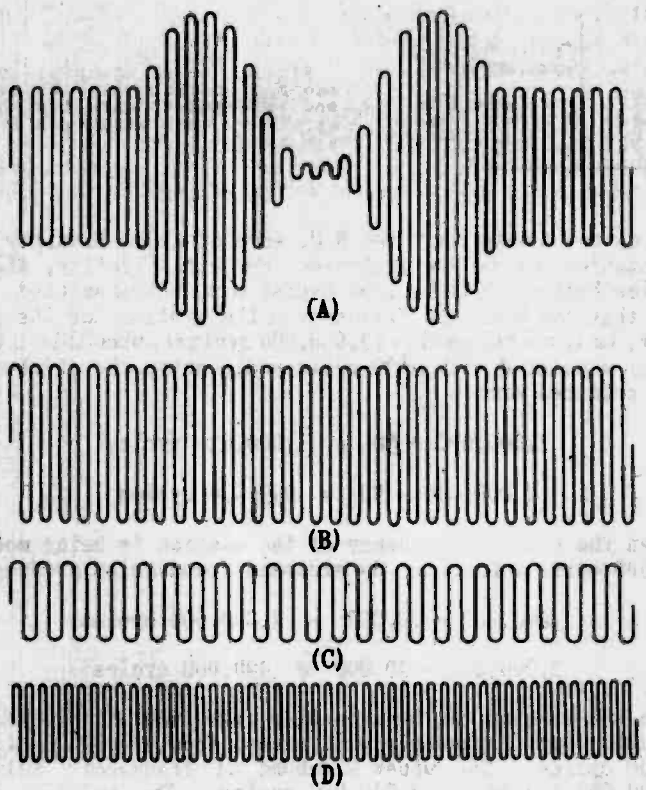


Fig. 13 (A) A modulated radio-frequency wave.
(B) Carrier-frequency component of wave shown at A.
(C) Lower sideband frequency component of same wave.
(D) Upper sideband frequency component of this wave.

modulated R.F. wave, having a frequency of 1,000 kilocycles; the second component is an unmodulated AC wave having a frequency of 998,000 cycles; the third component is an AC wave with a frequency of 1,002,000 cycles. These three components are illustrated at B, C and D in Fig. 13. The first one, whose frequency is 1,000,000 cycles, is known as the carrier frequency. The second, whose frequency is 998,000 cycles, is known as the lower sideband frequency and the third, whose frequency is 1,002,000 cycles, is called the upper sideband frequency. The frequency of the lower sideband is equal to the carrier frequency (1,000,000 cycles) minus the audio frequency contained in the modulated R.F. wave (2,000 cycles). The frequency of the upper sideband is equal to the carrier frequency plus this audio frequency. Notice that the amplitudes of the sideband frequencies are only half as great as that of the carrier frequency, assuming that the R.F. wave is 100% modulated as shown in Fig. 13. These sideband frequencies will exist whenever an A.F. wave or waves modulates an R.F. wave. The relative position and amplitude of the carrier and its sideband are shown in Fig. 14.

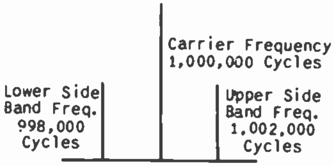


Fig.14 Relative positions and amplitudes of carrier wave and sideband frequencies when carrier is modulated by a single tone.

Let us now assume that the R.F. wave of a high-fidelity broadcasting station is to be analyzed. For high fidelity, all audio frequencies between 30 and 10,000 cycles must be transmitted. Again assuming that the assigned frequency of the station, or its carrier frequency, is 1,000 kilocycles (1,000,000 cycles), when this 1,000,000 cycles is modulated with a 30-cycle audio note, the sideband frequencies produced are:

$$1{,}000{,}000 + 30 = 1{,}000{,}030 \text{ cycles}$$

$$1{,}000{,}000 - 30 = 999{,}970 \text{ cycles}$$

Also, when the carrier frequency of the station is being modulated by a 10,000-cycle audio note, the sideband frequencies produced are:

$$1{,}000{,}000 + 10{,}000 = 1{,}010{,}000 \text{ cycles}$$

$$1{,}000{,}000 - 10{,}000 = 990{,}000 \text{ cycles}$$

When the station is broadcasting high-fidelity programs, the lower sideband of frequencies will extend from 999,970 cycles down to 990,000 cycles. The upper sideband of frequencies will range from 1,000,030 cycles to 1,010,000 cycles. The relation between the carrier and the upper and lower sidebands is illustrated in Fig. 15. Notice that although the station is broadcasting on an as-

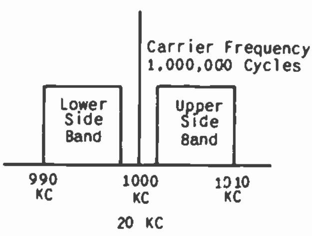


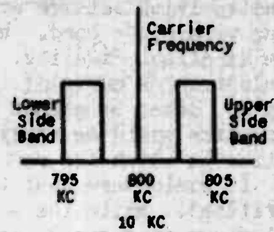
Fig.15 Relative positions and amplitudes of carrier wave and sideband frequencies when carrier is modulated by all audio tones between 30 and 10,000 cycles.

signed frequency of 1,000 kilocycles, it is actually broadcasting on all frequencies ranging from 990,000 to 1,010,000 cycles, a total band width of 20 kilocycles.

Ordinary broadcasting stations, not of the high-fidelity type, usually broadcast the audio frequencies ranging from 100 to 5,000 cycles. Thus, a station whose assigned frequency is 800 kilocycles, or 800,000 cycles, would have an upper sideband of frequencies between 800,100 and 805,000 cycles, and a lower sideband of frequencies between 799,900 and 795,000 cycles, a total band width of

10,000 cycles, or 10 kilocycles, as shown in Fig. 16. This means that this station is actually broadcasting on all the frequencies within this 10-kilocycle band. It is for this reason that the present allocation of frequencies in the broadcast band is such that

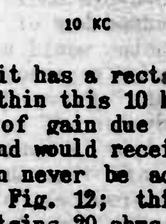
Fig. 16 Carrier wave and sideband frequencies for audio modulation from 100 to 5,000 cycles.



the assigned frequencies of various stations differ from each other by at least 10 kilocycles. If all the stations throughout the country were to broadcast high-fidelity programs, they would each need a band width of 20 kilocycles, and as a result, there would be only half as many 20-kilocycle channels in the present broadcast band as there are now 10-kilocycle channels.

It should be evident that the radio receiver must be capable of amplifying all the radio frequencies within this band of 10 kilocycles equally well, if there is to be no frequency discrimination; that is, if the balance between the high and low audio notes is to be maintained in the same proportion that it had at its origination. Then, every sideband frequency, both of the upper and lower sidebands, must receive the same amount of amplification. Unfortunately, a tuned circuit is resonant at just one frequency and not to a band of frequencies. To receive this 800-kilocycle station with absolute freedom from frequency distortion, the tuned circuit should respond equally well to all frequencies between 795 and 805 kilocycles. Reference to curve A in Fig. 12 will show that such is not the case.

Fig. 17 Ideal response curve.



The ideal response curve of a tuned circuit has a rectangular shape as shown in Fig. 17. All frequencies within this 10 kilocycle band width would receive the same amount of gain due to the tuned circuit. All frequencies not in this band would receive absolutely no gain. Such a theoretical ideal can never be achieved in practical construction. Notice curve B of Fig. 12; this is a resonant curve of the tuned circuit when it contains 20 ohms resistance. While it is by no means the theoretical rectangalar curve of Fig. 17, nevertheless the band of frequencies between 795 and 805 kilocycles receive more nearly the same amount of gain than they do in the same tuned circuit when the resistance is only 10 ohms. Now notice curve C; the amount of amplification received by the 10-kilocycle band is, for all practical purposes, constant for every frequency within the band. However, also notice that other frequencies lying outside of the band receive almost as much gain as those within the band. While a response curve of this type would give excellent fidelity, that is, there would be no frequency discrimination, a curve of this type would produce very little selectivity. Other broadcast stations operating upon either 790 or 810 kilocycles would be received almost as loudly as the 800-kilocycle station to which the receiver was tuned.

It would seem that to have high fidelity, selectivity must be sacrificed. While the amount of sacrifice need not be as great as that shown in curve 3, it is true that a compromise must be made between selectivity and high fidelity. Naturally, the sharper the resonant curve of the tuned circuit or circuits of the receiver, the greater will be the selectivity and the better able the receiver will be to pick up one station and reject all others. On the other hand, due to the phenomenon of sidebands, if perfect reproduction (high fidelity) is to be obtained from the receiver, it must amplify not one frequency, but a band of frequencies at least 10 kilocycles and preferably 20 kilocycles in width. This demands a fairly flat resonance curve which may be obtained by inserting resistance in the tuned circuit, or, as we shall later see in the study of superheterodyne receivers, it may also be secured by tuning the various tuned circuits of the receiver to slightly different frequencies, thus making the over-all response curve of the receiver fairly flat throughout the desired band width.

The curve shown at A in Fig. 12 is ordinarily not obtainable with tuned circuits, such as used in receivers; that is, most practical tuned circuits contain more resistance than the one used for the derivation of this curve. Furthermore, one tuned circuit will not provide sufficient selectivity for the proper operation of a receiver and at least three and preferably more tuned circuits must be used in every receiver to provide the desired selectivity. Fig. 18 illustrates the response curves of various tuned circuits. The one at A is very selective; notice that at a frequency just 5 kilocycles from resonance, the response is only 20% as great as it is at the resonant frequency. These frequencies of 795 and 805 kilocycles correspond to an audio frequency of 5,000 cycles. Therefore, a 5,000-cycle audio frequency, if present at all in the output of the loudspeaker of this receiver, would be very, very weak. Other audio notes would be suppressed in a proportional amount, depending upon their frequency, the lower audio notes receiving the least suppression. Curve B is somewhat more desirable. At frequencies 5 kilocycles off resonance, the response is 90%. Curve C is, as far as fidelity is concerned, quite excellent. Its response at 5 kilocycles off resonance is about 97%. The condition represented by curve A produces "sideband cutting"; that is, all the frequencies in the sidebands do not receive the same amount of amplification. Such a condition always results in poor tone quality from the loudspeaker of the receiver. Curve B would give much better tone quality and curve C would probably give excellent tone quality. Curves

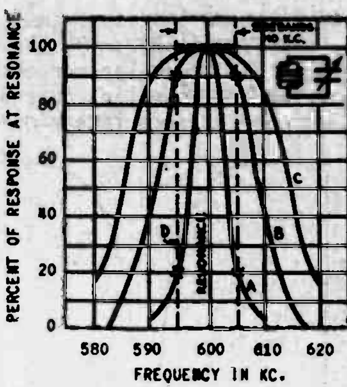


Fig. 18 Response curves of typical tuned circuits.
(A) Very selective.
(B) A good compromise between selectivity and tone quality.
(C and D) Poor selectivity, but excellent tone quality.

B and C, however, indicate rather broad tuning; that is, they admit a very large band width of frequencies. We must remember that there are probably other stations operating upon frequencies of 790 and 810 kilocycles and by reference to this figure, it is seen that the response of curve C is 90% at these frequencies. Its selectivity, therefore, is very, very poor. Curve B, on the other hand, has a response of about 40% at 10 kilocycles off resonance where the adjacent channel stations would lie. One way out of this difficulty is to design the tuned circuits to provide the necessary selectivity and then to design the audio-amplifier stages to amplify the high frequency audio notes more than those of low frequency. Since the output of the detector is particularly deficient in high audio notes due to the sideband cutting, the characteristic of the audio amplifier will tend to amplify these weak, high-pitched audio notes more than the low ones and thus tend to produce the correct balance between the highs and lows in the output.

8. **PARALLEL TUNED CIRCUITS.** In Lesson 14, it was learned that a parallel tuned circuit offers maximum opposition (impedance) to the flow of current from the voltage source at the resonant frequency and relatively low impedances at frequencies to either side of resonance. This phenomenon is the result of the phase difference between the coil current and the condenser current. It was shown that if the two currents were 180 degrees out of phase and were exactly equal, the line current would be zero. However, since all circuits contain some resistance, it is impossible for the coil current to be exactly 180 degrees out of phase with the condenser current and, as a result, they cannot perfectly cancel. Therefore, there is a minimum line current flowing, even at the resonant frequdncy. In addition, it was learned that the line current is in phase with the applied voltage and that a parallel tuned circuit has the characteristics of a resistor; that is, it causes no phase difference between the line current and the applied voltage at the resonant frequency. At frequencies below resonance, the coil current is greater than the condenser current and the tuned circuit

acts like an inductor; that is, it causes the line current to lag the applied voltage. On the other hand, at frequencies above resonance, the condenser current is greater than the coil current and, as a result, the line current leads the applied voltage and the tuned circuit acts like a capacitor.

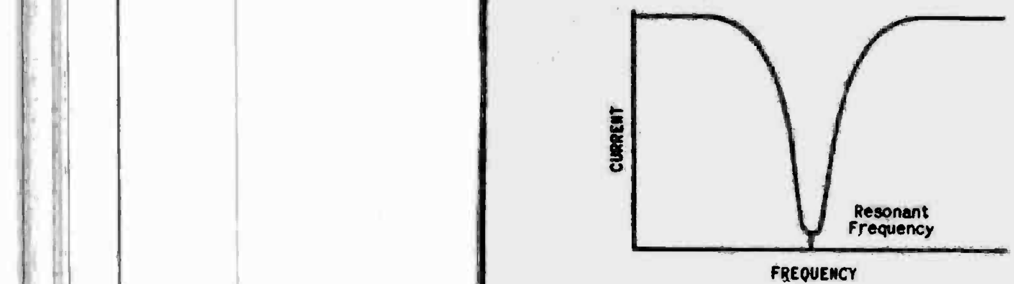


Fig. 19 Plot of line current against frequency for a parallel tuned circuit.

It is possible to draw a resonant curve for a parallel tuned circuit. The line current may be plotted against the frequency. When this is done, a curve similar to that shown in Fig. 19 is obtained. Notice that the line current is practically constant except for frequencies near resonance. The more usual curve representing parallel resonance is that obtained when the shunt impedance of the tuned circuit is plotted against the frequency. The shunt impedance is, as you will remember, the applied voltage divided by the line current, or it may be thought of as the impedance into which the voltage source is forcing current. When such a curve is constructed, it has the appearance of the one shown in Fig. 20. Notice that this curve is very similar to the one plotted for a series tuned circuit, except that shunt impedance is plotted against frequency instead of current.

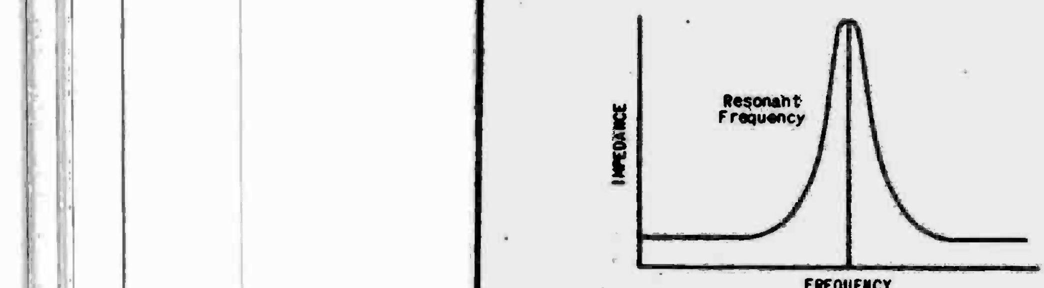


Fig. 20 Plot of shunt impedance of a parallel tuned circuit against frequency.

The fact that a parallel tuned circuit acts like a very high resistor at the resonant frequency, makes it valuable for use as a plate load impedance for a vacuum tube amplifier stage. In the lesson on audio-frequency amplifiers, it was made evident that for appreciable gain from an amplifier stage, the plate load resistor or impedance should be very large compared to the plate resistance of the tube. One of the disadvantages of a resistance-coupled audio amplifier is that the use of a very large resistor in the plate circuit necessitates a high-voltage power supply, since a good part of the voltage of the supply is dropped across the plate load resistor and is not available for plate voltage.

A parallel tuned circuit could not be used with an audio amplifier for the following reasons. The ordinary audio amplifier must amplify all frequencies from about 50 to 5,000 cycles. The upper frequency limit (5,000 cycles) is one hundred times as great as the lower frequency limit (50 cycles). It would not be possible to design any tuned circuit, either series or parallel, that would offer the same impedance to a 50-cycle current that it would to a current having a frequency one hundred times as large (5,000 cycles). On the other hand, it is easily possible to construct a parallel tuned circuit that will offer practically the same impedance at radio frequencies to a band of frequencies 10 kc. wide. Why this is possible will now be shown. Suppose that the frequency band extends from 1000 to 1010 kc. In this case, the upper frequency limit (1010 kc.) is only 1.01 times as great as the lower frequency limit. It is thus evident that the band width to which a parallel resonant circuit will offer practically the same impedance depends on the position of this band of frequencies in the frequency spectrum. This same tuned circuit would offer essentially the same impedance to a 100-kc. band between 10,000 and 10,100 kc. A very high impedance can be obtained by the use of a parallel tuned circuit and, at the same time, there is practically no DC voltage drop across it, which eliminates the need of a high-voltage power supply.

Additional selectivity is obtained by the use of a parallel tuned circuit as the plate load of a vacuum tube, since frequencies of undesired stations, if they are able to get into the grid circuit of a vacuum tube would be amplified only slightly as the parallel tuned circuit would offer practically no impedance to the frequencies of the undesired stations; therefore, their amplification would be practically negligible. As we shall learn in the lesson on radio-frequency amplifiers, certain precautions must be observed when using parallel tuned circuits as plate leads for vacuum tubes. Such amplifier stages have a tendency to be unstable and special care must be taken in their design.

Increasing the resistance of a parallel tuned circuit changes the resonance curve as shown in Fig. 21. Curve A is for a parallel

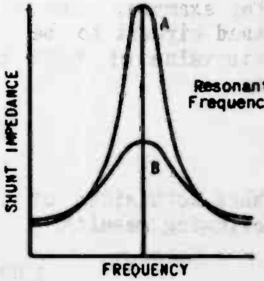


Fig.21 Illustrating the effect of resistance in a parallel tuned circuit upon its shunt impedance.

tuned circuit that contains 10 ohms resistance and curve B is for one containing 20 ohms. Notice that the addition of resistance to the tuned circuit causes the shunt impedance to be lower at the resonant frequency. The value of the shunt impedance at the resonant frequency may be found by this formula:

$$\text{Shunt impedance} = \frac{1}{R} \times \frac{L}{C} \qquad (15)$$

Where: L is in henries
C is in farads
R is in ohms

This formula is derived by the use of mathematics too complicated to be given at this time. It is, also, only approximate and becomes more inaccurate as the resistance of the tuned circuit is increased.

The resonant frequency of a parallel tuned circuit may be found by formula (7), which was used to determine the resonant frequency of a series tuned circuit. This, however, is possible only if the resistance of the parallel tuned circuit is low. Since this is always the case with parallel tuned circuits used in Radio and Television, this formula will be satisfactory for practical use. Actually, however, the presence of resistance in a parallel tuned circuit will affect the resonant frequency very slightly; it has no such effect upon the resonant frequency of a series tuned circuit.

Notice that formula (15) which gives the shunt impedance of a parallel tuned circuit at the resonant frequency contains the resistance (R) of the tuned circuit in the denominator of the fraction; as R is made larger, the shunt impedance is decreased. The inductance (L) is in the numerator; therefore, as the inductance is increased, the shunt impedance is increased. The capacity (C) is in the denominator; therefore, an increase in capacity would result in a reduction of the shunt impedance. It can thus be seen that the ratio of the inductance to the capacity has considerable effect upon the shunt impedance of the parallel tuned circuit at resonance. To produce resonance at a given frequency, many different values of inductance or capacity could be used. The only requirement is that their product (L × C) be of the correct value to satisfy formula (7), which gives the resonant frequency of a tuned circuit.

For example, suppose that it is desired to construct a parallel tuned circuit to be resonant at 1,000 kilocycles. Substituting this value of 1,000 kilocycles in formula (7), there is obtained:

$$1{,}000 = \frac{159}{\sqrt{L \times C}}$$

When both sides of this equation are multiplied by $\sqrt{L \times C}$, the following results:

$$1{,}000 \times \sqrt{L \times C} = 159$$

Next, this equation is divided by 1,000, which gives:

$$\sqrt{L \times C} = \frac{159}{1,000} = .159$$

Finally, this last equation is squared and the following expression is obtained:

$$L \times C = .025281$$

This means that to be resonant at a frequency of 1,000 kilocycles, the product of the inductance in microhenries and the capacity in microfarads must be equal to .025281. It does not state that the inductance of the capacity must be any definite value, but that their product must be equal to this number if the circuit is to be resonant at 1,000 kilocycles. The following table shows what values of inductance and capacity could be used to produce a circuit resonant at this frequency.

CAPACITY	INDUCTANCE
.0001 microfarads	252.81 microhenries
.0002 "	126.4 "
.0003 "	84.27 "

Other values, of course, could be used, but these will serve to illustrate our purpose. As an exercise, it would be well for you to prove that these values of capacity and inductance will produce resonance at 1,000 kilocycles, by substituting them in formula (7) and solving for the frequency.

Let us now assume that the resistance of the parallel tuned circuit is to be 10 ohms. We shall calculate the shunt impedances of the parallel tuned circuit, using the three different sets of values given in the preceding table. To substitute in formula (15), L should be in henries and C in farads; however, if they are in microhenries and microfarads respectively, the same answer will be obtained, since their ratio will be unchanged.[1] Substituting the first set of values in formula (15), we obtain:

$$\text{Shunt impedance} = \frac{1}{10} \times \frac{252.81}{.0001} = 252,810 \text{ ohms}$$

For the second set of values, we obtain:

$$\text{Shunt impedance} = \frac{1}{10} \times \frac{126.4}{.0002} = 63,200 \text{ ohms}$$

For the third set of values, we obtain:

$$\text{Shunt impedance} = \frac{1}{10} \times \frac{84.27}{.0003} = 28,090 \text{ ohms}$$

[1] If the inductance is given in millihenries, however, it should be converted to henries and the capacity to farads in order to prevent confusion.

All three of these parallel tuned circuits are resonant at 1,000 kilocycles; yet the shunt impedance offered by each of them at the resonant frequency is different. From the above results, there may be seen the desirability of using a large value of inductance and a low value of capacity in constructing a parallel circuit to have as large a shunt impedance as possible.

We must, of course, realize that using a larger value of inductance means that more turns of wire will be wound upon the coil; this will increase its resistance. It is practically impossible to increase the inductance of a circuit without increasing its resistance somewhat. The resistance, however, will not increase as fast as the inductance. For example, in the first set of values, the coil has 3 times as much inductance as it has in the third set. It is very probable that its total resistance would be at least $1\frac{1}{2}$ times as much as it is in the third case. Thus, while there would be an increase in the shunt impedance when the inductance of the coil is increased, such action would increase the total resistance and the increase in the shunt impedance would not be as large as might be expected.

THE L × C PRODUCT FOR COMMON FREQUENCIES

The L × C product means the product of the inductance and capacity required to produce resonance at a certain frequency. In the following table, the inductance must be in microhenries and the capacity in microfarads.

FREQUENCY IN KILOCYCLES	L × C	FREQUENCY IN KILOCYCLES	L × C
10	253.	1050	.02297
20	63.3	1100	.02093
30	28.14	1150	.01915
40	15.83	1200	.01759
50	10.13	1250	.01622
60	7.04	1300	.01498
100	2.53	1350	.01389
150	1.126	1400	.01292
200	.633	1450	.01204
250	.405	1500	.01126
300	.2814	2000	.006332
350	.2067	3000	.002814
400	.1583	4000	.001583
450	.1250	5000	.001013
500	.1013	6000	.000704
550	.0837	7000	.000515
600	.0704	7500	.000450
650	.0599	10000	.000253
700	.0515	15000	.0001126
750	.0450	20000	.0000633
800	.0396	30000	.0000282
850	.0350	50000	.0000101
900	.0313	60000	.0000070
950	.0281	100000	.00000253
1000	.02533	300000	.000000281

Notes

(These extra pages are provided for your use in taking special notes)

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MIDLAND RADIO
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POWER & LIGHT BUILDING, KANSAS CITY, MISSOURI

UNIT NO. 1

REGENERATION AND VACUUM TUBE OSCILLATORS

LESSON NO. 23

TROUBLE SHOOTERS

.......WILL POWER, DETERMINATION, AMBITION

A howling blizzard drives out of the north. The temperature drops close to zero. Snow piles in huge drifts along the highways. Then, without warning, communication is interrupted and the daily routine of the affected communities is seriously affected.

At the very first indication of interrupted service, the trouble department swings into action. They do not wait until the storm subsides. Neither do they sit idly by, hoping that everything will come out all right. They don heavy clothing, leave warmth and comfort for zero temperatures and frosted ears, and face the gusty, snow-laden wind in a heroic attempt to locate a 'dead wire'.

You will agree that locating the seat of trouble amid a maze of far-flung communication lines is not easy. Particularly, under unfavorable weather conditions. But .....regardless of inconvenience, the trouble must be located and remedied so that the normal routine of the business world can roll along without interruption. And this also applies to life.....YOUR LIFE.

You want to progress toward your objective--SUCCESS --without interruption. But.....should trouble occur .....something which would threaten your progress..... you could not afford to sit idly by and say, 'Oh, well, I'll wait until the storm blows over and then start over again.' If you did this, you might wait for years and years and never arrive at your objective. You want to call your 'trouble shooters' into action without delay .....'Will Power', 'Determination', and 'Ambition'..... overcome whatever it may be that is threatening your future success.....AND THEN CONTINUE RIGHT ON TO SUCCESS!

Practically every successful man has, at one time or another, had his plans for success interrupted. If they had permitted such interruptions to discourage them and had 'quit', they would not be successful today and enjoying the rich rewards of prosperity. When the going gets the toughest, grit your teeth, tighten up your belt, and WORK AND FIGHT HARDER THAN EVER! Remember, that when your efforts are rewarded by the golden smile of success, YOU WILL BE ABLE TO TAKE IT EASY AND ENJOY LIFE, WHILE THE FELLOWS WHO 'QUIT' ARE WONDERING WHERE THEIR NEXT MEAL IS COMING FROM.

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Lesson Twenty-Three

REGENERATION and VACUUM TUBE OSCILLATORS

"Modern day superheterodyne radio receivers, as well as all transmitters, could not function if it were not for vacuum tube oscillators. An oscillator does not receive a radio signal, but rather converts DC power into R.F. power. Keep this in mind as you study this lesson.

"A knowledge of regeneration is also important to all Radio and Television technicians, and since it is associated with the study of an oscillator, I am going to tell you about both of these interesting phenomena in this lesson."

1. TYPES OF VACUUM TUBE CIRCUITS. Preceding lessons have discussed the operation of vacuum tubes as amplifiers and as detectors. In a distortionless amplifier circuit the output voltage is an exact reproduction of the input voltage and the output is controlled at all times by the input voltage. When a vacuum tube is used in a detector circuit, its function is to rectify and amplify the input voltage. Also, in a detector circuit, the output voltage is continuously controlled by the input signal.

As well as working efficiently as an amplifier or as a detector, a vacuum tube may also be used for other purposes. Of the numerous additional applications, we are interested at the present in the function of a triode vacuum tube as a regenerative amplifier and as an oscillator. By mere inspection, it is sometimes difficult to ascertain the exact performance of a vacuum tube circuit. For example, the circuit shown in Fig. 1 may be an amplifier, a regenerative amplifier, or an oscillator. To make a definite decision as to the tube's class of operation, it is necessary to become familiar with additional facts concerning the characteristics of the circuit.

If the circuit in Fig. 1 were a true amplifier, the voltage appearing across the secondary of the output transformer would be an exact reproduction of the waveform of the input voltage applied to the primary of the input transformer. Also, the amplitude, waveform and frequency of the output voltage would be *controlled* entirely by the input voltage. The input voltage is the one and only source of grid excitation in a true amplifier circuit.

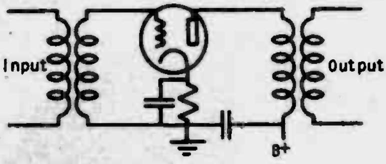


Fig.1 Single-stage vacuum tube circuit which may be an amplifier, a regenerative amplifier or an oscillator, depending upon circuit conditions.

In the discussion of "feedback" in Lesson 19 on audio-frequency amplifiers, it was found that a portion of the output voltage could pass through circuit components back into the grid circuit of the tube. Should this occur in sufficient magnitude, it causes a general instability of the amplifier circuit and extensive filtering in both grid and plate circuits is necessary in order to prevent the feedback from interfering with its normal operation. *When a portion of the output energy supplies energy which is in phase with the original signal to the input of the same tube or amplifier, it is said that the process of "regeneration" is taking place.* For regeneration to occur, it is essential that the output energy be returned to the input in the proper phase relationship. The energy from the output must appear at the input so as to be directly in phase with the input voltage, thus adding to the input voltage and causing increased grid excitation. This, of course, results in a greater voltage output. If the output energy were fed back to the input in such a manner as to be directly out of phase with the input voltage, a partial or complete cancellation would occur, resulting in decreased grid excitation and decreased voltage output. This is known as "degeneration". In Lesson 20, it was found that degeneration of the input signal occurs when the parallel by-pass condenser is removed from the biasing resistance.

If regeneration occurs within an amplifier circuit, it is called a "regenerative amplifier". Such an amplifier possesses several characteristics which prevent it from being classified as comparable with a true amplifier. Outstanding among these characteristics is the fact that a much greater voltage gain is secured through a given tube when operated under regenerative conditions. This is a decided advantage and upon first thought might seem to be sufficient to warrant its popular use. There are disadvantages, however, to this method of amplifier operation which tend to limit its popularity. A regenerative R.F. amplifier, for example, is very selective and may cause the sidebands of the R.F. signal to become attenuated, thus impairing the audio quality. Then, too, a regenerative R.F. amplifier is difficult to maintain under perfect control; that is, the entire amplifier is apt to begin oscillating with the least surge or interruption. When excessive regeneration occurs in an A.F. amplifier, the output generally suffers severe harmonic and frequency distortion, both of which are undesirable.

Mention has been made of the fact that a regenerative amplifier is difficult to maintain under control. This statement means that there are complications associated with the freedom of perfect control over the amount of regeneration which takes place from the output to the input circuit. Slight regeneration of the signal will cause no appreciable instability; however, when it becomes excessive, the normal operation of the entire amplifier is destroyed. When in this condition, the output voltage from the amplifier is no longer governed by the input signal voltage, but rather is determined by the regenerative energy. Such a circuit is generally known as an "oscillator". *An oscillator circuit is a vacuum tube with its associated apparatus arranged so as to permit excessive regeneration to occur, thereby making it possible for the amplified energy in the plate circuit to supply the input or grid exciting voltage.*

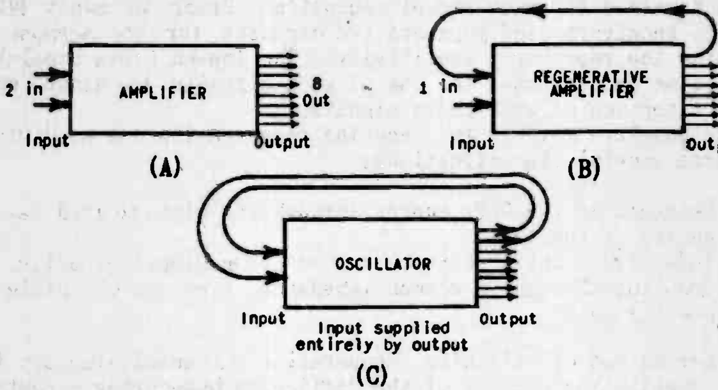


Fig.2 (A) Block diagram of a true amplifier circuit in which the voltage gain is four times.
(B) Block diagram of regenerative amplifier circuit in which one-eighth of the output energy is returned to the input. The voltage amplification in this circuit is seven times.
(C) Block diagram of an oscillator. Sufficient energy from the output is returned to the input so as to maintain the correct grid exciting voltage without the application of external energy.

The block diagrams shown in Fig. 2 illustrate the essential difference between an amplifier, a regenerative amplifier and an oscillator. At A, the output is four times greater than the input, indicating that the amplifier has increased the original signal four times. Notice that none of the output signal voltage is returned to the grid circuit in a true amplifier. The regenerative amplifier is shown at B. One-eighth of the output voltage is being fed back to the input circuit. When this amount of the signal is returned, the same total output can be maintained from the regenerative amplifier *with only one-half the original input.* The output is now seven times as great as the input, so the over-all amplification has been increased from 4 to 7 times, due to the regenerative action. C in Fig. 2 illustrates the conditions existing when one-fourth of the output is fed back to the input of the vacuum tube circuit. With more regeneration, it is possible for the output energy to supply all of the input energy; hence, the original signal is no longer needed and even though it may be present, it is not responsible for any of the output voltage. The circuit is now acting as an oscillator.

From this discussion, it is apparent that a simple vacuum tube circuit such as shown in Fig. 1 may operate as an amplifier, a regenerative amplifier, or an oscillator, depending on the degree of regeneration. If no regeneration exists, it is a "true amplifier" circuit; a slight amount of regeneration causes it to perform as a "regenerative amplifier"; with excessive regeneration, it becomes an "oscillator".

2. **REGENERATION.** Whereas the principle of regeneration is no longer incorporated in modern broadcast receivers, it still maintains prominence in short-wave receivers and in commercial receivers designed for weak-signal reception. Prior to about 1927, all radio receivers used regenerative circuits for the purpose of increasing the receiver's sensitivity. The low-mu tubes available at that time necessitated the use of such circuits to assure consistent reception of weak radio signals.

The possible methods for securing regeneration can be divided into three general classifications:

1. Feedback of the R.F. energy through the plate to grid capacity of the tube.
2. Inductive coupling between the output and input circuits.
3. Coupling through a common impedance, such as the plate power supply.

The latter method of obtaining regeneration is unsatisfactory for circuit application because of the difficulty in securing a control of its magnitude. Should the R.F. energy find a path of low opposition from the plate circuit to the grid circuit through an impedance (coil, resistor, condenser, power supply, etc.) common to both, it is virtually impossible to employ a means of accurately governing its strength. Uncontrollable regeneration is unsuitable for any application, so the design of the circuit should be such that regeneration does not occur through this source. "Common impedance" coupling is generally a result of inadequate circuit filtering. The remedy obviously consists of inserting efficient filters in each grid and plate circuit so as to confine the input and output signals to their respective circuits. Such "decoupling" or "by-pass" filters are constructed with a series coil or resistor and a shunt condenser to the cathode.

All regenerative circuits in radio receivers employ the principle of inductive feedback or capacitive feedback. By either of these methods, regeneration may be secured in a radio-frequency amplifier or in a detector[1] stage. In earlier radio receiver design, several manufacturers used regeneration in the R.F. amplifier of the receiver. These regenerative circuits did increase the voltage gain through the R.F. amplifier to a great extent; however, they were difficult to control. Skill and patience were required in or-

[1] Regeneration cannot be applied to a diode detector circuit because a diode does not produce an amplified output voltage.

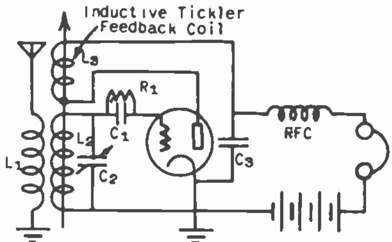
der to properly adjust the regeneration control until maximum voltage amplification was secured without the entire amplifier breaking into "oscillations". Such a sensitive control could not easily be adjusted by the average layman and the benefits which should have been derived were generally lost. The annoying howls and squeals which resulted from improper adjustment aroused a general dissatisfaction which was quickly responsible for its obsolescence.

When regeneration is applied to a detector stage, it is possible to obtain a more smooth and even control of the feedback energy. A regenerative detector is also capable of supplying tremendous amplification to a weak input signal voltage, thus making it possible to operate headphones in the plate circuit or to supply appreciable voltage excitation to an audio-frequency amplifier. The over-all selectivity also increases when regeneration is employed in the detector stage. These facts are largely responsible for the extended application of regeneration to this portion of a radio receiver.

3. REGENERATIVE DETECTOR CIRCUITS. By investigating the operation of a grid or plate detector, it will be found that R.F. currents are present in the plate circuit in addition to the low-frequency audio currents. The purpose of the plate circuit filter is to by-pass these R.F. variations and prevent them from passing through the headphones or other plate load impedance. If, however, a portion of this energy is returned to the grid circuit, regeneration of the input R.F. signal is obtained.

There are a number of possible ways to secure regeneration in a vacuum tube detector; one of the most common is shown in Fig. 3. This typical regenerative circuit employs the grid-leak, condenser method of detection and the inductive or "tickler" coil (L_3) is used to feedback the R.F. variations from the plate circuit to the grid circuit, thus producing a greater grid signal variation and consequently louder volume in the headphones. Batteries are being used to supply the plate voltage. This is advisable if best results are expected from the circuit, because the sensitivity is so extremely high that the slightest hum or noise produced by a vacuum tube rectifier circuit would create intolerable interference with the received signal.

Fig.3 Circuit diagram of a regenerative grid-leak detector circuit using a tickler coil for regeneration.



The operation of the circuit in Fig. 3 may be explained as follows: Radiated energy from a broadcast station causes an R.F. voltage to be induced in the antenna and an R.F. current flows through the primary coil L_1 to ground. As the R.F. current passes through

L_1, by electromagnetic induction a corresponding voltage is produced in the secondary L_2. The inductive reactance of L_2 is balanced by the capacitive reactance of C_2 by tuning the variable condenser, then an oscillating current is established in the resonant circuit L_2C_2. This oscillating current varies in amplitude in accordance with the modulated incoming signal. The oscillating circuit L_2C_2 contains some resistance in the coil, the wiring and the condenser plates which tends to dampen the strength of the oscillating current and prevent it from rising to an abnormally high value. A high oscillating current causes large R.F. voltage variations to appear across the tuned circuit. The resistance in the resonant circuit L_2C_2 also assists to prevent the oscillating current from "breaking over" into the undamped or continuous state of oscillations. It should be remembered that the amplitude of the R.F. oscillating current in L_2C_2 must increase and decrease in accordance with the modulation impressed on the incoming signal. Should the oscillating current be prevented from varying in conformity with the modulation, severe amplitude distortion of the audio signal will result. It is possible, however, to decrease the resistance of the tuned circuit L_2C_2 to a rather low value without causing amplitude distortion of the impressed modulation, in which case the higher oscillating current produces larger voltage variations across L_2C_2 and more grid excitation.

When the original R.F. signal voltage variations are applied to the grid of the regenerative detector, the high-frequency component of the plate current will flow through the tickler coil L_3 then back to the cathode through the by-pass condenser C_3. If the coil L_3 is in proper inductive relationship with L_2, the high-frequency current passing through it will cause a voltage to be induced in L_2 which is in phase with the voltage induced in L_2 from the original signal current through L_1. Thus, the energy fed into L_2 from L_3 increases the amplitude of the oscillating current in L_2C_2.

Increased grid excitation results from the higher oscillating current, thus causing a greater amplitude of plate current changes, a greater average plate current change and louder volume from the headphones.

The R.F. energy fed from L_3 into L_2 increases as the distance between L_3 and L_2 is decreased. Likewise, the feedback into the grid circuit is decreased as L_3 is moved farther from L_2. Therefore, it is possible to vary the amount of energy returned from plate circuit to grid circuit by varying the distance between the tickler coil L_3 and the grid coil L_2. The arrow drawn through L_2 and L_3 in Fig. 3 indicates that the distance (inductive relationship) between the two coils is variable. The dot on the bottom of coil L_3 indicates that L_3 is the coil which can be moved to vary this inductive relationship. In actual construction, the coil L_3 is connected by a shaft to a knob on the front of the receiver. This provides a means of varying the feedback energy, thereby controlling the amplification and selectivity of the circuit.

The "feedback" voltage from L_3 into L_2 must be in such a direction as to *add* to the voltage already existing in L_2 in order to secure regeneration. Should the relationship between these two coils be such that the voltage induced in L_2 from L_3 bucks against the existing voltage in L_2, then *degeneration* occurs and the signal as heard in the headphones is quickly extinguished. At A in Fig. 4 the magnetic field around L_3 is shown linking through the turns of L_2. Let us assume that when the coils are related in this manner, the induced potential in L_2 is *adding* to the existing voltages across L_2; thus the signal is being regenerated and the amplification and selectivity are increased. Now, at B in Fig. 4, the coil L_3 is wound in the opposite direction and it is shown that the magnetic flux through L_2 is also opposite to the condition at A. Therefore, the voltages induced in L_2 from L_3 are now in such a direction that they *buck against* the initial voltages across the oscillating circuit and a partial or complete cancellation occurs. Under this condition, the oscillating current is quickly extinguished, the grid excitation decreases and the detected audio signal in the headphones fades out. "Degeneration" of this nature is undesirable; therefore, it is quite important for the feedback or tickler coil to bear the proper relationship to the grid coil, if regeneration is to be secured.

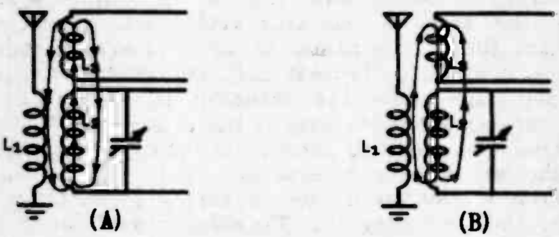


Fig.4 (A) Current through tickler coil produces a magnetic field in such a direction to cause REGENERATION.
(B) Current through tickler coil sets up a magnetic field in the opposite direction, so DEGENERATION is produced.

Reversing the connections to the feedback coil has the same effect as winding it in the opposite direction. If upon constructing or operating a regenerative detector circuit of this kind, it is found that degeneration occurs as the coupling between the tickler and grid coils is increased, it is only necessary to reverse the two connections to the tickler coil to remedy the trouble and secure satisfactory operation. This is true not only when the tickler coil is variable as in Fig. 3, but also when a fixed tickler is used, such as will be discussed on succeeding pages.

Increasing the feedback into the grid circuit gives greater amplification; however, there is a limit to this desirable operation. Beyond a certain point, regeneration causes the detector circuit to function as an oscillator; it will then be capable of supplying its own input voltage and the original modulated signal delivered to the grid circuit from the antenna will not appear in the output. The point of maximum amplification and selectivity in a regenerative circuit is attained just below the point of oscillation. For this reason, all regenerative detector circuits must be equipped with a control that is smooth, even, and effective. The "tickler coil" regeneration control in Fig. 3 is satisfactory in all three respects.

Other methods of satisfactorily securing and controlling regeneration are shown in Figs. 5, 6, and 7. In Fig. 5, the plate circuit inductance L_3 is made variable[1] and acts as a regeneration control. The feedback from the plate circuit to the grid circuit occurs through the interelectrode capacity of the tube from plate to grid. The R.F. energy fed through the tube's interelectrode capacity passes through the grid condenser C_1 into the tuned grid

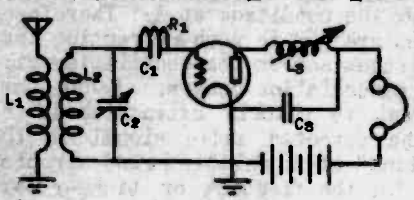


Fig.5 Regenerative grid-leak detector circuit in which the feedback energy occurs through the plate-to-grid interelectrode capacity of the tube.

circuit L_2C_2. It will arrive in the proper phase relationship with regard to the original oscillating current in L_2C_2 so as to increase its amplitude the same as was true with "tickler coil feedback". In three-element tubes, the plate to grid interelectrode capacity is high enough to allow sufficient R.F. energy to be transferred to the grid circuit and cause the detector to supply its own input voltage. By varying the inductance of the plate coil L_3, it is possible to control the feedback energy into the grid circuit, thereby controlling the amount of regeneration. This may be done by increasing L_3 from a low value, or by initially setting L_3 at its maximum value, then reducing it. The audio signal in the headphones greatly increases as the circuit approaches the point of oscillation.

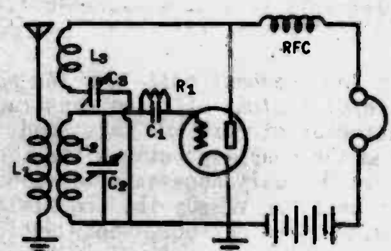


Fig.6 Circuit diagram of regenerative grid-leak detector in which the tickler coil is fixed and the regeneration control consists of variable condenser C_3.

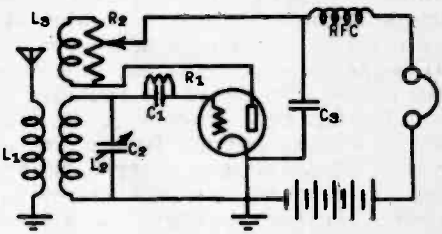
The circuit shown in Fig. 6 employs a fixed tickler (feedback) coil with a variable condenser C_3 connected in series. The R.F. energy from the plate of the tube is prevented from passing through the headphones by the high inductive reactance of the R.F. choke and is compelled to take the path through L_3 and C_3 in order to return to the cathode. As the R.F. energy passes through L_3, by mutual induction a feedback voltage of the proper phase relation is produced in L_2. Varying the capacity of the condenser C_3 varies

[1] A variable inductance of this type is known as a "variometer".

the impedance of this path to the passage of the R.F. energy; thereby controlling the amplitude of the R.F. current through L_3 and the regeneration. Increasing the capacity of C_3 increases the feedback and decreasing its capacity reduces the feedback. The fixed tickler coil L_3 must be connected so as to provide regeneration and not degeneration.

The circuit shown in Fig. 7 also employs a fixed tickler coil. To control the feedback, a potentiometer R_2, is connected across the tickler coil. When the movable arm of the potentiometer is at the bottom, the tickler is shorted out; hence, no R.F. energy passes through it and there will be no feedback into the grid circuit. Moving the arm of the potentiometer to the top increases the opposition to the passage of the R.F. energy through R_2; therefore, it takes the easier path through the low inductive reactance of the tickler coil. Upon passing through L_3, by mutual induction, an "in-phase" feedback voltage is induced in the grid circuit. The fixed tickler coil L_3 should have enough turns on it so that the circuit is forced into oscillations when the arm of the potentiometer is at the top. By moving the potentiometer arm down, the R.F. energy through L_3 is decreased. The regenerative circuit is properly ad-

Fig.7 Circuit diagram of a regenerative grid-leak detector in which the tickler coil is fixed and the feedback is controlled by the resistance R_2.



justed for maximum sensitivity and selectivity just below the point of oscillation.

Adjusting the regeneration control causes a slight change in resonance of the tuned grid circuit. For this reason, it is often found necessary to retune the condenser C_2 as the regeneration control is varied. A greater amount of feedback energy is required for a given degree of regeneration at low radio frequencies than at high radio frequencies. Therefore, if a regenerative circuit is being designed for operation over a certain frequency band, the inductance and capacity values selected for the control should be such as to permit a slight oscillation of the circuit at the lowest frequency to be received. When a regenerative receiver is tuned from a low frequency to a high frequency, it is necessary to reduce the amount of feedback in order to prevent the circuit from oscillating.

It can be shown, both experimentally and theoretically, that the amount of amplification obtainable from a regenerative detector circuit is much greater for a weak radio-frequency input signal voltage than for one greater in strength. This means that the same adjustment of a regenerative detector circuit gives an enormous amplification to a weak signal, whereas, only a fraction of this amplification would be secured if the signal were much stronger. The following table illustrates how the amplification due to regeneration in a detector circuit varies with the strength of the received signal voltage. The tuned grid circuit is assumed to have a voltage gain of 40.

SIGNAL VOLTS INDUCED IN GRID CIRCUIT	VOLTS ACROSS GRID WITH NO REGENERATION	VOLTS ACROSS GRID WITH CRITICAL REGENERATION	VOLTAGE AMPLIFICATION DUE TO REGENERATION
.000001	.00004	.31	7700
.00001	.0004	.66	1600
.0001	.004	1.4	360
.001	.04	3.1	77
.01	.4	6.6	16

Greater amplification is secured with weaker input signal voltages because of the square law relationship between the grid voltage and grid current on the lower end of the E_g-I_g curve. Stronger input signals drive the operation to the linear portion of this curve; hence, the amplification obtained at the point of critical regeneration (just below the oscillating point) is less.

The regenerative detector circuits shown in Figs. 4, 5, 6 and 7 all use the grid-leak condenser method of detection. This method is more satisfactory than grid-bias detection because of its higher sensitivity. Grid-bias detectors will operate in regenerative circuits the same as grid-leak detectors, but grid-leak detectors are more common for the above reason.

Whereas regeneration is an inexpensive method of securing an enormous amplification from a one-stage receiving circuit, it has several disadvantages. First, the increased selectivity, resulting from the decrease in effective resistance of the tuned grid circuit, tends to suppress the high A.F. sideband frequencies and thus impair the tone quality. Then, too, the adjustments required to give the greatest amplification depend on the frequency of the received signal, making it necessary to readjust the regeneration controls each time a new signal is tuned in. A third disadvantage is the fact that the regeneration adjustments are very critical and considerable skill is required to perform them correctly. When the regeneration is increased to the point where the feedback is sufficient to supply the grid excitation, oscillations will be established in the detector circuit. These oscillations will inevitably occur from time to time due to accidental improper adjustment and cause annoyance in the form of howls and squeals.

When a regenerative detector circuit is oscillating, the oscillations will reach the antenna and the energy will be radiated. The receiver is really acting as a small transmitter and its radiation may have a range as great as 10 miles. This is apt to cause serious interference with other receiving sets which might be tuned to approximately the same frequency.

These disadvantages of regeneration have been responsible for its discontinued use in modern radio receivers. At the present, it is considered better practice to obtain the additional radio-frequency amplification with tuned radio-frequency amplifiers, rather than by the use of a regenerative circuit.

The discussions just concluded on various types of regenerative detector circuits have borne out their operation, particularly with respect to the additional amplification and selectivity that is obtained. It is very important for the student to bear in mind that in all these circuits the process of detection is also taking place at the same time. The modulated R.F. signal voltage applied to the grid is demodulated (by rectifying and filtering) and the audio frequency impressed on the incoming signal is heard from the headphones. Simultaneously with the detection of the incoming signal, additional selectivity and amplification are secured through the regeneration, as explained. With excessive regeneration, the operation of the tube as a detector is destroyed and no audio is heard from the headphones, because the circuit and tube then act as an oscillator.

4. **VACUUM TUBE OSCILLATORS.** It has frequently been mentioned that excessive regeneration in a vacuum tube circuit causes it to break into a state of oscillation. This critical point beyond which it is impossible to increase regeneration and still maintain satisfactory signal reception occurs when the feedback from the plate circuit into the grid circuit becomes sufficient for the output energy from the plate circuit to supply the grid exciting voltage. The vacuum tube and its associated circuit is then called a "self-excited oscillator". It is necessary to not only feed back a certain amount of energy from the plate circuit to the grid circuit, but the condition of proper phase relation must also be satisfied. The plate circuit energy must be introduced into the grid circuit so as to reinforce the existing energy in the grid circuit rather than subtract from it. This means that the plate circuit feedback must be in phase with the oscillating current in the grid circuit. Should the plate circuit energy be fed into the grid circuit out of phase with the oscillating current, a partial or complete cancellation of the grid circuit energy will occur and the entire circuit soon becomes inoperative.

The use of a vacuum tube as an oscillator is of extreme importance in both radio transmitter and radio receiver circuits. A vacuum tube oscillator is the only method whereby a continuous amplitude of alternating voltage at high radio frequencies can be secured. Previous mention has been made of the fact that a high-frequency carrier wave is necessary in order to transmit a radio signal from a broadcasting antenna. During the broadcasting of speech and music, this high-frequency carrier wave has the audio-frequency intelligence impressed on it. The generation and amplification of the carrier wave is fundamentally the purpose of a radio transmitter. In the most elementary stage of a radio transmitter, the oscillator circuit generates the carrier wave, then the vacuum tube circuits following the oscillator are adjusted so as to amplify this high-frequency voltage. Prior to the perfection of triode vacuum tubes, the carrier wave was generated with electric sparks and arcs. The carrier wave as generated by these primitive methods was unsatisfactory for sound broadcasting due to the fact that the amplitude did not remain constant even when no modulation was impressed on it. They were used mainly for the transmission of radiotelegraph or code signals.

Any vacuum tube that is capable of amplifying can act as an oscillator; that is, a generator of R.F. voltages. It is not possible to generate extremely high-frequency voltages with mechanical generators,[1] so the operation of a vacuum tube in this capacity is of extreme importance. If the vacuum tube were not capable of performing this all-important job, modern Radio and Television as we know it today would not exist. All superheterodyne receivers contain at least one oscillator circuit, some possessing two. The use of these oscillator circuits in modern radio receivers is largely responsible for their excellent performance.

There are hundreds of ways to connect a vacuum tube and its associated circuit so as to satisfy the conditions necessary to establish oscillations. Some types of oscillator circuits are applicable only to radio transmitters and others are primarily for receiver applications. Then, too, there are other oscillator circuits used in the design of testing equipment, such as audio-frequency oscillators, test oscillators for circuit alignment, etc. A complete description of all these various types of oscillator circuits cannot be included in this lesson.

We shall use a circuit whose operation is typical of most oscillators; then in lessons to follow, the other circuits will be discussed. For the purpose, the Hartley oscillator circuit has been selected. It is well known for its versatile applications.

5. **THE HARTLEY OSCILLATOR.** This oscillator is constructed as shown in Fig. 8. Before explaining its operation, we shall point out certain facts pertaining to the circuit in general. Batteries

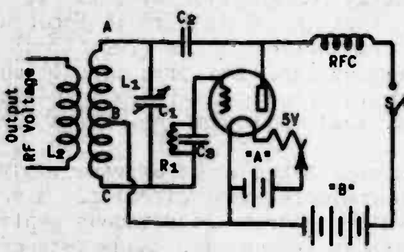


Fig. 8 Diagram of Hartley oscillator circuit.

are being used for filament and plate supply; however, they could just as well be replaced by a transformer secondary winding to supply the filament voltage and a vacuum tube rectifier circuit to supply the plate voltage. No grid-biasing battery is shown in the circuit because the bias on a self-excited oscillator is best secured with a grid-leak resistor. The grid-leak resistance in the Hartley circuit is R_1. The oscillating circuit in Fig. 8 consists of the inductance L_1 and the capacity C_1. When inductance and capacity are associated in this manner, an oscillating current will be established between them at the resonant frequency of the combination. The frequency of the oscillating current (resonant frequency) may be changed by altering either the inductance of the coil or the capacity of the condenser.

[1] The highest frequency ever generated by a mechanical generator was 200 kc., using the Alexanderson machine.

At resonance, the inductive reactance and capacitive reactance are equal and the oscillating current is opposed only by the resistance contained in the oscillating circuit. The effect of this resistance is to produce a continual damping force against the oscillating current; hence, if the succeeding current cycles are to be constant in amplitude, it is necessary to reinforce them with energy fed from an external source. In all vacuum tube oscillators, the necessary reinforcement is acquired from the energy contained in the plate circuit. Referring to Fig. 8, this energy will be delivered into the oscillating circuit through condenser C_2. Since the tube is capable of amplifying an applied grid voltage, the plate circuit contains more energy than the grid circuit, thereby making this feedback possible.

It must be kept in mind that an oscillator circuit is for the purpose of *generating* a high-frequency voltage, not for *amplifying* an externally applied signal. An oscillator, when functioning properly, will deliver a high-frequency voltage from its output, which in turn can be fed into the amplifiers or may be delivered directly to an antenna and radiated. Oscillators should not be confused with the detector circuits previously discussed. All detector circuits are for the purpose of receiving and reproducing a signal which has been radiated from a transmitter whereas, an oscillator is not supplied with a radio-frequency signal, but actually generates one itself.

As in all vacuum tube operation, it is necessary to supply DC power to the plate circuit of an oscillator. *The amount of DC power supplied to the plate circuit is equal to the plate voltage times the average plate current.* The oscillator converts this DC plate circuit power into R.F. power in the tuned circuit L_1C_1. Because of its ability to convert DC power into high-frequency AC power, it is often called a "converter" instead of an oscillator. The high-frequency AC power produced in the oscillating circuit L_1C_1 may be transferred by mutual induction into an output coil L_2. The R.F. voltage developed across this coil may be used for any purpose desired, such as to supply grid excitation to an amplifier tube or supplying R.F. power directly into an antenna from which it is radiated.

With the results expected from the oscillator circuit in mind, let us proceed to discuss its theoretical operation. First, assuming that the filament of the tube is heated and emitting electrons, the switch S in the plate circuit is closed. A current then flows from the B battery. A part of this current passes to the filament, from the filament to the plate inside the tube, through the R.F. choke, then back to the positive terminal of the B battery. The other portion of the total current from the B battery takes a path which may be considered in parallel with the current which passes through the tube. Both paths are shown by the dark lines in Fig. 9. The second current leaves the negative terminal of the B battery, passes to point B on the inductance L_1, up through the inductance to A, through the capacity C_2, then joins the current which has passed through the tube and together they return to B plus through the R.F. choke. The current through this parallel path flows for only a short length of time; that is, the time required for condenser C_2 to become charged. As soon as the voltage across the condenser plates is equal to the voltage of the plate supply

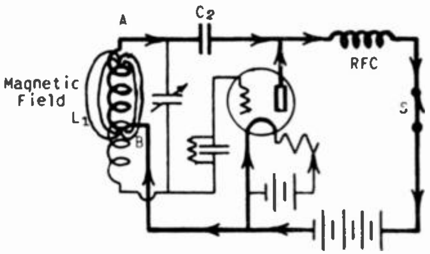


Fig.9 Diagram of Hartley oscillator with the path of the initial plate current drawn in heavy lines.

battery, the current through this circuit stops. To make certain that the path taken by this initial charging current is seen clearly, Fig. 10 has been drawn for illustration. From this figure, it is evident that the initial charging current passes through the inductance B-A, the capacity C_2 and the R.F. choke, then returns to the positive terminal of the battery. It is also apparent that the condenser C_2 will be charged to the full value of the plate supply voltage. The coil B-A and the R.F. choke both have low DC resistance, so if it were not for the presence of C_2 in the circuit, the B supply voltage would be shorted.

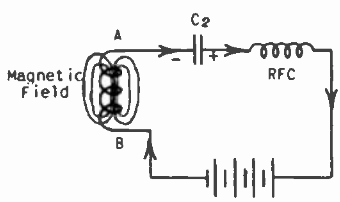
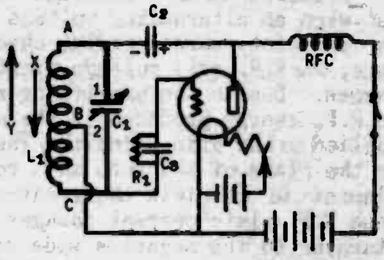


Fig.10 Portion of Hartley oscillator circuit through which initial surge of charging current flows.

The initial charging current passing through B-A and C_2 builds up an instantaneous magnetic field around the coil B-A. The establishment of this magnetic field is of extreme importance, because it supplies the initial impulse of energy which starts the oscillating current in the tuned circuit L_1C_1. As the current which charges C_2 passes through the coil B-A, lines of force rise out from the turns on B-A and in so doing, generate a counter voltage in the coil. Then, when the condenser C_2 becomes fully charged, this current will cease, causing the expanded field around B-A to collapse, thus generating another voltage within the coil winding. The initial voltage induced in B-A, as the field is rising, causes a voltage to be applied directly across the variable condenser C_1; hence, C_1 becomes charged. Then, as C_1 begins to discharge, the second voltage induced in B-A (as the field collapses) occurs at the proper time to reinforce the discharging current from C_1, thus causing a weak oscillating current to be set up in the resonant circuit L_1C_1.

Fig. 11 shows a diagram of the Hartley oscillator circuit with the path of the oscillating current in dark lines. This weak oscillating current flows first in one direction, then in the opposite direction through the inductance L_1, thus causing the condenser C_1 to be alternately charged and discharged. Due to the presence of resistance in this oscillating circuit (the resistance of

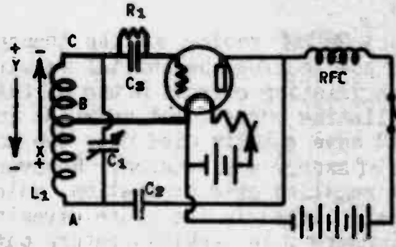
Fig.11 Hartley oscillator with the oscillating circuit drawn in heavy lines.



the coil windings), these weak oscillations would soon die out if no reinforcement of energy were supplied. Additional energy, however, is supplied to the oscillating circuit almost instantaneously, because just as soon as a changing current is established through L_1, the grid of the vacuum tube receives an exciting voltage at the same frequency.

To clearly illustrate the manner in which this grid exciting voltage is applied, let us refer to Fig. 12. At first glance, it may appear that Fig. 12 is an entirely different circuit than Figs. 9 and 10; however, close inspection will reveal that they are exactly the same, except that the oscillating circuit has been turned upside down. The object for drawing the circuit in this manner is

Fig.12 Hartley oscillator with the grid circuit drawn in dark lines to illustrate how the grid exciting voltage is secured.



to make possible a clear conception of how the grid exciting voltage is supplied. When the oscillating current is passing up through the inductance L_1 in the direction of arrow X, a voltage drop will be created ($I \times X_L$) across B-C; then when the oscillating current is coming down through the inductance L_1 in the direction of the arrow Y, another voltage drop is developed across B-C; however, it is opposite in direction. Of course, at the same time these voltage drops are occurring across B-C, there will also be voltages developed across A-B; however, these will be disregarded for the present, because we are primarily interested in the grid exciting voltage. Alternating voltages created across the coil B-C are applied directly between the grid and the negative side of the filament through the resistance R_1 and condenser C_3. R_1 generally has a value of from 10,000 to 50,000 ohms and C_3 is about .00025 mfd. The alternating voltage developed between grid and negative filament will be the same in frequency as the voltages across B-C, which, in turn, are the same as the oscillating current.

Previous lesson material has definitely confirmed the fact that when an alternating voltage is applied between grid and negative filament, corresponding changes in plate current will occur. Hence, the R.F. grid voltage excitation produces R.F. plate current changes. Due to the amplifying ability of the three-element tube, the R.F. energy produced in the plate circuit is greater than that supplied to the grid circuit. The R.F. plate current changes leaving the plate of the tube must return to the negative side of the filament to complete their circuit. Fig. 13 shows the path that these R.F. plate current changes follow. They are prevented from returning to the negative side of the filament through the B battery by the presence of the R.F. choke. They pass with relative ease through the condenser C_2 and the portion of the oscillating circuit from A to B since this path offers very little opposition.

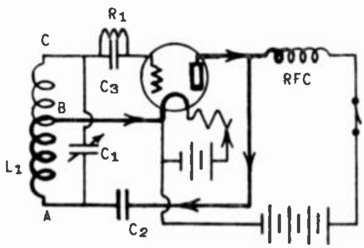


Fig.13 Hartley oscillator with the feedback path from the plate to the oscillating circuit drawn in dark lines.

A brief review of the transpired operation reveals that we have now secured the initial requirement necessary for maintaining an oscillating current in the circuit L_1C_1. It was stated that the oscillating current set up by the initial charging of condenser C_2 would have quickly died out, due to resistance, unless a reinforcement of energy was secured. However, the initial oscillating current supplied grid excitation, which in turn caused R.F. energy to be established in the plate circuit of the oscillator tube. This R.F. energy, in seeking a return path, passed through the oscillating circuit L_1C_1. Therefore, the return of energy from the plate circuit to the oscillating circuit supplies the necessary reinforcement to the initial oscillating current, thus preventing its amplitude from being decreased by resistance.

The R.F. energy fed back from the plate circuit into the oscillating circuit arrives at exactly the proper time so as to be in phase with the initial oscillating current; hence, the amplitude of the oscillating current is increased. As the oscillating current increases in amplitude, the voltage drops produced across L_1 from B to C also increase, thereby supplying greater R.F. exciting voltage to the grid of the tube. The increased R.F. grid excitation results in a higher amplitude of R.F. plate current changes, which in turn causes more energy to be fed back through the condenser C_2 into the oscillating circuit.

The R.F. energy supplied from the plate circuit will continue to reinforce the amplitude of the oscillating current in L_1C_1 and the increased oscillating current will continue to supply additional grid excitation until some limit is reached. The amplitude "building-up" of the oscillating current occurs somewhat as illustrated in Fig. 14. The initial oscillating current is very low in amplitude and each succeeding cycle is increased until the maximum os-

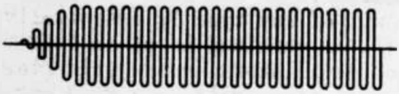


Fig.14 Diagram to illustrate how the oscillating current in the tuned tank circuit builds up in amplitude until the saturation point is reached.

cillating current is established in the resonant circuit. The limit to this building-up process occurs when the tube becomes "saturated". Saturation occurs when an increased grid exciting voltage will no longer produce an increased amplitude of plate current changes. It is evident that this point of saturation is determined primarily by the characteristic curve of the tube, which in turn depends upon the plate, grid and filament voltages. Altering any one of these three voltages will change the characteristic curve of the tube and result in a different amplitude of oscillating current in L_1C_1.

So long as all applied voltages remain constant and the emission from the filament is normal, the amplitude of the oscillating current in the resonant circuit will remain absolutely constant. The frequency of this oscillating current depends upon the resonant frequency of L_1 and C_1. Changing the capacitance of C_1 or the inductance of L_1 will change the output frequency. By proper circuit design, it is possible to secure an alternating voltage output from a Hartley oscillator circuit at any frequency throughout the audible and radio-frequency spectrum. The Hartley oscillator is not generally used for the production of audio frequencies; however, by proper selection of L_1C_1, it may be made to do so. This circuit is employed primarily for generating R.F. signals, which, after being amplified, serve to act as a carrier wave for audio frequencies. When the transmission of code is desired instead of speech and music, the carrier wave is not modulated, but rather is interrupted by a telegraph key. When a "dot" is to be transmitted, the carrier wave is radiated for a short period of time and when it is desired to transmit a "dash", the carrier wave is radiated approximately 3 times as long. A rapid and successive interruption of the carrier wave in this manner comprises the transmission of code signals. Such transmission is generally known as "CW radiation". The letters

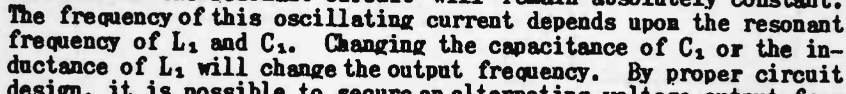


Fig.15 Code signals as radiated from a CW transmitter.

"CW" are used to mean "continuous waves"; that is, the amplitude of the carrier is not varied.

Several dots and dashes as transmitted from a CW station are shown in Fig. 15. Regardless of whether it is desired to transmit CW or telephone signals, a high-frequency carrier wave is always essential for radiation from an antenna. Carrier waves are generated by a satisfactory oscillator circuit, such as the Hartley circuit just described.

6. **GRID BIAS IN THE HARTLEY OSCILLATOR.** The method of securing grid bias in an oscillator circuit of any type is essentially different from the manner in which it is obtained in an amplifier circuit. All efficient self-excited oscillators secure grid bias by use of a grid-leak resistor. All oscillators will draw grid current when functioning properly and, as this grid current passes through the grid-leak resistance, the necessary bias voltage will be developed. Previous discussion of amplifier circuits has emphasized the fact that grid current should not flow in a properly adjusted amplifier. The operation of a vacuum tube as an oscillator is entirely different in this respect, because the grid should go positive at certain intervals in all types of oscillator circuits in order to secure the most satisfactory operation.

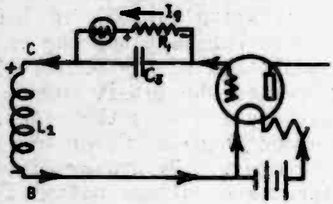


Fig.16 Grid circuit of Hartley oscillator to illustrate the path of the grid current.

Fig. 16 shows the portion of the Hartley oscillator circuit necessary to explain how the grid bias voltage is developed by the flow of grid current. Comparison of Fig. 16 to Fig. 12 shows the portion of the oscillator circuit which has been redrawn for this explanation. When the oscillating current in the tuned circuit L_1C_1 passes through the inductance in such a direction as to make C positive and B negative (positive alternation), the grid of the tube will be made positive with respect to negative filament. The positive grid then attracts electrons from the space charge and grid current flows in the direction of the arrows on Fig. 16. The path of this current is through the grid-leak resistance R_1, through the inductance L_1 from C to B, then returns to the negative side of the filament to complete its circuit. For normal operation, the size of R_1 is generally from 10,000 to 50,000 ohms. A voltage drop equal to $I \times R$ will be developed across R_1 as the grid current passes through this resistance. The direction of the voltage is shown in Fig. 16. The milliammeter connected in series with R_1 measures the amount of grid current.

The negative alternation of the oscillating current develops a voltage across the grid coil B-C in such a direction as to make the negative side of the filament positive with respect to the grid.

No grid current will flow during this alternation. Since grid current flows only during one alternation of the oscillating current, it is evident that only pulses of current will be flowing through the grid circuit. These pulses are of short duration since they flow only during the time that the grid is positive with respect to the negative side of the filament.

A pulsating direct current has been previously shown to consist of a DC and an AC component. A low-pass filter is capable of separating a pulsating DC current into its two components. A filter of this type is effectively contained in the grid circuit, consisting of the grid-leak resistance R_1 in parallel with the grid condenser C_3. The reactance of C_3 to the R.F. AC component of the grid current is relatively low, at least much less than the resistance of the grid leak R_1; hence, the AC component of the grid current pulses will pass through the grid condenser, but the DC component is blocked from this path. Assuming C_3 has no leakage, the opposition offered to the DC component is infinite; therefore, the DC must return to the negative side of the filament through the grid-leak resistance R_1. The passage of the DC component of the grid current through R_1 develops a steady DC voltage across it which serves as grid bias for the oscillator tube. The end of R_1 that is made negative by the flow of grid current is toward the grid of the tube and the end of R_1 that is made positive is toward the negative side of the filament. Hence, the voltage across R_1 applies a *negative* grid bias to the oscillator tube.

The R.F. voltages developed across L_1 will always be slightly greater in amplitude than the negative bias voltage across R_1, thus assuring that the grid of the tube will be made slightly positive during each cycle of the oscillating current. The grid must go slightly positive so as to maintain the flow of grid current through R_1 to develop the necessary negative grid bias.

The action of the grid leak and condenser is practically the same in all other types of self-excited oscillator circuits. Circuit diagrams and explanations of other oscillators are contained in future lessons.

7. BLOCKING THE GRID CIRCUIT OF A HARTLEY OSCILLATOR. By increasing the size of the grid-leak resistance to an exceptionally high value, it is possible to "block" the grid of the oscillator tube at regular intervals. This has the effect of modulating the R.F. voltage output at a low-frequency rate.

To maintain normal operation of a Hartley oscillator, the upper limit for the size of the grid-leak resistance is approximately 50,000 ohms. Increasing the grid leak to over 100,000 ohms will generally cause the blocking action to occur. The use of a high grid-leak resistance develops such a large grid bias when grid current passes through it that the amplitude of the plate current pulses are decreased until they are no longer capable of supplying the necessary feedback into the grid circuit to maintain oscillation. As a result, the oscillations in the tuned circuit L_1C_1 gradually die out and the entire oscillator circuit stops functioning. As the oscillating current dies out, the grid excitation is decreased to the point where the grid is no longer driven positive; hence, the high negative grid bias previously developed returns to a less negative value. Before the grid bias reaches zero, the plate current has again started to flow through the plate circuit; as the plate current rises to its previous value, a pulse of energy is transferred through the blocking condenser C_2, back into the oscillating circuit which sets up a weak oscillating current. This oscillating current again supplies grid excitation and the oscillator circuit builds up to normal operation again. As soon as sufficient grid current is flowing through the high grid-leak resistance, a high negative bias is again developed which causes the oscillator circuit to block the second time. This action continuously repeats at definite intervals (depending upon the size of the grid-leak resistance) so the operation of the oscillator circuit blocks, builds up; blocks, builds up; etc.

The amplitude of the oscillating current in the tuned circuit L_1C_1 follows the blocking and building up action of the circuit and, therefore, appears as shown in Fig. 17. The frequency of the R.F.

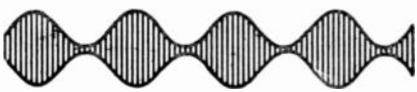


Fig.17 Appearance of the oscillating current in a Hartley oscillator when being blocked with a high grid-leak resistance.

oscillating current is still determined by the size of the inductance and capacity in the tuned circuit, but the current amplitudes are no longer constant; they rise and fall in accordance with the frequency of the blocking action. The effect is just the same as though the R.F. carrier wave were modulated with an audio frequency. The output of the oscillator, then, consists of the generated R.F. signal modulated at an A.F. rate. The frequency of modulation can be varied by changing the size of the grid-leak resistance. Increasing the size of the grid-leak resistance will cause the frequency of the blocking action to be decreased, thus producing an output carrier wave which is modulated at a lower A.F. rate. Decreasing the size of the grid-leak resistance will increase the frequency of the blocking action, which means that the output of the oscillator will be modulated with a higher A.F. note.

When an oscillator is operating in a blocked condition, it is possible to tune a radio receiver to its frequency and hear the audio modulation. It will be found that the use of a high grid-leak resistance results in a steady low-pitched audio note from the loudspeaker and a fairly low grid-leak resistance will produce a high-pitched note. When the size of the grid-leak resistance is decreased to about 50,000 ohms or below, the negative bias voltage developed is insufficient to cause the blocking action; hence the generated R.F. carrier wave remains constant in amplitude. When unmodulated, no sound will be heard from the loudspeaker when the radio set is tuned to the frequency of the oscillator. Should one of the R.F. amplifying stages in the radio set be regenerating slightly, it is likely that a whistle will be heard when the set is tuned close to the frequency of the oscillator, even though the oscillator is not modulated.

8. **USE OF OSCILLATORS.** The reason for studying the theoretical operation of an oscillator circuit at this time is to enable the comprehensive study of superheterodyne receivers and the operation of test oscillators for radio circuit alignment. A separate tube or one section of a dual purpose tube is used in all superheterodyne receivers to generate a constant amplitude R.F. voltage. The output of the oscillator in a superheterodyne is "mixed" with the incoming radio signal selected by the tuning circuits. The result of this "mixing" action (heterodyning) is the production of a new frequency equal to the difference between the frequency of the modulated radio signal and the frequency of the oscillator. This new frequency is called the "beat" or "intermediate" frequency, and it is modulated in exact accordance with the original A.F. modulation impressed on the incoming signal. The modulated I.F. (intermediate frequency) is then amplified and fed to the "second detector" where the A.F. is removed from the I.F. signal. The superior performance of superheterodyne receivers in comparison with T.R.F. (tuned radio frequency) receivers is largely due to the production of this beat or intermediate frequency. Nearly all receiver manufacturers have adopted the superheterodyne principle because of the greater sensitivity, selectivity, and fidelity which can be obtained from it with a minimum of tubes, circuit design and expense. The underlying principles concerning the operation of these two methods of radio signal reception will be explained in Lessons 24 and 27 of this unit.

All radio service men find that the use of a "test oscillator" is very essential for the proper adjustment of a radio receiver circuit. The test oscillator is really a miniature broadcasting station which supplies an R.F. voltage modulated at an A.F. rate. By connecting a test oscillator to the antenna and ground terminals of a radio set, it is possible to adjust the tuning circuits in the receiver very accurately, thus assuring the best possible performance of that receiver when it is used for the reception of modulated R.F. signals from broadcast stations. Lessons in Unit 2 will be devoted to the operation of commercial test oscillator circuits and the methods of using such apparatus for radio circuit alignment.

The first lesson in Unit 3 is devoted entirely to a complete and detailed description of various types of oscillator circuits used for radio transmission. This lesson will treat the subject of oscillator operation more thoroughly than the information contained herein, particularly as to the voltage, current and power relations. Other fundamental, self-excited oscillator circuits, such as the Colpitts, the Meissner, the tuned grid-tuned plate, etc., will be discussed and their adaptability to the generation of high-frequency carrier waves for the transmission of radio signals. The study of crystal-controlled oscillators also constitutes an interesting phase of radio theory.

(3) USE OF OSCILLATORS: The reason for studying the theory and operation of oscillator circuits at this stage is to enable the comprehensive study of superheterodyne receivers and the operation of test oscillators for radio receiver alignment. A separate tube in the section of sound circuits is used in all superheterodyne receivers to generate a constant amplitude R.F. voltage. The output of the oscillator in a superheterodyne is "mixed" with the incoming radio signals selected by the tuning circuits. The result of this "mixing" action (heterodyning) is the production of a new frequency equal to the difference between the frequency of the modulated radio signal and the frequency of the oscillator. This new frequency is called the "beat" or "intermediate" frequency, and is modulated in exact accordance with the original R.F. modulation impressed on the incoming signals. The modulated I.F. (intermediate frequency) is then amplified and fed to the "second detector" where the A.F. is removed from the I.F. signal. The superior performance of superheterodyne receivers in comparison with T.R.F. (tuned radio frequency) receivers is largely due to the production of this new intermediate frequency. Nearly all receiver manufacturers have adopted the superheterodyne principle because of the greater sensitivity, selectivity, and fidelity which can be obtained from it with a minimum of tubes, circuit design and expense. The underlying principles concerning the operation of these two methods of radio reception will be explained in Lessons 24 and 27 of this unit.

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The first lesson in Unit 9 is devoted entirely to a complete and detailed description of various types of oscillator circuits used for radio transmission. This lesson will treat the subject of oscillator operation more thoroughly than the information contained herein, particularly as to the voltage, current and power relations. Other fundamental, self-excited oscillator circuits, such as the Colpitts, the Meissner, the tuned grid-tuned plate, etc., will be discussed and their adaptability to the generation of high-frequency carrier waves for the transmission of radio signals. The study of crystal-controlled oscillators also constitutes an interesting phase of radio theory.

COMMON FRACTIONS AND THEIR DECIMAL EQUIVALENTS

Fraction	*Decimal*	*Fraction*	*Decimal*	*Fraction*	*Decimal*	*Fraction*	*Decimal*
1/64	.0156	1/4	.2500	1/2	.5000	3/4	.7500
1/32	.0313	17/64	.2656	33/64	.5156	49/64	.7656
3/64	.0469	9/32	.2813	17/32	.5313	25/32	.7813
1/16	.0625	19/64	.2969	35/64	.5469	51/64	.7969
5/64	.0781	5/16	.3125	9/16	.5625	13/16	.8125
3/32	.0938	21/64	.3281	37/64	.5781	53/64	.8281
7/64	.1094	11/32	.3438	19/32	.5938	27/32	.8438
		23/64	.3594	39/64	.6094	55/64	.8594
1/8	.1250	3/8	.3750	5/8	.6250	7/8	.8750
9/64	.1406	25/64	.3906	41/64	.6406	57/64	.8906
5/32	.1563	13/32	.4063	21/32	.6563	29/32	.9063
11/64	.1719	27/64	.4219	43/64	.6719	59/64	.9219
3/16	.1875	7/16	.4375	11/16	.6875	15/16	.9375
13/64	.2031	29/64	.4531	45/64	.7031	61/64	.9531
7/32	.2188	15/32	.4688	23/32	.7188	31/32	.9688
		31/64	.4844	47/64	.7344	63/64	.9844
15/64	.2344					1	1.0000

Notes

(These extra pages are provided for your use in taking special notes)

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MIDLAND RADIO
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UNIT NO. 1

RADIO-FREQUENCY AMPLIFIER CIRCUITS

LESSON NO. 24

THE JUMPER

.......IN LEAPS AND BOUNDS, HE JUMPS AROUND, BUT NEVER GETS AHEAD.

This little story is true. We write it in the hopes that it will never refer to you.

About twenty years ago, we knew a young fellow who possessed remarkable energy. He was always in a great rush.....always had something big just ahead of him. People liked this young man, for he had a pleasant smile and an exceptional personality. Frequently, the remark was heard, "That fellow is bound to make his mark in the world."

As time went on, the young man made several outstanding accomplishments. He had a host of friends, and included among them were dozens of outstanding and influential people. Surely, he had the background for amazing success. Everything seemed to be in his favor. But something went wrong.

Today, that same man is very much worried about his future. He has a fine family and is still "chuck full" of energy and pep. But he has no money in the bank to speak of. He has no job of any consequence. Of course, he still has hosts of friends. And he still delights in telling you about all the prominent people that he knows. But for some reason, his clothes have become shabby, and he no longer radiates prosperity and confidence which can come only with financial security. Many people wondered why he was a failure. Yet the reason was most apparent.

From the very beginning, the object of our true story had continually sought ways and means of making "quick money". He jumped from one thing to another, never remaining in one job long enough to become proficient at it. He refused to study. He worked on the theory that "lady luck" would come his way some day and he'd "strike it rich".

As time went on, the many influential friends he had won lost faith in him. Of course, they still thought he was a nice fellow. But.....well, he never stuck to anything. Today, this man is on the verge of entering that period of life when success is rare, if it has not already been achieved. His wife knows what the future holds for her family, but she is helpless. His children still have faith in "daddy", and feel confident he will get rich some day. But fate is cruel and heartless. Daddy's most productive days are gone. From now on, he will just "get by".

As we told you before, this is a true story. And there are thousands upon thousands of similar cases throughout our nation. But they need not worry you, IF you will "stick to what you start" and ignore the beautiful, "easy-money" rainbows that are always "just beyond reach"!

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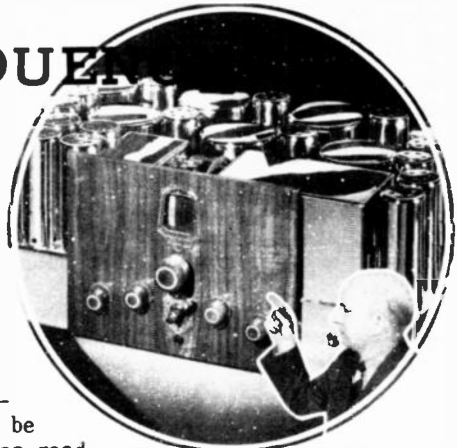
JONESPRINTS
KANSAS CITY, MO.

Lesson Twenty-Four

RADIO-FREQUENCY AMPLIFIER CIRCUITS



"For a modern radio receiver to be capable of satisfactory performance, it must be sensitive, selective and possess good tone quality. The design of the audio-frequency amplifier, which amplifies the detector output and operates the loudspeaker, affects the sensitivity and fidelity to a great extent, but we cannot neglect the importance of the radio-frequency amplifier which precedes the detector stage.

"It will be shown in this lesson how the R.F. amplifier plays a tremendously important part in the operation of a radio receiver."

The reception of radio programs without the use of vacuum tubes is possible as was discussed in Lesson 18. By means of a crystal detector, local radio programs may be received at a volume sufficient to operate earphones. During the first few years of broadcasting, when radio reception was novel, a person was delighted to hear any type of radio program, weak and distorted though it might be. The fact that earphones were necessary was no deterrent to the rapid growth of popularity which radio enjoyed. As the years passed the novelty of radio wore off. The public demanded more than the mere reception of radio programs; they demanded that a program have entertainment value, be relatively free from noise and have an output of sufficient strength to operate a loudspeaker so that the entire family might easily listen. Naturally, the amount of energy extracted by the antenna was too small to satisfy these demands and therein the need for amplification arose.

First, there was the "one-tube" receiver, the single tube acting as a detector. While it was not capable of producing an output sufficient to operate a loudspeaker, it was more selective than the crystal detector and could reproduce the signals of stations several hundred miles away.

The next popular type of receiver was the regenerative detector followed by two stages of audio amplification. The output of this receiver would operate a loudspeaker, when the programs of local stations were being received. Usually, however, these sets were not sensitive enough to reproduce with loudspeaker volume the programs of stations that were at all distant.

It would be reasonable to suppose that the next step would be to add further stages of audio-frequency amplification to increase the output of the receiver. This practice, however, brought forth many new problems. First, an attempt to add more than two stages of A.F. amplification resulted in instability and a tendency for the output to be so badly distorted as to be unacceptable. Then, again, there was the matter of selectivity. The air was rapidly becoming crowded with stations; something had to be done to make the receiver able to discriminate between them. Since selectivity is vitally important, it is advisable that we now turn our attention to a discussion of this subject.

1. SELECTIVITY. *The selectivity of a receiver may be defined as a measure of its ability to discriminate between wanted and unwanted signals.* Vacuum tubes themselves are not selective; they will amplify any frequency fed to their grid circuits, whether it is of the desired station or an interfering station. The problem, therefore, is to prevent as much as possible the signals of the unwanted stations from reaching the grids of the amplifier stages.

As was discussed in the preceding lesson, only a tuned circuit, consisting of an inductance and a capacity, has the ability to allow current of a particular frequency to pass through it more easily than current of any other frequency. The selectivity of a receiver, therefore, depends upon the judicious use of tuned circuits.

Ordinarily more than one, sometimes as many as eight or more, tuned circuits are needed to give the desired selectivity. In most receivers, some selectivity is obtained between the antenna and the grid of the first amplifier stage and additional selectivity is acquired between the first and second stages and between the third stage and the detector. Thus, it is common practice to use a tuned circuit between the antenna and the first amplifying tube; this reduces the strength of the unwanted signals considerably. Those which do get through to the grid of the first tube are amplified along with the desired signal. The output of the first tube is then fed into a second tuned circuit by means of which the ratio between the desired signal and the undesired signals is further increased. This tuned circuit feeds a second amplifier tube, the output of which is again introduced into a tuned circuit. By this method, the desired selectivity may be obtained.

In a few cases, manufacturers have so designed their receivers that all of the selectivity is secured before the desired signal receives any amplification. A number of tuned circuits connected together to form a so-called "preselector circuit" make this possible.

We have not yet considered the type of amplifiers these vacuum tubes must be. Obviously they cannot be A.F. amplifiers because the received signal has never been fed into a detector stage and since they are not detectors, there is only one thing left for them to be, and that is "radio-frequency amplifier stages". They are amplifiers since they are working over the straight portion of the grid voltage-plate current characteristic curve and since they are amplifying the signal before it has been detected; that is, while it is a radio-frequency wave, it is proper that they be called radio-frequency amplifiers.

It is impossible to gain any additional selectivity after the signal has been passed through the detector; that is, no selectivity may be obtained in the A.F. amplifier stages. It would, therefore, seem advisable to use several R.F. amplifier stages to attain the desired selectivity. Another point which indicates the desirability of R.F. amplifiers instead of A.F. stages is that the A.F. amplifier must amplify such a wide band of frequencies (from 100 to several thousand cycles at least) that the chances for distortion are very great. On the other hand, the R.F. amplifier needs to amplify only a small band of frequencies, a process which it is able to do with a minimum of distortion. To avoid distortion, it would be better to use all R.F. amplifier stages, one detector tube and no A.F. stages; yet, this is not possible. The fallacy of this argument lies in the fact that no detector has, as yet, been developed with an output of sufficient strength to operate a loudspeaker; therefore, at least one audio stage must be used. It is probable that some inventive genius of the future will design a detector capable of handling the energy required to operate a loudspeaker. Such an invention would relegate A.F. amplification in radio receivers to the position now held by the spark gap, the coherer and other devices reminiscent of the early days of radio.

2. FIDELITY. *The fidelity of a receiver may be defined as a measure of how well it reproduces the actual sound wave originating in the broadcasting studio.* When a note of a certain loudness and frequency is sung into the microphone, its reproduction from the loudspeaker of a radio receiver should have the same loudness and frequency as that of the original note; there should be no change in its waveform. Any such change constitutes distortion and a departure from perfect fidelity. Absolutely distortionless reception is not possible at the present state of the radio art, as no receiver may be said to have perfect fidelity as long as its output is distinguishable from the original production. Such a state of affairs is no particular cause for alarm as the general public has so accustomed itself to slightly imperfect reproduction that it is doubtful whether a distortionless receiver (if it were possible) would warrant any additional cost. Modern receivers approach the ideal through at least a part of the audio range, and are wholly acceptable, to all but the most critical ears.

The audio-frequency spectrum may, on the average, be said to extend from 16 to 16,000 cycles. The best radio transmitters have an audio range of 30 to 10,000 cycles and are known as "high-fidelity" transmitters. The range of most transmitters is less than this; 60 to 7,500 cycles would be average values.

A very few receivers will reproduce frequencies of 30 and 10,000 cycles, but such frequencies usually do not receive as much amplification as does a frequency in the middle of the audio range. 100 to 5,000 cycles would include all frequencies satisfactorily reproduced by the average console receiver, while the midget or table model has an even narrower range.

Since good fidelity is one of the requirements of modern day receivers, it is necessary that this factor be taken into account in the design of R.F. amplifier circuits. If the receiver is too selective, it will not admit the full band of frequencies which the broadcasting station is transmitting; that is, there will be "sideband cutting" with consequent distortion and poor fidelity. It can thus be seen that the two factors, selectivity and fidelity, demand opposite circuit conditions, for which reason a compromise must be effected. A receiver may be made very selective, as much as anyone could desire, but its fidelity under this condition would be so poor that speech might be unintelligible. On the other hand, the fidelity may be made, not perfect, but acceptable and of very good quality, at which point the selectivity is so poor that the receiver is impractical.

Most receiver manufacturers try to strike a happy medium in designing their amplifiers to secure as much fidelity as possible and still obtain the necessary selectivity. This may sometimes be accomplished by designing the A.F. stages to amplify certain frequencies more than others. The frequencies which are over-amplified by the audio stages are those which have been partially attenuated[1] by sideband cutting in the R.F. stages. By such a process, an acceptable receiver may be produced.

Other manufacturers make the selectivity of their receiver variable. When one is attempting to receive a distant station, maximum selectivity is desirable and tone quality is not of paramount importance. For a strong local program, not much selectivity is required and the maximum fidelity is then made available by varying the selectivity or fidelity control.

3. **SENSITIVITY.** *The sensitivity of a receiver may be defined as a measure of the over-all amplification from the antenna-ground terminals of the receiver to the loudspeaker.* It is, of course, desirable to have a high sensitivity in order that a very small amount of input power may produce satisfactory loudspeaker volume.

Before continuing with a discussion of sensitivity, it is well that we inquire into the measurement of the strength of a received signal. The energy radiated from a broadcasting antenna spreads out in all directions and the voltage induced in a receiving antenna only a few miles distant is very small.

This voltage depends upon two things: the effective height of the antenna and the field strength of the radio transmitter at that point. The effective height of an antenna is governed by many things other than its actual distance above the ground. As an example, it depends upon the proximity of the antenna to grounded objects as well as its actual physical height. *The field strength of a radio signal at a particular position is a measurement of the effectiveness of the signal in inducing a voltage in a receiving antenna at that spot.*

If a signal is able to produce a voltage of one millivolt in an antenna whose effective height is one meter, it is said to have

[1] Attenuate means to reduce in force, value or strength; to weaken. It is a word often used in radio literature to describe the weakening of a signal.

a field strength of 1 millivolt per meter (sometimes written 1 mv/m). If the effective height were 4 meters, the voltage induced in the antenna by the same signal would be 4 millivolts, but the field strength would still be 1 millivolt per meter. *Thus, the field strength may be defined as the voltage induced in a receiving antenna of one meter effective height.* The total voltage induced in an antenna is the product of its effective height in meters and the field strength of the signal in millivolts or microvolts per meter. Thus, a signal of 8 mv/m would produce a voltage of 32 millivolts in an antenna of 4 meters effective height.

If the receiving antenna is very close to a broadcasting antenna (within a few hundred feet), it may be that the received signal is as high as 1 volt per meter; this, however, is unusual. On the other hand, if the receiving antenna is located several thousand miles from the broadcasting antenna, the field strength of the station at that point would probably be only a few microvolts per meter.

Most modern radio receivers will give satisfactory loudspeaker volume when the voltage induced in the receiving antenna is as low as 10 to 15 microvolts. By adding more and more amplifying stages, it is, of course, possible to increase the sensitivity of any receiver. Thus, it is possible to increase the sensitivity to such a point that a received signal of only 1 microvolt or less would produce satisfactory loudspeaker volume.

There are, however, other factors to be considered which are directly associated with sensitivity. In the output of the loudspeaker, in addition to the program of the station, there is also static which is of two forms, natural and man-made. Natural static is caused by thunderstorms, magnetic storms and by electrical disturbances in the ether which may, or may not, be due to sunspots. Man-made static, on the other hand, is caused by neon signs, diathermy and X-ray equipment, sparking motors, telephone dial clicks and other equipment of an electrical nature. All these devices generate small noise voltages which are radiated and may be picked up by the receiving antenna; or the noise voltages may be fed back into the power line which is supplying the receiver and thereby reach its circuits. The total of all these disturbances, static, etc., is known as the noise level and will, of course, differ for various localities.

The noise level may range from a few tenths of a microvolt per meter in an unusually quiet and secluded spot to several millivolts per meter in a particularly noisy location. This voltage is the actual voltage induced in the receiving antenna due to all these disturbances. Let us assume that the noise level in a given locality is 5 microvolts per meter. If the sensitivity of the receiver in that location is 1 microvolt per meter, it does not necessarily follow that a signal having a field strength of 1 microvolt per meter will be reproduced satisfactorily by this receiver. The noise voltage of 5 microvolts per meter is five times as great as the field strength of the desired station at that point. Both the signal of the station and the noise voltage will be picked up by the antenna and amplified by the receiver. In the output of the receiver, the noise voltage will still be five times as great as the signal voltage and the program will probably be unintelligible due to the excessive noise. It is thus seen that there is a maximum usable sensitivity which is determined by the noise level in the location where the receiver is to be operated.

It is not possible to tune out these noise voltages since they consist of pulses of energy of very short duration which may be considered to cover a very wide band of frequencies. If the field strength of a station at a particular point is less than the noise level at that point, such a station can never be received satisfactorily, no matter what the sensitivity of the receiver may be. As we all know, the noise level is higher on some days than others; the static is especially annoying on cloudy days or during thunder storms and the usable sensitivity of a receiver is much less than normal.

Many schemes have been devised for increasing the usable sensitivity of a receiver by placing the antenna at a sufficient height above the ground to be out of the noise range or field caused by motors, etc. By this method, the total noise voltage induced in the antenna is somewhat lower and, by using a lead-in wire which is either shielded or so arranged that any noise voltage induced in it will be cancelled out, the so-called "signal-to-noise ratio" may be increased and a signal of a lower field strength may be reproduced with satisfactory volume without too much interference.

Curves illustrating the selectivity, fidelity and sensitivity of a modern, high quality, laboratory-built receiver are shown in Figs. 1, 2 and 3. They show the performance of the Scott Philharmonic receiver. This receiver has a fidelity or selectivity control, by means of which the selectivity may be varied as desired. By reference to the graph in Fig. 1, it may be seen that when the control is set for maximum selectivity, a very sharp resonance

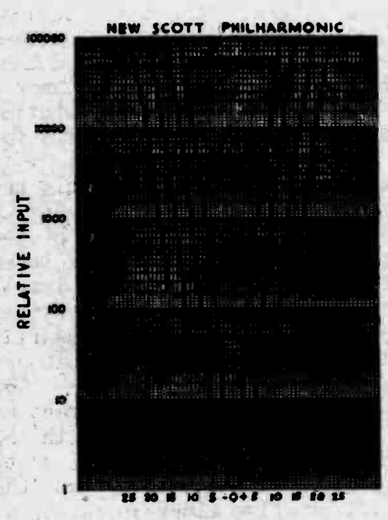


Fig.1 Selectivity curves of a modern high-fidelity receiver. This receiver is equipped with a selectivity control. (Courtesy of E. H. Scott Radio Laboratories, Inc.)

curve is obtained. This graph is slightly different from any previously given and may require a little explanation. The horizontal scale has a zero at the resonant frequency and is graduated in kilocycles to show off-resonant frequencies. The vertical scale shows the relative input necessary to produce the same amount of response as a signal of the resonant frequency. Thus, it may be seen that when the control is in the most selective position, the relative input of a signal 10 kc. off resonance is 20,000. This means that an adjacent channel station (10 kc. off resonance) would need to have a field strength 20,000 times as great as that of the desired station if it is to produce the same output. It is also evident that when the control is set for minimum selectivity (maximum fidelity), the receiver will pass a wide band of frequencies, thereby precluding any possibility of sideband cutting.

The set of curves shown in Fig. 2 illustrates the sensitivity of this receiver at various frequencies. The receiver has 5 bands and a separate curve is used to show the input in fractions of a microvolt necessary to produce satisfactory output for each band.

The fidelity of this receiver is graphically shown in Fig. 3. The various curves show the relative output of the receiver at different audio frequencies compared to 400 cycles, a frequency which is nearly always used as a standard in fidelity measurements. The six curves correspond to six different positions of the tone control. When the control is in the maximum bass position, a filter circuit is used to reduce the output at 60 cycles to avoid the production of excessive hum. In a like manner, a 10,000-cycle filter is used to reduce the response at this frequency. Otherwise, a

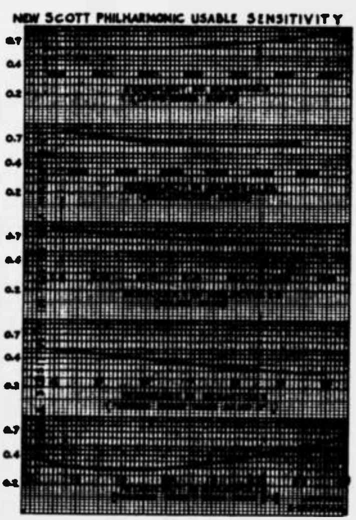


Fig.2 Sensitivity curves of the various frequency bands of a high - fidelity receiver. (Courtesy of E. H. Scott Radio Laboratories, Inc.)

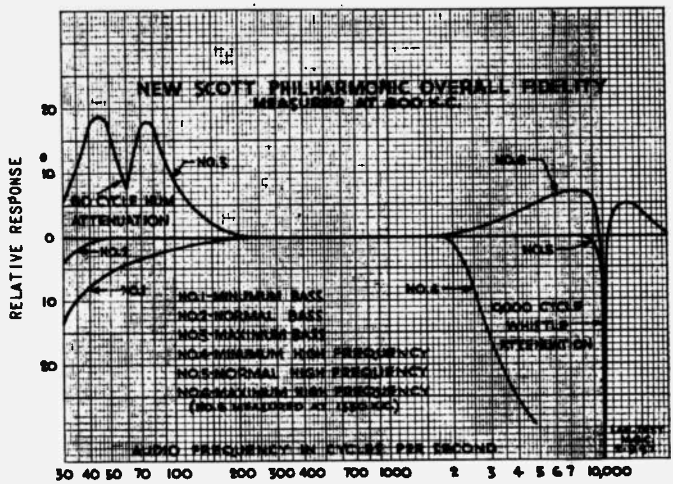


Fig.3 Fidelity curves of a high-fidelity receiver. (Courtesy of E. H. Scott Radio Laboratories, Inc.)

whistle might be generated by the interaction of the sideband frequency corresponding to 10,000 cycles and the carrier of the adjacent-channel station.

4. TYPES OF R.F. AMPLIFIERS. Theoretically, any one of the types of coupling used for A.F. amplification could also be used for R.F. amplification. Thus, it would be possible to have resistance, impedance or transformer-coupled R.F. amplifiers. Reviewing the desirability of each, when used as A.F. amplifiers, we find that the greatest gain is secured from the transformer type, while a better frequency response may be obtained from impedance or resistance-coupled amplifiers. Frequency response in R.F. amplifiers, however, is something that need not be given very much consideration; the ratio of the maximum to the minimum frequency being amplified at any one time is very small compared to the same ratio in A.F. amplifiers.

Suppose, for example, that the receiver is tuned to a station whose carrier frequency is 1,000 kc. The response of the R.F. amplifier should be such that all frequencies between 995 and 1,005 kc. are amplified equally well. The ratio of 1,005 to 995 is 1.01 to 1. On the other hand, the audio amplifier must give equal amplification to all frequencies between 30 and 5,000 cycles (preferably higher for good fidelity). The ratio of 5,000 to 30 is 167 to 1; a much greater ratio, and consequently frequency response is relatively more important in A.F. amplifiers. Since frequency response is not a problem, it would seem desirable to use transformer-coupling between the R.F. amplifier stages in order to secure the greater gain thereby possible. In addition, tuned circuits must be employed to secure the necessary selectivity and may be used to more advantage with transformer coupling than with either of the other two types.

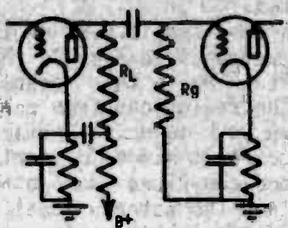


Fig.4 Showing the resistance coupling between two amplifier stages.

Resistance coupling is especially undesirable at radio frequencies as the interelectrode tube capacities tend to by-pass the signal. A consideration of Fig. 4 will make this clear. This figure shows the resistance-capacity coupling between two stages of A.F. amplification. A simplified equivalent circuit is shown in Fig. 5. In this figure, the condenser C_{pf} represents the plate to

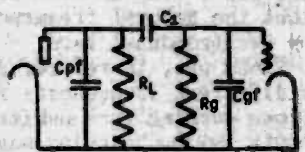


Fig.5 A circuit equivalent to that of Fig. 4. It is used to show the impracticability of resistance-coupled R.F. amplifiers.

filament capacity of the first tube, while the condenser C_{gf} represents the grid to filament capacity of the second tube. Notice that these capacities are connected directly across the load circuit. Thus, a large part of the high-frequency signal voltage will be by-passed through these condensers and will not be transferred from one tube to the following.

For the foregoing reasons, nearly all R.F. amplifiers employ transformer coupling, which will now be considered in detail.

5. **TUNED RADIO-FREQUENCY AMPLIFIERS.** Fig. 6 shows a one-stage tuned radio-frequency[1] amplifier. An R.F. transformer is used to

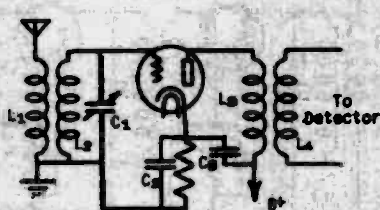


Fig.6 A single stage of tuned radio-frequency amplification.

couple the antenna to the input of the amplifier tube. The secondary of this R.F. transformer is tuned by a variable condenser and

[1] Often abbreviated T.R.F.

as has been previously explained, this secondary and the variable condenser constitute a series tuned circuit. Since the action of tuned circuits was studied in detail in Lesson 22, it will not be repeated.

A two-stage T.R.F. amplifier connected to a grid-bias detector is illustrated in Fig. 7. We will now discuss the operation of the circuit shown in this figure.

The radiations from many broadcast stations are striking the antenna and inducing voltages therein. The antenna is itself a tuned circuit since it contains inductance and capacity. The inductance comprises the antenna coupling coil L_1, the connecting wires and the antenna itself. The capacity is composed of the capacitive effect between the antenna wires and the ground. Since the antenna is a tuned circuit, it will naturally be resonant at some frequency and would allow a larger current to flow at that frequency than at any other. It should be noticed that no provision has been made to tune the antenna circuit. This is usually the case with receiver antennas. Transmitting antennas, on the other hand, are always tuned. When the antenna is untuned, it is said to be "aperiodic". The antenna coupling coil provides enough inductance so that the natural frequency of the antenna is low, usually just below the broadcast band.

There are, therefore, in the antenna circuit, the currents of many different frequencies representing as many different broadcast stations surging back and forth through the circuit. These surging currents create varying magnetic fields about L_1 which, in turn, induce voltages into L_2 by electromagnetic induction. Thus, the voltages induced in L_2 are those of many different broadcast stations, some weak, some strong, some of a high frequency and some of a low frequency.

The first R.F. amplifier stage is now tuned by varying the capacity of C_2 until the tuned circuit L_2C_2 is resonant to the frequency of the desired station. When this has been brought about, the voltage of the resonant frequency which has been induced in L_2 is able to produce a relatively large oscillating current through the tuned circuit, while the currents due to all other frequencies

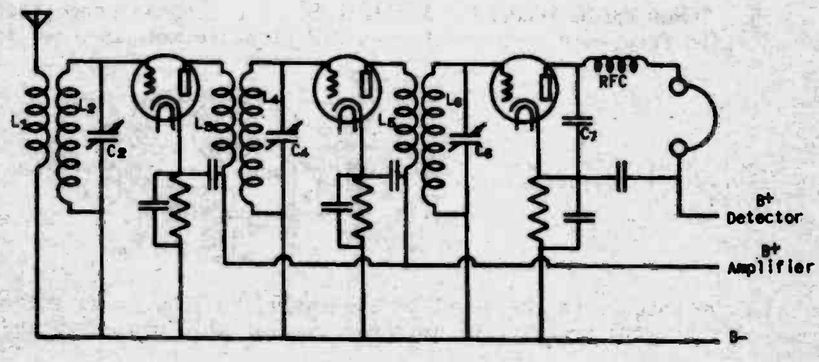


Fig. 7 A two-stage TRF amplifier connected to a grid-bias detector.

will be small in comparison. This oscillating current flowing in L_2C_2 produces a voltage drop across C_2 larger than the voltage induced into L_2 from L_1, due to the gain of the series tuned circuit. The amount of this gain is proportional to the reactance (either inductive or capacitive since they are equal at resonance) of this circuit and inversely proportional to its resistance. To make the gain as large as possible, the resistance should be minimized and the reactance should be as large as feasible and still conform with other requirements.

The R.F. voltage across C_2 provides grid excitation for this tube. It adds to and subtracts from the bias voltage and the plate current is varied accordingly. It is assumed that the proper grid bias, plate voltage and heater voltage have previously been applied to the tube and that it is operating over the straight portion of its grid voltage-plate current characteristic curve. The plate current is a pulsating direct current and has a waveform exactly like the R.F. voltage induced in the antenna by the desired signal. It has, however, higher amplitudes due to the gain of the tuned circuit and the amplification produced by the tube.

Since one tuned circuit does not provide sufficient selectivity, it is probable that those stations differing from the desired station by 10 or 20 kilocycles will also produce an appreciable voltage across C_2. These voltages will be amplified by the tube in the same proportion as was that of the desired station, since the tube does not possess the ability to discriminate between frequencies. Thus, it is quite possible that the plate current of the first tube will consist of the variations of the desired signal as well as those of adjacent frequencies. Although the interfering signals may have the same field strength as that of the desired signal, the tuned circuit will give more gain to the desired signal and the plate current variations due to this frequency will be larger than those caused by the interferring frequencies.

This plate current produces a magnetic field about L_3 which induces an R.F. voltage into L_4. The second R.F. stage is tuned by varying C_4 until the natural frequency of the tuned circuit L_4C_4 is equal to that of the desired station. When such is the case, the R.F. voltage across L_4, due to the desired frequency, will produce a relatively large oscillating current through the tuned circuit, while the currents produced by the interfering frequencies will be of much smaller magnitude. As a result, the R.F. voltage produced across the condenser C_4 by the desired signals is proportionally greater than that produced by the interfering frequencies. Thus, the second tuned circuit serves to further increase the selectivity.

The second tube now amplifies all the voltages developed across C_4. The amplitudes of the plate current changes of this tube are greater than those of the voltages across C_4. The tube, however, amplifies all of the frequencies appearing across C_4 equally well and the plate current of this tube will have some variations due to the interfering frequencies.

This plate current sets up a varying magnetic field about L_5 and, in turn, induces an R.F. voltage into L_6. The detector stage must now be tuned to the desired frequency by varying the capacity of the condenser C_6 until the resonant frequency of the tuned circuit L_6C_6 is equal to that of the desired station. When this has been done, the R.F. voltage across L_6, due to the desired station, produces an oscillating current in the tuned circuit and again due to the gain of the tuned circuit, a larger voltage is created across C_6. By this time, the ratio between the voltage of the desired frequency and the voltages of the interfering frequencies is so great that the interfering frequencies can no longer be considered as a source of interference. Ordinarily, at least three tuned circuits are required to accomplish this result.

As has been previously explained in the lesson on detection, the R.F. voltage across C_6 causes the plate current of the detector tube to vary at an R.F. rate. Since the detector tube is operating on the lower bend of its grid voltage-plate current characteristic curve, the negative alternations are cut off and the average value of the plate current is equal to the impressed A.F. wave. The R.F. component of the plate current is then filtered out by condenser C_7 and the R.F. choke (marked R.F.C.). The A.F. component or the average current flows through the headphones and reproduces the program of the desired station.

Since the secondary of an R.F. transformer has more turns than the primary, a step-up in voltage is also obtained from the plate circuit of one stage to the grid circuit of the succeeding stage. There is, however, a limit to this step-up ratio. In order for the tube to produce appreciable amplification, it must work into a load which is several times as great as the plate resistance of the tube. This may be accomplished only by using primary windings having a large number of turns and, consequently, a high value of inductance. It is usual practice to make the primary of an R.F. transformer quite large in order to secure the maximum amplification possible from the tube and then to design the secondary of the R.F. transformer to secure some step-up in voltage.

For a number of years, the majority of receivers employed two stages of T.R.F. amplification as illustrated in the diagram. The output of the R.F. amplifier was fed into a grid-leak detector which was then amplified by two stages of A.F. amplification and its output fed to a loudspeaker. These T.R.F. sets, as they were called, have largely been superseded by the superheterodyne which will be studied in Lesson 27.

We should not form the opinion that the study of tuned radio frequency amplification is unimportant since T.R.F. receivers are but seldom used. A clear understanding of the superheterodyne receiver is impossible without a thorough knowledge of the operation of a T.R.F. amplifier stage.

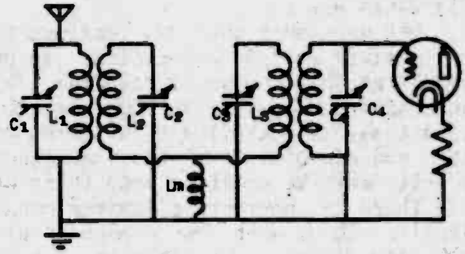
The circuit shown in Fig. 7 is not complete and would not operate properly. As we shall learn later in this lesson, each of the R.F. amplifier stages must be neutralized before efficient results may be secured.

6. PRESELECTORS. In the T.R.F. amplifier, the amplification and selectivity are obtained simultaneously. Each stage increases the ratio between the wanted and unwanted signals. A few receivers, however, are designed to secure the selectivity first and the amp-

lification later. Such receivers employ a system of tuned circuits known as a preselector. The preselector is placed between the antenna and the first R.F. stage and the R.F. stages use transformers that are untuned.

An example of this arrangement is shown in Fig. 8. There are four tuned circuits between the antenna and the first R.F. stage. L_1C_1 is a parallel tuned circuit and is tuned to the frequency of the desired station. A parallel tuned circuit offers maximum impedance to currents of the resonant frequency and a comparatively low impedance to all other frequencies. Therefore, the frequency of the desired station will produce a relatively large voltage drop across the tuned circuit since it must flow through a high impedance and all other frequencies will produce small voltages as the tuned circuit offers small opposition to them. The voltage across the tuned circuit is transferred by mutual induction to the second tuned circuit. The desired frequency is able to produce a larger voltage in L_2 than other frequencies due to the frequency discrimination of L_1C_1.

Fig.8 A preselector circuit used with untuned R.F. amplifiers.



The second tuned circuit consists of L_2, C_2 and L_m; L_2 and L_m are in series. When it is tuned to the desired signal, an oscillating current flows through this circuit. This current produces a voltage drop across L_m. It is obvious that the desired signal will create a much larger voltage than will any interfering frequency.

The inductor L_m is also a part of the third tuned circuit; L_m and L_3 are in series. Thus, the voltage across L_m, produced by the oscillating current of the second tuned circuit, is transferred to the third tuned circuit and causes an oscillating current to flow through L_3 and C_3. This current develops a voltage across L_3 which is transferred to L_4. The oscillating current of the fourth tuned circuit then creates a voltage across C_4 which varies the plate current of the first R.F. stage.

Each of the four tuned circuits increases the ratio of the desired signal to that of undesired signals and the amplifier which has no frequency discrimination then amplifies whatever frequency is applied to it. All tuning takes place in the preselector.

The coil L_m is a mutual reactance; it is common to both the second and third tuned circuits. Sometimes a condenser is used instead of a coil. The preselector of such a receiver is shown in Fig. 9. The condenser C_m is part of the second and third tuned circuits. The voltage developed across C_m transfers energy from L_2C_2 to L_3C_3.

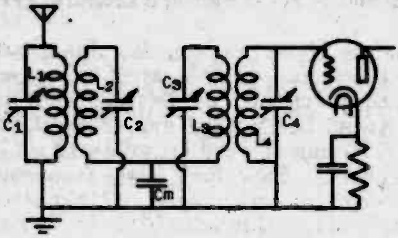


Fig.9 A preselector circuit using a condenser for mutual coupling.

7. **DESIGN OF R.F. TRANSFORMERS.** As stated before, the ratio of the reactance of a series tuned circuit to its resistance should be as large as possible to produce maximum gain. In order that the reactances be large, the inductance must be great and the capacity small, or the ratio of the inductance in henries to the capacity in farads must be very large. Other factors, however, limit the value this ratio may have.

Let us assume that the maximum frequency to be amplified by the receiver is 1600 kilocycles. To produce resonance of a tuned circuit at this frequency requires that the product of the inductance and the capacity of the circuit be a definite value. This product may be satisfied by using many different values of inductance and capacity. If the inductance is to be made large, the capacity must be small to keep their product constant.

There is, however, a minimum capacity attainable in any tuned circuit. Thus, when the condenser plates are completely out of mesh, its capacity is not zero, but is a definite minimum value. In addition, the capacitive effects between the connecting wires and the distributed capacity of the R.F. transformer secondary limit the minimum capacity obtainable to approximately 40 mmfd. or more. Since the minimum capacity is limited, the maximum value of inductance which will tune to the highest frequency is also limited.

The frequency range to be covered is ordinarily from 550 to 1600 kilocycles. The ratio of the highest frequency to the lowest is approximately 3:1. From the formula, $F = 159 + \sqrt{LC}$, it may be seen that the frequency varies inversely as the square root of the capacity, if the value of the inductance is kept constant. Thus, increasing the capacity four times would halve the frequency, etc. Since the frequency range to be covered is 3:1, the variable condenser must have a capacity range from maximum to minimum of 9:1. The minimum capacity is fairly well established by the stray capacity of the circuit and as the maximum capacity must be 9 times as great, it follows that the maximum capacity is likewise definitely determined. Thus, it may be seen that once the frequency range has been decided upon, the maximum capacity, minimum capacity and inductance of the circuit are at once fixed.

There now remains the primary winding to be considered. The fact that a small primary is inadvisable due to the low amplification obtained from the tube has been previously mentioned. Thus, the primary has a fairly well established value and as the secondary is also fixed, the turns ratio is determined.

The step-up in voltage between the primary and secondary is not equal to the turns ratio of an R.F. transformer as is the case with an audio or power transformer. The coupling between air core coils is never as great as between two coils mounted on the same iron core. The magnetic field of the primary is not confined to the core to such an extent and many of the lines of force do not cut through the turns of the secondary and are thus ineffective in producing a voltage in the secondary. Such lines are known as leakage lines or leakage inductance. Thus an R.F. transformer having a turns ratio of 4:1 might have a voltage step-up of only 1.2:1.

It is not possible to use iron core transformers for radio frequencies.[1] In any iron core transformer, the varying magnetic field induces voltages into the iron core which cause circular currents to flow through the core. These currents are known as eddy currents and they increase in amount as the frequency of the primary current is raised. To minimize their effect as much as possible, the core is composed of thin sheets of iron electrically insulated from each other by a thin coat of lacquer. Such construction reduces the length of the electrical paths, but does not interfere with the magnetic path. The sheets are known as laminations.

Even with this design, the eddy currents produced when an R.F. current is passed through the primary are very large and their heating of the iron core dissipates such a considerable power as to make their use at radio frequencies impractical.

Furthermore, iron core transformers have very close coupling and, as will be explained later, the coupling between the primary and secondary windings of an R.F. transformer is somewhat critical and has a direct effect upon the selectivity of the tuned circuit.

The forms upon which R.F. transformers are wound are constructed of bakelite or some other insulating material. The material should have low dielectric losses as it will be in the electrostatic field produced between the turns and thus will affect the distributed capacity. The wire used in winding the transformer may be enameled, silk or cotton covered.

Fig.10 An R.F. transformer.

In the very early receivers, the R.F. transformers were quite large, being 2 or 3 inches in diameter and 3 to 5 inches long. Throughout succeeding years, they became smaller and smaller in size and, at present, they are an inch or less in diameter and approximately 1¼ to 2¼ inches long. An illustration of an R.F. transformer such as used in modern receivers is shown in Fig. 10.

[1] Recently it has become possible to use a form of iron core coil to amplify the intermediate frequencies produced in a superheterodyne receiver. The core consists of particles of finely divided iron, carefully insulated from each other by a binding compound applied under high pressure.

After the inductances of the primary and secondary have been selected, it is then necessary to calculate the number of turns required to produce these values. The exact calculation of the physical dimensions of a coil for a given inductance is somewhat complex. The following formula, however, is accurate to within approximately 2%. It is:

$$n = \frac{\sqrt{(9 \times L) + 10 \times L \times b}}{a}$$

Where:
- L is the inductance in microhenries
- n is the number of turns
- a is the radius of the coil form in inches
- b is the length of the winding in inches

The following example illustrates the use of this formula.

Example (1) How many turns must a winding have if it is to be 2 inches long, have a radius of 1 inch and an inductance of 300 microhenries? Substituting these values in the above formula, we obtain:

$$n = \frac{\sqrt{(9 \times 300) + 10 \times 300 \times 2}}{1}$$

$$= \sqrt{2700 + 6000}$$

$$= \sqrt{8700}$$

$$= 93 \text{ turns}$$

8. LOSSES IN R.F. COILS. To keep the losses of an R.F. transformer at a minimum, it is necessary to reduce the resistance of the windings to the least possible value consistent with economy. The losses created when a high-frequency current flows through an R.F. winding are considerably greater than those produced by a direct current flowing through the same winding. The effect is the same as though the coil has a greater resistance to radio-frequency currents than it has to direct current and such has been found to be the case. Its R.F. resistance is greater than its ohmic or DC resistance.

The major cause of this phenomenon is known as "skin effect" and is due to the fact that high-frequency currents show a tendency to flow only along the outer surface, or "skin" of the conductor and not through its center. Thus, only a small proportion of the total cross-sectional area of the wire is effective in carrying the current. Since the effective cross section is reduced, the resistance to the flow of current is thereby increased. Why the high frequency currents behave in this manner may be explained as follows.

Referring to A, Fig. 11, it is seen that the flow of electrons is uniformly distributed throughout the cross section of a wire when it is carrying a direct current. There are as many flowing in the center as there are on the outer surface. When an alternating current of a medium frequency flows through the wire, the concentric magnetic field which exists about the wire rapidly expands and collapses as the current rises and falls. This magnetic field in expanding and collapsing cuts through the wire itself and induces a voltage within the wire which, according to Lenz's Law, is in such a direction as to oppose the flow of current through it. Whatever magnetic field there is around the wire must first have expanded from the center of the conductor and, when it collapses, it must collapse to the center of the conductor. Therefore, the center of the wire is cut by more lines of force than is the surface. For

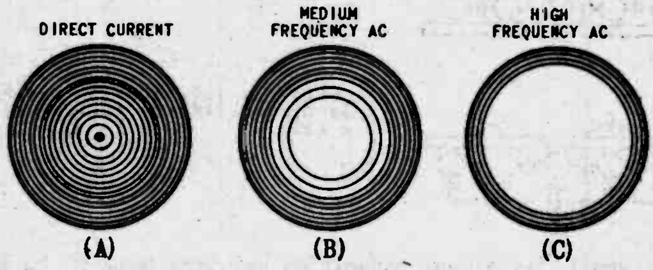


Fig.11 (A) Distribution of current in a conductor when direct current flows through it.
(B) The effect that a medium frequency AC has upon the current distribution.
(C) Illustrating skin effect when a high-frequency current flows through a conductor.

this reason, the induced voltage is greatest at the wire's exact center. This causes the opposition to the current flow to be greatest at the center and least at the surface and thus the current or electron flow is not uniformly distributed as with direct current, but is densest at the outer surface as shown at B in Fig. 11. When the current under consideration is of an extremely high frequency, such as a radio frequency, this effect is tremendously increased and practically all the current flows along the outer surface of the conductor as shown at C. While the resistance of an R.F. transformer coil to direct current may be only 10 to 200 ohms, it is quite possible that its effective resistance is 150 to 2000 ohms or more at radio frequencies.

One way of minimizing the loss due to skin effect is to increase the surface area of the conductors. This may be done by using Litz wire to wind the radio-frequency transformer. Litz wire is composed of 25 or more strands of fine wire, each individually insulated from the others by enamel. It is more expensive than ordinary magnet wire, but due to the greater surface area of its conductors, it has a lower R.F. resistance.

Another undesirable property of a tuning coil is its distributed capacity. When a voltage is applied to a coil, there is a small voltage difference between each two adjacent turns. These turns are conductors and are insulated from each other by the insulation of the wire. They, therefore, form minute capacities which in the aggregate may be considered as one capacity placed in parallel with the coil. This is shown in Fig. 12. At low frequencies, the reactance of this distributed capacity is so large that its effect may be neglected. At higher frequencies, this reactance may become small enough to tune the coil, thereby forming a parallel tuned circuit. Thus every coil has a natural frequency determined by its inductance and its distributed capacity. At frequencies higher than the natural frequency of the coil, most of the current is by-passed by the distributed capacity and only a small part flows through the coil itself. Thus it may be seen that the distributed capacity is undesirable.

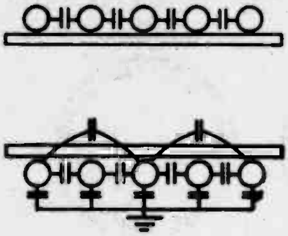


Fig.12 Illustrating the various capacitances that exist in a coil.

The small individual capacities existing between turns have the wire insulation for dielectrics and it is quite possible that there will be some losses in this dielectric, due to dielectric hysteresis. Any such loss will add to the apparent resistance of the coil. An additional disadvantage of distributed capacity in a tuning coil is its reduction of the frequency range through which the coil may be tuned by a variable tuning condenser. Thus, when the variable condenser is set at minimum capacity, there still exists across the coil the distributed capacity. This serves to limit the highest frequency to which the circuit may be resonated.

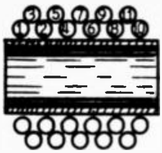
The distributed capacity of a tuning coil may be kept at a minimum by using small wire which has the effect of reducing the plate size of the individual capacities, or by leaving spaces between adjacent turns of the coil which increases the thickness of the dielectric. This, of course, cannot be carried too far, as the use of too small a wire will increase the resistance and leaving too much space between adjacent turns will reduce the inductance and, hence, the coil will require more turns, which again would increase the distributed capacity. The larger the coil, the greater its surface area will be and the more distributed capacity it will have. This is another reason favoring the use of small tuning coils.

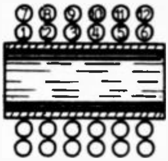
When coils have several layers, the problem of distributed capacity is even more serious. Thus in the case of an audio transformer, the windings consist of many layers and, while the frequencies used are relatively low, yet the distributed capacity is so large as to produce undesirable effects at the higher audio frequencies.

Many different schemes have been devised to reduce the distributed capacity. Thus, A in Fig. 13 shows a two-layer coil wound in a manner called "bank winding". The advantage of this type of winding in reducing the distributed capacity may be seen by referring to B, Fig. 13. This figure illustrates an ordinary two-layer coil with a common type of layer winding. The voltage difference between turns 1 and 7 may be considerable. Likewise, the voltage between any turn of the first layer and the turn of the second layer immediately above it is apt to be rather high. This is the same as saying that the small condenser formed by these two turns is charged to a relatively high voltage. On the other hand, with the bank type of winding, the voltage between the turns of one layer and those of the other is small. Thus at A, Fig. 13, the voltage between turn 1 and turn 3 would naturally be small, since it would be equal to the voltage built up across two turns, while the voltage between turn 1 and turn 7 of B in the figure would be equal to the voltage built

Bank Winding

(A)





Ordinary Two-Layer Winding

(B)

Fig.13 (A) Bank winding used to minimize the effect of distributed capacity.
(B) Ordinary layer winding in which the distributed capacity is large.

up across six turns. If the coil consisted of several hundred turns per layer, the reduction in voltage between nearby turns obtained by this method of winding would greatly decrease the current flowing in these small capacity circuits and the tendency for R.F. currents to be by-passed by the distributed capacity would be lessened.

9. DESIGN OF VARIABLE CONDENSERS. The actual constructional details of variable condensers were discussed thoroughly in Lesson 11 and will not be repeated. There are, however, a few additional facts about their construction and use which should be given some attention.

The stationary or stator plates of a variable condenser should always be connected to the grid of the tube, while the rotating or rotor plates should be at ground potential. This type of connection is advisable to eliminate "hand" capacity. Suppose, for example, that the connections were reversed and the rotor connected to the grid. As previously explained, R.F. voltages will be developed across the condenser due to the signal and, if the rotor is connected to the grid, it will not be at ground potential. The rotor plates are joined to the shaft which, in turn, is rotated by a dial or knob on the panel of the receiver. When an attempt is made to tune in a station, the presence of one's hand on or near the knob will change the tuning of the circuit. The hand is at ground potential and, when placed on the knob, it is close to the shaft to which the rotor plates are connected. Thus, a capacity will exist between the hand and the rotor plates. This capacity is in parallel with that of the tuning condenser. Therefore, a station may be tuned in by rotating the knob with the hand, but, as soon as the hand leaves the knob, the total capacity across the coil is changed and the station is not properly tuned. All of this can be avoided by making sure to connect the rotor plates to ground. When they are so connected, there can be no capacity between the hand and the rotor plates since they are both at the same potential.

The shape of the rotor plates have considerable bearing upon the convenience of tuning. The earliest variable condenser employed semi-circular stator plates and rotor plates as shown at A, Fig. 14. This type of plate produces a relationship between the amount of rotation and the total capacity, which is linear; that is, the capacity is directly proportional to the degree of rotation. When the rotor plates have been rotated through 90 degrees, the capacity of the condenser is half of its maximum. Straight line capacity plates (abbreviated S.L.C.) are not suitable for tuning in radio receivers. This may be explained by the fact that the frequency to which the circuit is resonant does not vary directly with the capacity of the circuit, but inversely as the square root of the capacity. Thus, equal changes in capacity will not produce equal changes in frequency. For example, when the condenser plates are almost completely intermeshed, a further rotation of 1 degree might produce a change in the resonant frequency of only 1 kilocycle. The same 1 degree rotation when the plates are almost out of mesh would probably produce a change in frequency of 10 to 15 kilocycles. Thus, the low-frequency stations would be approximately 10 degrees apart on the dial, while at the high-frequency end of the dial there would be nearly three stations for each degree of rotation. Such extreme crowding at the high-frequency end would make accurate tuning impossible.

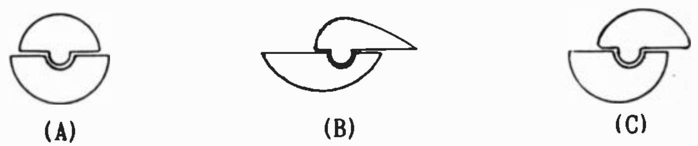


Fig.14 (A) The shape of the rotor plates of a straight-line capacity condenser.
(B) A straight-line frequency condenser.
(C) A centraline condenser.

To overcome this difficulty there was designed the straight line frequency (abbreviated S.L.F.) condenser. The stator plates are semi-circular while the rotor plates are shaped like illustrated at B, Fig. 14. The relationship between the degrees of rotation and the frequency to which a tuned circuit would be resonant is linear; that is, equal changes in rotation produce equal changes in the resonant frequency. With this type of condenser, stations separated by 10 kilocycles in frequency come in at equally separated points on the dial. Such a condenser would be ideal except for the fact that there are many more high-frequency stations than those of low frequency. Hence, one-half of the dial will be far more crowded than the other half.

To remedy this situation, a third type of condenser was designed with plates shaped like those at C, Fig. 14. It is called a centraline or midline condenser and it is so designed that stations will be approximately equally spaced throughout the entire rotation of the dial; that is, this type of condenser compensates for the fact that there are more high-frequency stations than those of low frequency. This type of condenser is used in practically all modern receivers.

10. SINGLE CONTROL TUNING. The very earliest receivers had such a multiplicity of controls that accurate tuning was not only difficult; it was well-nigh impossible. As late as 1928, it was still necessary to manipulate three dials in order to tune in a station. This was not only inconvenient, but the average person would not take the time necessary to accurately tune in a station and, therefore, perfect reception was not obtained.

As may be seen by reference to Fig. 7, a receiver consisting of two stages of T.R.F. will have three tuned circuits, one between the antenna and the first R.F. stage, another between the first and second R.F. stages and a third between the second R.F. stage and the detector. To tune such a receiver to a station requires that all three of these tuned circuits be properly resonated. If these three circuits are to be tuned by a single control, three variable condensers must be ganged as was explained in Lesson 11. All of the rotors are mounted upon a common shaft and changing the capacity of one condenser will change that of the other. At any setting of the dial, the three tuned circuits must be exactly resonant at the same frequency. For this to be accomplished, the three inductances which these three variable condensers tune must have exactly the same value. Likewise, each variable condenser must have exactly the same capacity as the other two at any setting of the dial. The total capacity of each of the tuned circuits will depend not only upon the capacity of the condenser, but also on the stray capacity associated with each circuit due to circuit wiring. Since this is apt to be different in the three circuits, some method of compensation must be devised to assure that the three circuits are correctly resonated at any setting of the dial.

Each variable condenser has a small trimmer or padding condenser connected in parallel with it. The trimmer consists of two sheets of spring brass separated by a sheet of mica. Its capacity is varied by increasing or decreasing the tension between the pieces of spring brass by means of a screw holding the assembly together.

Trimmers ordinarily have maximum and minimum capacity values of 30 and 5 mmfd., respectively. Since their total capacity is rather low, they will be more effective at the high-frequency end of the dial where the tuning condenser is unmeshed and the capacity of the circuit is dependent upon the distributed capacity, etc. If the stray capacity of one of these tuned circuits is lower than that of the other two, it may be made equal to the others by increasing the capacity of the trimmer condenser associated with that stage. The procedure of making the stray capacities of the three stages equal is called "aligning" the receiver and will be discussed in considerable detail in a later lesson.

11. SELECTIVITY OF MULTIPLE TUNED STAGES. The fact that the total selectivity of any radio receiver depends upon the number of tuned circuits in the receiver is clearly illustrated by the diagram shown in Fig. 15. This diagram shows four resonance curves. The one marked A is the resonance curve of one tuned circuit of a receiver employing two stages of T.R.F. amplification. Curve B shows the selectivity secured with two of the tuned circuits of this set, and curve C shows the combined over-all selectivity gained

by using three tuned circuits. Adding a fourth tuned circuit would produce curve D.

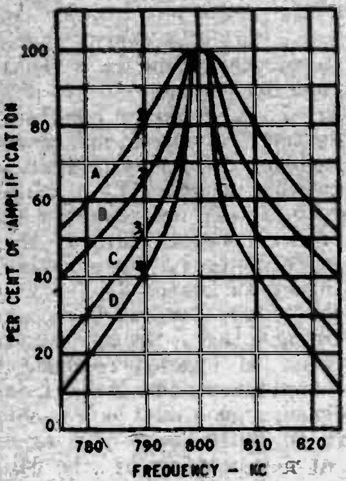


Fig.15 Showing how several tuned circuits increase the over-all selectivity.

The resonant frequency in this particular case is 800 kilocycles. Notice that with one tuned circuit a frequency 10 kilocycles off resonance (790 kilocycles) receives only 80% as much amplification as the resonant frequency. This is shown at point 1 on curve A.

The second tuned circuit also amplifies the 790-kilocycle frequency just 80% as much as the resonant frequency. Hence, the total amplification received by this frequency after it has passed through two tuned circuits is .8 × .8 = .64, or 64% as much as the resonant frequency.

By the time that the 790-kc. frequency has passed through three tuned circuits, it has received .8 × .8 × .8 = .512, or 51% as much amplification as the resonant frequency. A fourth tuned circuit reduces this to approximately 41%.

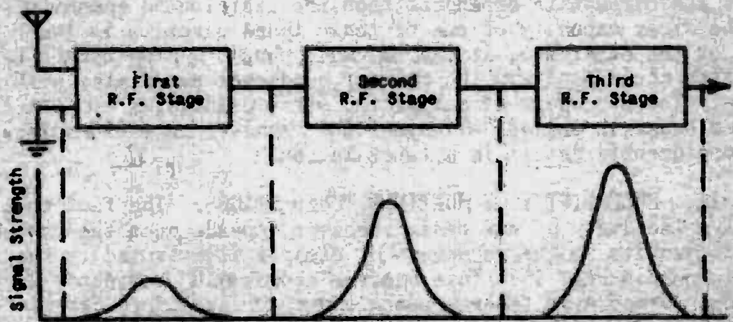
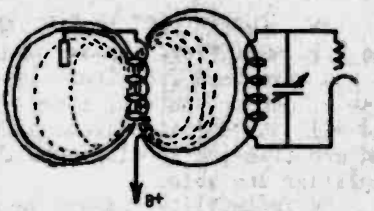


Fig.16 Diagram illustrating how several tuned stages amplify and increase the sharpness of tuning.

Fig. 16 illustrates how several stages of T.R.F. amplification amplify and sharpen the over-all selectivity curve.

Another factor which affects the shape of a resonance curve considerably is the amount of coupling between the primary and secondary of an R.F. transformer. With close coupling, the selectivity is rather poor, while with loose coupling, a considerable increase in selectivity may be obtained. Close coupling, of course, means that the primary and secondary windings are placed closely together so that nearly all of the magnetic field surrounding the primary coil cuts through the turns of the secondary while with loose coupling, the two windings are separated somewhat and only a portion of the field surrounding the primary is effective in inducing voltages in the secondary. Why this difference in coupling is able to produce a change in selectivity may be explained by reference to Fig. 17.

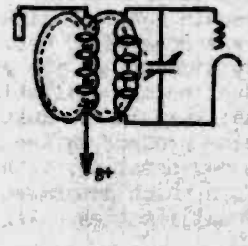
Fig.17 Illustrating how loose coupling increases selectivity.



This figure shows diagrammatically the two windings of an R.F. transformer with very loose coupling. (The looseness of the coupling is exaggerated in order to clarify the explanation.) Let us assume that in the primary winding there are currents of two frequencies; the desired frequency and an interfering frequency. Since the two have already passed through one stage of amplification, the desired frequency is stronger than the interfering frequency and the magnetic field set up by the desired frequency is represented by the solid lines enveloping the primary coil. Notice that this field extends a considerable distance from the primary and is able to cut through the turns of the secondary.

On the other hand, the field surrounding the primary, due to the interfering frequency, is considerably weaker and may be represented by the dotted lines shown in the figure. As this field is relatively weak, it does not extend outward from the surface of the coil for any great distance. With coupling as loose as shown here, this second weak field will not be able to induce any voltages into the secondary and, for this reason, additional selectivity is obtained.

Fig.18 Illustrating why broad tuning is obtained with closely coupled circuits.



Now assuming that the two fields surrounding the primary are the same as before, let us change the coupling by moving the secondary winding close to that of the primary. This would constitute a close-coupled case. Fig. 18 illustrates the circuit under these conditions. It may now be seen that the field created by both the desired frequency and interfering frequency are able to cut the turns of the secondary winding and, therefore, induce voltages therein. This means that the selectivity obtainable with this coupling will not be as good as with loose coupling since some of the interfering frequency will be transferred to the following stage.

Close coupling, then, has the effect of broadening the resonance curve and making the circuit less selective. Loose coupling increases the selectivity of the receiver, but may cause sideband cutting if the increase is too great.

12. **INSTABILITY IN R.F. AMPLIFIERS.** It has been assumed that the R.F. amplifiers studied up to this time have operated efficiently and have been free from causes which would tend to make them unstable. Unfortunately, every R.F. amplifier is inherently unstable and will not operate unless particular care is taken in its design and construction to eliminate the factors which tend to render the amplifier unstable.

By instability is meant the tendency to break into oscillations. As was learned in Lesson 23, a vacuum tube will operate as an oscillator or a generator of alternating currents if a portion of its output, of proper phase and magnitude, is fed into its input circuit. Under these conditions, the vacuum tube supplies its own input and is said to break into oscillations or to act as an oscillator. The frequency of this oscillation is determined by the resonant frequency of the tuned circuit or tank circuit associated with that stage.

It has been stated that any tuned circuit contains some resistance and that the feeding back of a small portion of the output energy into the tuned circuit produces the same result as if the actual resistance of the tuned circuit had been decreased. It was stated that this energy fed back from the plate to the grid circuit could be thought of as a negative resistance which cancelled the positive resistance of the tuned circuit. If the amount of negative resistance fed back into the grid circuit was not enough to completely cancel the positive resistance, the process was known as regeneration and it was found that a considerable increase in amplification might be obtained by this method. If, however, the negative resistance completely cancelled the positive resistance of the tuned circuit, then the vacuum tube acted as an oscillator and would generate high-frequency currents whether its input voltage was removed or not. The mere fact that energy is fed from the plate circuit to the grid circuit is insufficient reason for the production of oscillations since this energy must be of the proper phase; that is, it must be in such a direction as to add to that already present in the grid circuit. If it is of opposite phase, then degeneration, rather than regeneration, is produced. Other factors which determine the amount of regeneration are frequency and amplification. All R.F. amplifiers have a greater tendency to oscillate at the high-frequency end of the band than at the low. At the higher frequencies, the capacitive effects which could cause feedback have a lower capacitive reactance and thus are able to feed back more energy. Likewise, feedback due to magnetic effects is greater at the higher frequencies as a more rapidly changing magnetic field is able to induce larger voltages.

With very large amounts of amplification, the tendency toward oscillation is greatly increased as the difference between energy levels of the grid and plate circuits is so very great and a much smaller part of the total energy in the plate circuit need be fed back in order to produce oscillations.

Quite often an amplifier stage will oscillate when it is tuned to a high frequency while it will be stable at middle or lower frequencies. Again, a stage will stop oscillating when its plate voltage is decreased as a reduction in plate voltage causes the amplification to be less.

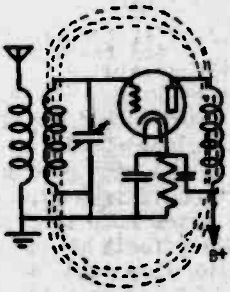
It must be remembered that if an R.F. amplifier stage oscillates, it will not function satisfactorily as an amplifier.

There are four methods by which the energy in the plate circuit of an R.F. amplifier stage may be fed back into its grid circuit. They are:

1. Stray inductive coupling
2. Stray capacitive coupling
3. Coupling through a common impedance
4. Coupling through the interelectrode capacity of the tube

Stray inductive coupling might be caused by the magnetic field surrounding the plate coil of an R.F. stage, cutting through and inducing voltages into the grid coil of that stage. This condition is shown in Fig. 19. We must remember that the amount of energy

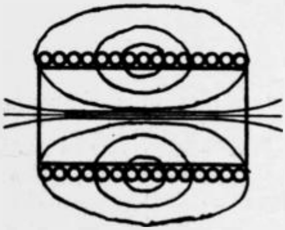
Fig. 19 Showing how feedback can occur from magnetic coupling between the plate and grid coils of an amplifier.



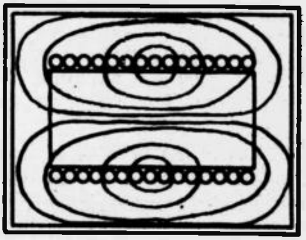
needed to cause oscillations is usually very small and it is quite possible that the voltages induced in the tuned circuit from the plate coil of this stage would be more than enough to produce oscillations. Stray magnetic coupling could also exist between the wire leading from the stator of the tuning condenser to the grid and the wire between the plate coil and the plate. If these two wires are run parallel for only a short distance, it is possible that the magnetic field surrounding the plate lead would induce voltages into the grid lead and cause oscillations.

Oscillations due to this source can be completely eliminated by shielding the R.F. transformers and by making certain that the plate and grid leads are not close together.

Before continuing further, it might be advisable to explain briefly the principle of shielding R.F. coils and transformers. Shields for use with R.F. transformers are composed of thin sheets of copper or aluminum and are usually in the form of cylindrical or rectangular containers completely surrounding the coil. The magnetic field about a high-frequency coil without shielding is shown at A, Fig. 20. When a coil such as this is placed within a shield, the magnetic field varying at an R.F. rate induces voltages into the shield itself. These voltages cause eddy currents to flow through the shield material which, in turn, create a magnetic field around the shield. According to Lenz's Law, this magnetic field will at every instant oppose the magnetic field around the coil. Thus, the effect of the shield is to limit the field of the coil to the space within the container. Any effect which the field of the coil might have upon an object outside of the container would be neutralized by the field of the shield. The field surrounding a shielded R.F. coil is shown at B, Fig. 20.



(A)



(B)

Fig.20 (A) The electromagnetic flux about an unshielded coil. (B) The electromagnetic flux about a coil having a non-magnetic shield.

In order that shielding shall be efficient, all the joints of the container should be soldered to insure that the resistance offered to the eddy currents shall be as low as possible.

It would seem that shielding a coil is very simple and need not be given more than passing consideration. However, it is found that the effects of the shield upon other factors of the coil are such that they must be taken into account. The first effect that the shield has upon the coil is to increase the coil's apparent resistance. The production of the eddy currents within the shield material constitutes a power loss as these eddy currents must flow through the resistance of the shield and thereby generate heat. This power can come only from the coil itself, which is furnishing the magnetic field to induce the voltages in the shield. Thus, it may be said that the losses of the coil are increased, which in effect is the same as adding more resistance to the coil.

It has been found that a close fitting shield tends to cause a larger increase in the apparent resistance of a coil than one which is somewhat roomier.

The other important effect which the shield has upon the tuning coil is to increase its distributed capacity. This may be seen by reference to Fig. 21. Notice that small capacity effects exist between various parts of the coil and the surface of the shield.

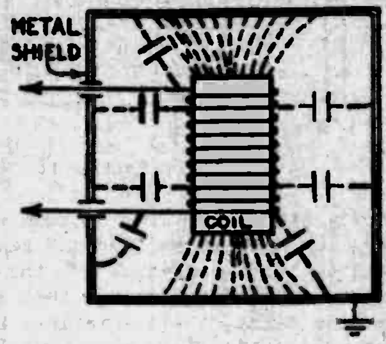


Fig.21 Showing how the shield around a coil increases its distributed capacity.

These capacitances all tend to increase the total distributed capacity of the coil. This effect is also greatest with close fitting shields. To minimize these two effects as much as possible, the shield container must always be much larger than the coil which it is shielding.

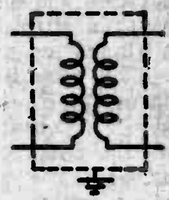


Fig.22 Symbol for a shielded R.F. transformer.

Shielding is represented in schematic diagrams by dotted lines. Thus, the dotted line enclosing the coil shown in Fig. 22 represents a shielded R.F. transformer. Instead of shielding the separate R.F. transformers, individual stage shields are sometimes employed. These are shown in Fig. 23. They consist of metal containers completely enclosing the components of one stage. Notice, however, that the plate coil of one stage is within the shield of the following stage so that there can be no feedback from this plate coil to the grid coil of the same stage.

All shielding should be thoroughly grounded to the chassis and the shield should not be used for the conducting path of the cathode or grid return circuits as this is apt to cause oscillations.

Stray capacitive coupling can exist between two coils or two wires. If the plate and grid leads are placed close to each other, it is possible that the capacity existing between the two is sufficient to cause the transference of some energy from the plate circuit to the grid circuit. In a like manner, it is possible for energy to be transferred from one coil to another through the ca-

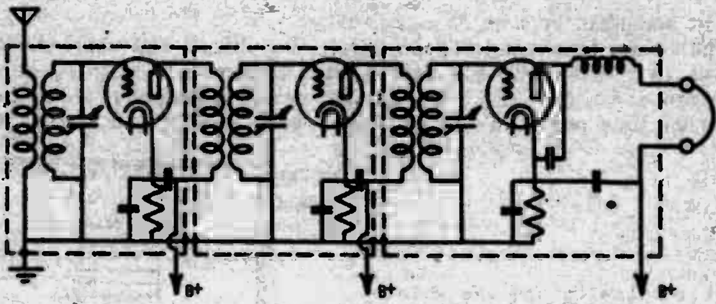


Fig.23 Illustrating the use of stage shields.

pacity effect existing between them. Shielding the coils eliminates the capacitive feedback as well as the magnetic feedback while care in the arrangement of the grid and plate leads will make the capacitive effect between them so small as to be negligible. In extreme cases, it is sometimes necessary to use shielded wire for the grid lead. This wire has, in addition to the ordinary insulation an outer covering of metallic braid. This outer covering is grounded to the chassis and thus acts to shield the lead from capacitive effects. Shields used to eliminate capacitive effects are called electrostatic shields.

All electrostatic shields must be thoroughly grounded. Otherwise, they become merely another plate of a capacity. Perfect electrostatic shielding cannot be obtained unless individual shields are placed around each stage.

How coupling through a common impedance may produce regeneration or oscillation may be seen by reference to Fig. 24. This illustration shows two T.R.F. stages securing their plate voltage from the same power supply which is shown in block form in this diagram. The power supply has an internal resistance as do all voltage sources. This resistance is represented by R in the diagram. It should be remembered that this resistor R is not a separate resistance included in the circuit, but is merely the internal resistance of the power supply shown separately in order to make this explanation clearer.

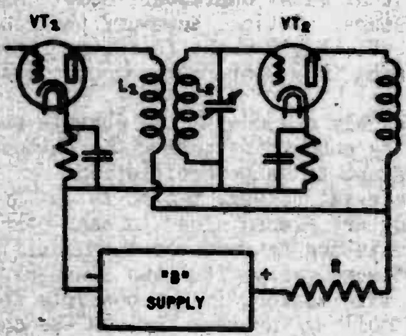


Fig.24 How feedback can occur due to coupling through a common impedance.

The plate current of VT_2 is a pulsating current varying at an R.F. rate. Its AC component in flowing through the internal impedance of the power supply produces an AC voltage drop with a waveform similar to B, Fig. 25. The DC voltage output of the power supply is represented by A, Fig. 25. The actual plate voltage applied to VT_1 is the voltage of the power supply minus the alternating voltage produced across its internal resistance. This voltage is represented by the diagram shown at C, Fig. 25. Since the plate voltage applied to VT_1 is varying at an R.F. rate, the plate current of this tube will vary accordingly at an R.F. rate and will transfer energy from L_1 to L_2. This energy is re-impressed upon the grid of VT_2 and thus regeneration has been effected through the common impedance in the plate circuit.

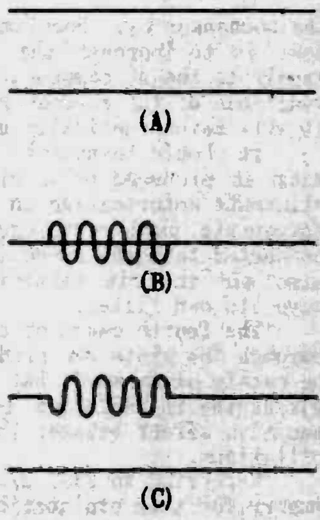


Fig. 25

(A) The DC voltage output of the power supply of the circuit shown in Fig. 24.

(B) The AC voltage dropped across the internal resistance of the power supply due to the varying plate current flowing through it.

(C) The actual voltage applied to the plates of the tubes due to the combination of these two voltages.

Since a power supply may be used with two or more stages of T.R.F. amplification, it is quite easy to see how a very small amount of coupling between the final R.F. stage and the first R.F. stage would produce sufficient transference of energy to cause oscillations.

The remedy for this condition is obvious. It is the AC component of the plate current flowing through the power supply that produces this feedback. This at once suggests that a cure may be effected by a filter circuit which would prevent this AC component from flowing through the power source. The same circuit with these additional features to eliminate oscillation from this cause is illustrated in Fig. 26. From the diagram it may be seen that the low-pass filter circuit consists of condenser C_8 connected between the lower end of the plate coil and the cathode, and resistor R_8 connected between the lower end of the plate coil and B+. Because of this resistor and condenser, the variations in the plate current will not flow through the power supply, but will be by-passed by

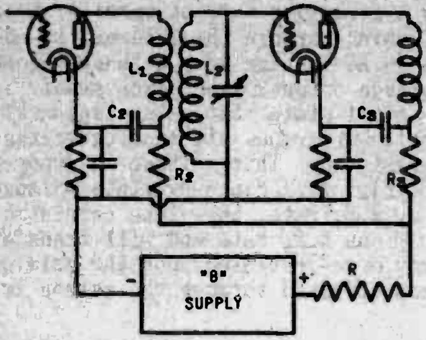


Fig.26 Showing how plate filters are connected to prevent coupling through a common impedance.

the condenser C_3. Sometimes the resistor R_3 is not used. Its purpose is to increase the impedance of the path through the power supply to the AC component, thereby forcing it to flow through the reactance of the condenser. Since it is never very large in value, it will have practically no effect upon the DC component.

It should be noticed that the elimination of this type of feed back is produced by a circuit exactly the same as that used to eliminate motorboating in resistance-coupled A.F. amplifiers. The components used serve exactly the same purpose. The condensers connected between each voltage tap of the voltage divider and ground also aid in this filtering action. Each amplifier stage should have its own filter.

The fourth cause of oscillations in R.F. amplifiers, feedback through the plate to grid capacitance of the vacuum tube, cannot be easily eliminated, but its effect can be neutralized. Before discussing the solution to this problem, let us see how this capacitive effect between the tube's electrodes is able to cause oscillations.

Referring to Fig. 27, we see the elements of a T.R.F. stage necessary for this explanation. The condenser shown in dotted lines represents the capacity existing between the plate and grid of the vacuum tube. The voltage applied to the grid circuit causes the grid voltage to vary at an R.F. rate. This, in turn, produces a pulsating plate current which also varies at an R.F. rate. When this plate current flows through L_2, it creates R.F. voltages across it, represented by E in the diagram. These R.F. voltages across L_2 cause an R.F. current to flow through the circuit as shown by the double-headed arrows. This current flows, during one alternation,

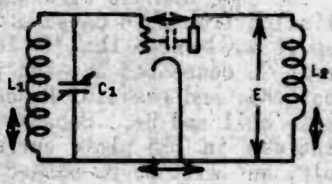
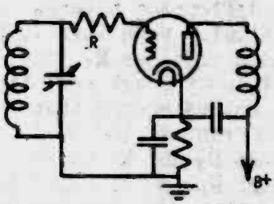


Fig.27 How coupling through the interelectrode capacity of the tube can occur.

from the top end of L_2 to the plate and by capacitive effect to the grid, through the tuned circuit L_1C_1 and back to the bottom of L_2. On the succeeding alternation, it flows in the opposite direction. In flowing through the tuned circuit L_1C_1, it develops R.F. voltages across the tuned circuit which, in turn, serve to excite the grid and cause the plate current to vary through even wider ranges. If the amount of energy transferred from the plate to the grid circuit by this method is sufficient to overcome all of the losses of the tuned circuit, sustained oscillations will be produced.

One of the very first methods used to prevent oscillations due to this cause was to insert a resistance of several hundred ohms in the grid circuit as shown in Fig. 28. This is known as the losser method of eliminating oscillations due to feedback through the interelectrode capacity of the tube. Its effect is this: the R.F. currents fed back through the interelectrode capacity must, necessarily, flow through the resistance R and, in so doing, they dissipate energy in the resistor. By purposely introducing this additional loss in the circuit, we have created a condition such that the energy fed back from the plate to the grid circuit is insufficient to produce sustained oscillations. The resistor ordinarily has a value of from 300 to 500 ohms.

Fig.28 Illustrating the use of a grid suppressor to eliminate oscillations caused by feedback through the interelectrode capacity. This is the losser method.



This system of preventing oscillations is simple, yet in many ways it is objectionable. The resistor wastes power and its presence creates some loss of the received signal.

A much more satisfactory method of preventing oscillation is to feed back from the plate to the grid circuit a current equal to but opposite in phase to that fed through the interelectrode capacity of the tube. This method is known as neutralization. Before discussing this subject, we shall first digress to take up the study of the Wheatstone Bridge upon which neutralization is based.

13. **THE WHEATSTONE BRIDGE.** The arrangement of four resistors as shown in Fig. 29 is called a Wheatstone[1] Bridge. A battery of voltage E is connected between two opposite points of the bridge while voltmeter V is connected between the two remaining points. One of the principle applications of the Wheatstone Bridge is for the measurement of resistance. How this may be done will now be explained. It is assumed that resistors R_1, R_2 and R_3 are variable and are accurately calibrated. R_4 is the unknown resistor whose

[1] Named in honor of Sir Charles Wheatstone (1802-1875), an English physicist and one of the pioneers of the art of telegraphy.

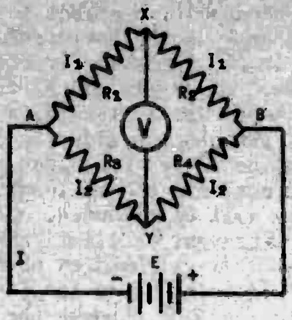


Fig.29 Diagram used to explain the principle of the Wheatstone Bridge.

value is to be determined. The process consists of balancing the bridge; that is, varying the values of the three known resistors until voltmeter V indicates zero voltage. When such is the case, the bridge is said to be balanced.

Let us now develop the theory of this arrangement. If the voltmeter indicates zero voltage, it signifies that there is no potential difference between the points X and Y; they are at the same potential. When this is true, the voltage drop between A and X, or through resistor R_1, must be equal to the voltage drop between A and Y, or through resistor R_3.

Let us assume that the total current flowing through the battery is represented by I, while that part of the current which flows through R_1 and R_2 shall be designated I_1 and the other part flowing through R_3 and R_4 shall be I_2. Using these designations, we may state that the voltage drop across R_1 is $I_1 \times R_1$, and the voltage drop across R_3 is $I_2 \times R_3$.

When the balance of the bridge has been attained, these voltages are equal and the following is true:

$$I_1 \times R_1 = I_2 \times R_3 \qquad (1)$$

By a similar line of reasoning, it is logical to conclude that the voltage drop across resistor R_2 must be equal to the voltage drop across R_4 when the bridge is balanced. This fact can be stated in the form of an equation as follows:

$$I_1 \times R_2 = I_2 \times R_4 \qquad (2)$$

One of the axioms[1] of elementary algebra states that if equals be divided by equals, the quotients are equal. Let us apply this axiom by dividing equation (1) by equation (2):

$$\frac{I_1 \times R_1 = I_2 \times R_3}{I_1 \times R_2 = I_2 \times R_4} \qquad \begin{matrix}(1)\\(2)\end{matrix}$$

[1] An axiom is defined as a self-evident or necessary truth.

This may be written:

$$\frac{I_1 \times R_1}{I_1 \times R_2} = \frac{I_2 \times R_3}{I_2 \times R_4} \qquad (3)$$

I_1 may be cancelled in the numerator and denominator of the left member of this equation and the same is true of I_2 in the right member. It then becomes:

$$\frac{R_1}{R_2} = \frac{R_3}{R_4} \qquad (4)$$

Or, this equation may be stated as a proportion such as $R_1:R_2 = R_3:R_4$. R_4 is the unknown resistor whose value is to be found and, by a fundamental principle of proportion which states that the product of the means when divided by one extreme gives the other extreme, R_4 may be found:

$$R_4 = \frac{R_2 \times R_3}{R_1} \qquad (5)$$

It is evident that the value of any resistor may be obtained by this method if three accurately calibrated variable resistors are available. The sensitivity of the device depends upon the sensitivity of voltmeter V, which sometimes is a very delicate galvanometer which requires an extremely small amount of current for a readable indication. In its commercial form, the component parts of the Wheatstone Bridge are contained in a small box with dials for changing the values of the known resistors.

While we are not going to use the Wheatstone Bridge at this time for the measurement of resistance, it was considered to be of sufficient importance to be included.

Remember that the conditions necessary for the balance of a Wheatstone Bridge are given by equation (4). The four arms of the bridge need not all be resistors. It would be possible to replace R_1 and R_3 with inductors, or two of the arms of the bridge may be condensers, or the four arms could be composed of two coils and two condensers. The conditions for balance remain the same. Thus the bridge of Fig. 30 would be balanced when this proportion is true.

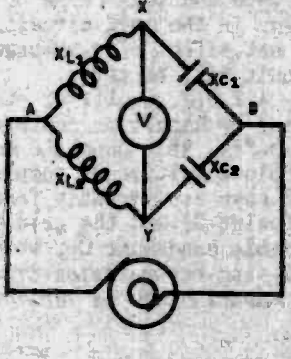


Fig.30 A Wheatstone Bridge composed of two inductors and two condensers.

$$\frac{X_{L_1}}{X_{C_1}} = \frac{X_{L_2}}{X_{C_2}} \qquad (6)$$

When this bridge is balanced, the application of an alternating voltage between points A and B will not produce any voltage difference between points X and Y. This is the fundamental principle of the Wheatstone Bridge and should be thoroughly understood.

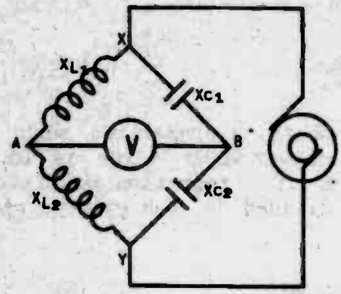


Fig.31 Showing how the voltage source and voltmeter may be interchanged without disturbing the balance of the bridge.

It may also be proved that when the bridge is balanced, the alternator and voltmeter may be reversed; that is, the application of the alternating voltage between points X and Y will not produce a voltage difference between points A and B. This is shown in Fig. 31. Thus, the conditions necessary for balance may also be stated as:

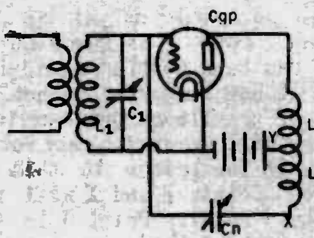
$$\frac{X_{L_1}}{X_{L_2}} = \frac{X_{C_1}}{X_{C_2}} \qquad (7)$$

Let us now investigate how the principle of the Wheatstone Bridge may be used to neutralize an R.F. amplifier and thus prevent its oscillation.

14. **NEUTRALIZATION.** Neutralization is used in an effort to cancel the effect of the energy fed from the plate to the grid circuit through the plate to grid capacitance of the tube and thereby prevent the stage from oscillating. The idea is to feed back energy equal in magnitude but opposite in phase to that transferred through the tube and thus cause a cancellation or neutralization of this energy in the grid circuit. If perfect cancellation is obtained, the net effect of a voltage across the plate circuit upon the grid circuit will be zero.

A T.R.F. amplifier stage using a method of neutralization invented by Hazeltine and known as the neutrodyne system is illustrated in Fig. 32. The plate coil is divided into two parts, L_a and L_b. The plate voltage is supplied at their junction, Y. Ordinarily, L_b will have considerably fewer turns than L_a. Between the bottom of L_b (point X) and the grid of the tube, there is connected a small variable condenser C_n, which is the neutralizing condenser. In sets employing neutralizing circuits, this condenser is placed so that its capacity may be varied by means of a screwdriver. It is com-

Fig.32 The Neutrodyne method of neutralization.



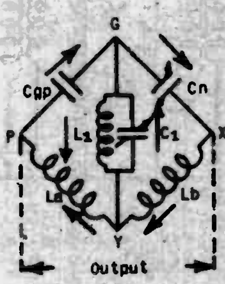
structed in the same manner as trimmer condensers used for alignment purposes.

Plate current flows from the plate through L_a to point Y, through the B battery and back to the cathode. Since it is a pulsating direct current varying at a radio-frequency rate, it induces R.F. voltages across both coils L_a and L_b. That part of the voltage across L_a forces an R.F. current through the interelectrode capacity of the tube and through the tuned circuit.

The voltage across L_b forces an R.F. current through the neutralizing condenser, through the tuned circuit and back to point Y. The voltage across L_a is 180° out of phase with that across L_b. Thus, when the potential of the top end of L_a is increasing in a positive direction, the potential of point X is increasing in a negative direction. Likewise, then the top of L_a is becoming more negative, point X is growing more positive. Since the two voltages are 180° out of phase, the respective currents which they cause to flow through the tuned circuit L_1C_1 are also 180° out of phase. This means that the R.F. voltages produced across the tuned circuit L_1C_1 due to the two R.F. currents will be 180° out of phase. If the two R.F. currents are exactly equal in value, then the two voltages produced across the tuned circuit will likewise be equal and since they are exactly out of phase, they will cancel and thus there will be no net R.F. voltage drop across L_1C_1 due to the voltage across the plate circuit. Of course, there will be a voltage across L_1C_1 due to the signal voltage induced from the preceding stage.

Now let us consider this circuit when viewed as a Wheatstone Bridge. At first sight, it is hard to realize that it is a bridge, but by redrawing it as shown in Fig. 33 and carefully comparing this figure with Fig. 32, it is seen that such is the case. L_a is one arm of the bridge and L_b a second arm. The neutralizing condenser

Fig.33 A circuit equivalent to that of Fig. 32, redrawn to show the components of the bridge.



C_n is the third arm and C_{gp} (the plate to grid capacitance) is the fourth. Point P is the plate and point G is the grid. The B battery has been omitted as it is not needed for the explanation.

It has been stated that if a bridge is balanced, the application of a voltage between two diagonally opposite points of the bridge will not produce any voltage across the two remaining points. Thus, if the bridge in this figure is balanced, the R.F. voltage between points P and X will not produce any voltage drop between points G and Y. Point G is the grid while point Y may be considered as the cathode or bottom end of the tuned circuit since the effect of the plate battery insofar as the R.F. voltages and currents are concerned is negligible. In any event, it would probably be by-passed by a large condenser whose reactance to R.F. would be very low.

Let us again review this action in a slightly different manner. During one alternation of R.F. voltage, point P is negative with respect to point X. Thus the voltage between points P and Y would force a current from point P through C_{gp} to point G, (the grid) down through the tuned circuit as shown by the left-hand arrow to point Y and thus back to point P.

At the same time, point X is positive with respect to point Y or point Y is negative with respect to point X, and an R.F. current will therefore flow from point Y upwards through the tuned circuit, as shown by the arrow on the right, to the grid, from the grid through the neutralizing condenser C_n to point X and back through the coil L_b to point Y. It may thus be seen that there are two currents flowing through the circuit L_1C_1 in opposite directions. As previously stated, these currents are 180° out of phase and if they are made equal in value, the effects which they produce on the tuned circuit will exactly cancel each other.

The condition necessary for balance in this circuit is:

$$\frac{X_{La}}{X_{Cgp}} = \frac{X_{Lb}}{X_{Cn}}$$

To find the values of these reactances, the frequency, of course, must be known. However, it may be shown that neutralization is

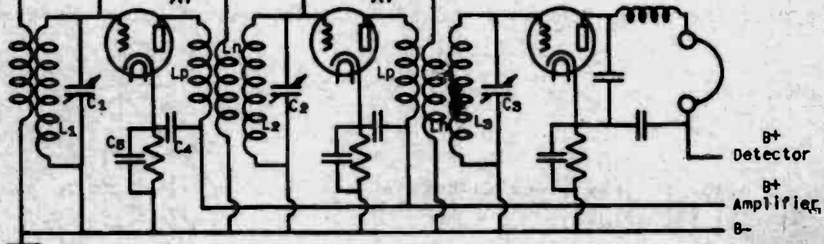


Fig. 34 A three-tube receiver employing the Neutrodyne method of neutralization. A separate winding is placed on each R.F. transformer to obtain the neutralizing voltage.

practically independent of frequency provided that the mutual inductance between coils L_a and L_b remains practically constant as the frequency changes.

The process of neutralization consists of varying the capacity C_n until the circuit no longer oscillates. The exact details of this procedure will be fully described in a servicing lesson.

Instead of dividing the plate coil into two parts as was done in Fig. 32, the neutralizing voltage is sometimes secured from a third coil as shown in Fig. 34. This diagram illustrates a two-stage T.R.F. amplifier using this method. The R.F. transformers have 3 windings: the plate coil, the secondary, which is part of the tuned circuit of the succeeding stage, and the neutralizing coil L_n. L_n must be wound in such a direction that the voltage at the end of this coil connected to C_n is opposite in phase to the voltage at the plate end of the plate coil L_p.

This circuit is really no different than the one first described. The bottom end of L_n is grounded and the bottom end of L_p is at ground potential so far as R.F. is concerned, since the condensers C_4 and C_8 have such low reactances to R.F. as to produce an R.F. short. Thus, in effect, the lower ends of L_p and L_n are connected together as was the case in Fig. 32.

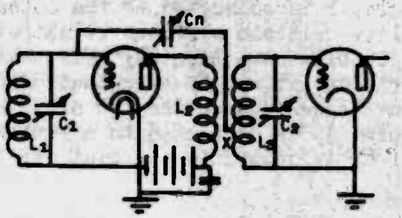


Fig.35 Neutrodyne method in which the neutralizing voltage is secured from the secondary of the R.F. transformer.

In many commercial circuits, the neutrodyne method of neutralization takes the form shown in Fig. 35. In this case the neutralizing voltage is secured from the tuned circuit of the succeeding stage. The voltage across that part of the tuning coil between point X and ground (designated as L_3) constitutes the neutralizing voltage. The primary and secondary must be wound in such directions as to make the voltage across L_3 opposite in phase to that across L_2.

When this circuit is redrawn in such a manner as to more clearly indicate the components which form the arms of the Wheatstone Bridge, it appears as shown in Fig. 36. Thus the voltage across L_2

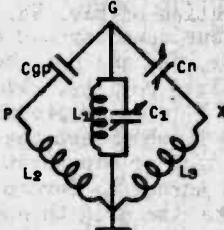


Fig.36 A circuit equivalent to that of Fig. 35, redrawn to show the components of the bridge.

forces an R.F. current through the interelectrode capacity through the tank circuit to ground; while the voltage across L_2, opposite in phase, forces an R.F. current through the tuned circuit in the opposite direction, through the neutralizing condenser and back to L_2. The capacity of C_n is varied until the magnitude of these two currents are equal, at which time the bridge is balanced and the tuned circuit L_1C_1 is not influenced by the voltage appearing across the plate coil L_2.

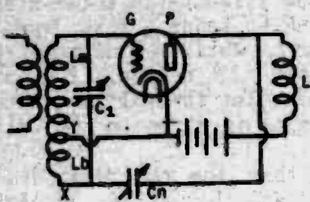


Fig.37 The Rice method of neutralization. The neutralizing voltage is obtained from the grid circuit.

A somewhat different method of neutralization is shown in Fig. 37. In this circuit, the tuning coil is tapped at point Y and the two parts of the coil are designated as L_a and L_b respectively. Point Y is connected to the cathode of the tube. In order to simplify this and previous illustrations, the circuits used to obtain grid bias have been omitted. The top end of L_a is connected to the grid and it can be seen that the grid excitation is that voltage developed between the top of L_a and point Y. The bottom end of L_b, point X, is connected to a neutralizing condenser C_n; the other end of C_n is joined to the plate of the vacuum tube.

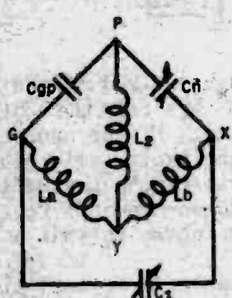


Fig.38 A circuit equivalent to that of Fig. 37, redrawn to show the parts of the Wheatstone Bridge.

The principle of operation of this circuit may be seen from an inspection of Fig. 38, which illustrates the circuit redrawn to show the four components of the Wheatstone Bridge. These components are L_a, L_b, C_{gp} and C_n. When the bridge is balanced, the voltage across the plate coil L_2, which is applied between the points of the bridge P and Y, will not produce any voltage across the two opposite points G and X, which are the two ends of the tuned circuit.

Another viewpoint is to consider that the R.F. voltage produced across L_2 forces a current through the interelectrode capacity to the grid through L_a to point Y and back to L_2. This R.F. current in flowing through L_a produces a voltage drop. In a like manner, the voltage across L_a forces another R.F. current through the neutralizing capacity to point X, through the coil L_b to point Y and back to L_a. This current produces an R.F. voltage drop across coil L_b. The voltage drop across L_a will be equal to that across L_b when the bridge is balanced and since they are opposite in phase, there will be no net voltage across the tuned circuit in which case the circuit is neutralized.

All R.F. amplifiers employing three-element tubes must be neutralized. As will be explained in Lesson 25, most modern receivers do not require neutralization of the R.F. amplifier stages due to the fact that screen-grid and R.F. pentode tubes are used. It might, then, seem that the study of neutralization is unnecessary; however, there are two good reasons why a thorough knowledge of this subject should be obtained by the student. First, it will probably be many years before the last receiver which uses neutralization is discarded. Second, neutralization must be used in every transmitter circuit since screen-grid tubes are not usually employed for high-powered stages.

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MIDLAND RADIO
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POWER & LIGHT BUILDING, KANSAS CITY, MISSOURI

UNIT NO. 1

SCREEN GRID AND PENTODE TUBES

LESSON NO. 25

DAVID GLASGOW FARRAGUT

.......HE HAD NONE OF THE ADVANTAGES WHICH YOU ENJOY

Born on a farm near Knoxville, Tennessee, July 5, 1801, young David encountered unusual hardships and dangers almost from the day of his birth. With his father away to the Indian wars, the Indians came to David's home and threatened to massacre the entire family, only to be driven away by a brave mother, who placed the lives of her children before her own safety.

At the age of seven, stark tragedy entered David's life. His mother died of yellow fever. He was adopted by Commodore Porter, bid his father farewell forever and was taken to Washington, where he spent a few months in school. Then, at the age of nine and one-half years, he was made a midshipman, entering a new life, full of hardships, adventures and brave deeds.

Today, we would be horrified at the thought of a youth only nine years old being thrown into the maelstrom of life. Times have changed. Now, a youth is expected to devote the first years of his manhood to securing an education which will make it possible for him to successfully wage the battle of life. Many marvelous advantages have been placed at his disposal. Amazing scientific inventions have resulted in the growth of huge industries who are constantly seeking ambitious young men with the necessary training. Opportunity beckons on every side.

Compare your own life with that of David Farragut. Think of the many tremendous advantages that you have. For example, it would have been impossible for David to secure training such as you are getting from Midland. The postman brings you your study material at regular intervals. David Farragut had to fight desperately for every bit of knowledge that he eventually secured. All you need to succeed is ambition and determination. And we feel that you are well supplied with both, else you would not be enrolled as a Midland student.

Keep your chin up, your shoulders back and march straight ahead to your success. Repeat the following sentence to yourself at frequent intervals, and you will be inspired to greater effort: "If David Farragut could win success and fame in spite of hardships and danger, I, too, can win success, because everything is in my favor!"

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Lesson Twenty-Five

SCREEN GRID and PENTODE TUBES

"It is a far cry from the two-element tube used in the earlier radio receiver to the multi-element tube which helps make the modern radio receiver possible.

"A knowledge of the construction and the electrical characteristics possessed by such tubes is of paramount importance to comprehend the design of present-day radio sets. In this lesson, I will tell you of four and five-element tubes; then in Lesson 30, I shall describe the more advanced types."

1. CONSTRUCTION. Up to this time in our studies, we have been dealing only with those tubes possessing three elements; that is, a filament or cathode, grid, and plate. As will be pointed out, a three-element tube has several disadvantages when used as an amplifier of high-frequency radio signals. As a detector, its low sensitivity retards its popular use. For A.F. amplification, a three-element tube is superior in some respects and inferior in others when compared to four and five-element tubes.

Screen-grid tubes were introduced in commercial radio receivers around 1930. In a very short length of time, they supplanted three-element tubes entirely for R.F. amplification. By their use, a greater sensitivity and more selectivity is obtained with a given number of R.F. stages, in addition to the desirable feature that the amplifying stages need not be neutralized to prevent self-oscillation. It is well that we investigate the constructional features of a screen-grid tube so that we may understand why it possesses these advantageous characteristics.

The line drawing in Fig. 1 shows the internal construction of a type 24 screen-grid tube.[1] Starting with the innermost element, the heater wire (not shown) is connected to two of the prongs on the base of the tube. The cathode is a metal sleeve surrounding the heater wire and is coated with material of such chemical nature that it is capable of supplying an abundant number of electrons

[1] This tube is the same in electrode structure and arrangement as the type 24-A.

when its temperature is increased. Surrounding the cathode, we next have the control grid. In the type 24 tube, the control grid winding consists of rather closely spaced turns and the entire winding extends from the top to the bottom of the electron-emitting cathode. The bottom end of the control grid winding is not connected to any other element, being supported by means of a small, glass insulator. The top end of the winding is connected to the metal cap on the top of the tube. On Fig. 1, this metal cap is labeled "control grid connection".

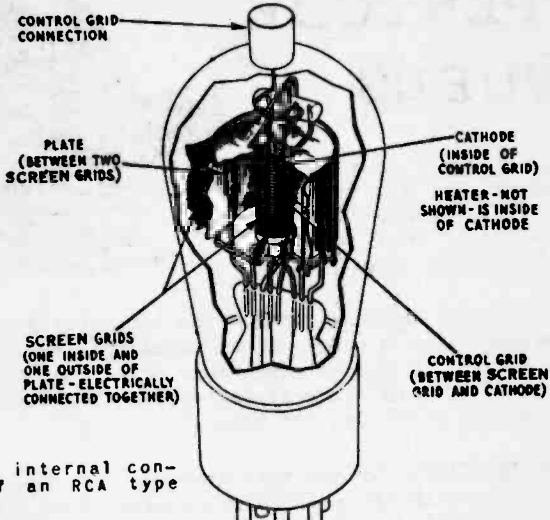


Fig.1 The internal construction of an RCA type 24 tube.

Next in the electrode arrangement is the inner screen grid, which surrounds the control grid. In Fig. 1 it is seen that the diameter of the inner screen-grid winding is greater than the diameter of the control grid winding, this being necessary to separate the two elements and permit adequate mechanical support so that normal vibration will not cause the two windings to touch. Also, the spacing between the control grid and the inner screen-grid windings is quite important insofar as the electrical characteristics of the tube are concerned. The screen grid is connected to a prong on the base of the tube.

Surrounding the inside screen grid is the metallic plate. The plate is a little smaller in area than in most triodes and is located a greater distance from the cathode. This difference in mechanical construction has quite an effect on the electrical characteristics of the tube. The plate of the tube is also connected to a prong on the base.

Surrounding the plate we have the second portion of the screen grid. Due to its location, this second portion is often called the outer screen. The inner screen is an ordinary coil or winding, but the outer screen consists of a closely woven wire gauze. The outer screen is connected to the inner screen inside the tube; therefore, any potential applied to the screen-grid prong on the base is simultaneously applied to both parts of the screen grid.

The electrical characteristics of the screen-grid or tetrode[1] tube are affected to a greater extent by the inner screen grid, the outer screen being mainly for the purpose of shielding the plate of the tube from external inductive and capacitive fields. A wire mesh is used for the outer screen because the heat produced by the inside elements (heater and plate) is thus permitted to radiate freely. This is of particular importance in tubes where a considerable amount of heat is given out by the filament or heater wire. Also, the use of a mesh material is advantageous since it is pliable and can be readily formed into any shape desired. A woven mesh is not used for the control grid and inner screen-grid portions of the tetrode tube, because these two grids are comparatively small and must be exceedingly accurate in diameter. If they were made with a wire mesh, it would be necessary for them to have a very open weave, under which condition the mechanical instability would probably result in unstable and inferior electrical characteristics.

Fig.2 The electrode arrangement in a screen-grid tube.

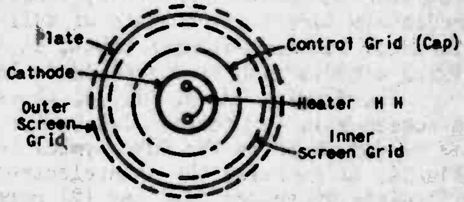


Fig. 2 again shows the electrode arrangement in a screen-grid tube. This is a view looking at the elements from the top of the tube. The heater wire is located in the exact center of the electrode assembly, surrounded by the electron-emitting cathode. Next comes the control grid which, in turn, is surrounded by the inner screen. The solid metal plate is next; then the entire assembly is enclosed by the outer screen. Bear in mind that the inner and outer screen grids are connected together within the tube and have only one prong on the base for external connection. Since the control grid connection is made to the metal cap on the top of the tube, the prong on the base ordinarily used for the control grid is made the screen grid connection.

2. CHARACTERISTICS OF A SCREEN-GRID (TETRODE) TUBE. Three outstanding characteristics are possessed by a screen-grid tube which account for its usefulness in R.F. amplifying circuits. Compared to a triode, these three characteristics are:

1. Lower control grid-to-plate interelectrode capacity.
2. Higher amplification factor.
3. Higher plate resistance.

[1] A "tetrode" tube means a four-element or screen-grid tube. All three terms are synonymous.

Fig.3 (A) Elements in a triode tube.
(B) C_1 indicates the capacity between plate and control grid.

A in Fig. 3 shows the electrode arrangement in a conventional three-element tube. At B in this same figure, the capacity C_1 represents the interelectrode capacity between the plate and grid elements. In typical triodes, this grid-to-plate capacity varies from 3 to 8 mmfd. As discussed in the previous lesson, a capacity of this value has a sufficiently low reactance at radio frequencies to permit an excessive feedback of energy from the plate to the grid circuit when the tube is employed as an R.F. amplifier. Excessive feedback is quite disastrous, because the amplifying stage is immediately forced into a state of self-oscillation. To correct this feedback in three-element tubes, it is necessary to use a neutralizing circuit such as discussed in Lesson 24.

The drawing at A, Fig. 4, shows the electrode arrangement in a screen-grid or tetrode tube. For convenience, the outer screen is seldom shown in the tube symbol on diagrams. The drawing at B, Fig. 4, illustrates the interelectrode capacities existing between (1) plate and screen grid and (2) screen grid and control grid. The distance between the plate and screen grid is generally much greater than the distance between the screen grid and the control grid. The small surface area exposed by the control grid and screen grid elements, in addition to the relatively wide separation, results in a low capacity between the plate and control grid elements. The capacity between the plate and control grid is also reduced by the same reasoning that connecting condensers in series reduces their effective capacity. Isolation of the plate and control grid elements in this manner helps to prevent the feedback of energy from the plate circuit to the grid circuit when this tube is used as an amplifier of R.F. voltages. By inspecting the manufacturer's characteristics for typical screen-grid tubes, it is found that the average control grid to plate interelectrode capacity is approximately .007 mmfd. This extremely low capacitance is produced not only by the electrode arrangement within the tube, but also by proper cir-

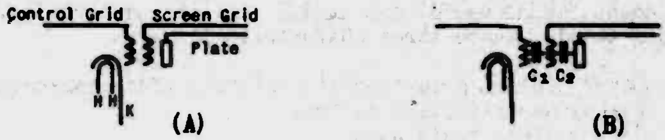


Fig.4 (A) Elements in a tetrode tube.
(B) C_1 and C_2 represent the interelectrode capacity.

cuit design and effective shielding which shall be discussed.

A typical R.F. amplifying stage, using a screen-grid tube is shown in Fig. 5. It will be noticed that the screen is maintained at a potential approximately one-half that of the plate voltage and is by-passed to the cathode through the .1 mfd. condenser C. It is not always necessary to operate the screen-grid voltage at exactly one-half the plate voltage; however, upon consulting the manufacturer's specifications for tetrode operation in R.F. amplifiers, it will be found that a screen-grid potential of over 90 volts is seldom recommended. The plate potential may be made as high as 250 volts in most tetrode tubes. As to the relative voltages applied to the plate and screen grid, the values are not extremely critical so long as the effect of secondary emission is properly suppressed. A complete discussion on secondary emission and its effect on the operation of a tetrode will be thoroughly discussed in a later paragraph of this lesson.

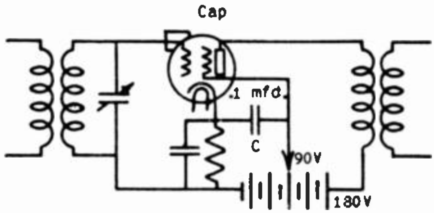


Fig.5 Typical screen-grid R.F. amplifier stage.

The by-pass condenser from the screen grid to the cathode, shown in Fig. 5, is essential for proper operation when the tube is amplifying R.F. voltages. This condenser must be sufficiently large in capacity so that its reactance to the frequency being amplified is low enough to be negligible. The condenser maintains a DC potential on the screen, but to R.F. voltages it affords such a low reactance path that the screen grid is at practically the same potential as the cathode. Since the cathode is effectively at R.F. ground potential, it follows that the screen grid is also at ground potential with respect to R.F. voltages. The presence of this grounded screen in between the plate and control grid of the tube is extremely effective in preventing the passage of feedback energy from the plate to the control grid. Without the by-pass condenser C, the interelectrode capacity between the plate and control grid will probably rise to a value sufficiently high to permit a feedback of energy from plate to control grid and cause the amplifying stage to break into a state of oscillation.

Since the screen grid is operated at a positive DC potential with respect to the cathode, it attracts electrons from the space charge. Also, from Fig. 1 it is seen that the screen is situated relatively close to the cathode; hence, the attraction exerted by the screen grid for the space charge electrons is largely responsible for their initial movement through the control grid. The plate of the tube, being located far from the cathode, is not nearly so effective as the screen in producing an initial movement of electrons from the space charge. Due to the wide spacing between the wires composing the inner-screen grid, most of the electrons that are drawn to the screen do not strike its surface, but, rather, pass on through the open spaces toward the plate of the tube.

After the screen grid has attracted the electrons from the space charge and caused them to pass through the control grid, the higher positive potential on the plate then exerts sufficient attraction to pull them on to its surface. Without the aid of the screen grid, it would be virtually impossible for the plate alone to attract the space-charge electrons. The screen grid then performs the very important function of causing the initial electron movement from the cathode toward the plate. Of course as these electrons are drawn through the control grid, any varying potential which may be applied to it will cause corresponding variations in the electron flow (plate current). Upon being attracted to the screen grid, a few of the electrons may strike the wires composing the grid winding, but most of them are drawn on through the open spaces by the higher positive potential of the plate.

A plate current flow is then set up in the plate circuit of the tetrode and any varying voltages applied to the control grid will cause corresponding plate current changes. Also, a slight flow of screen-grid current takes place, due to the few electrons which strike the grid wires and, of course, the screen-grid current will vary in accordance with the control grid voltages. The plate current variations must pass through the load impedance in the plate circuit and, due to the reactance or resistance of this load, corresponding voltages will be developed across the output circuit of the tube. The voltage amplification produced by the screen-grid tube will be equal to the ratio of the voltages developed across the plate load impedance to the input voltages applied to the control grid circuit.

The screen-grid current changes do not pass through a load impedance, but rather are returned directly to the cathode through the by-pass condenser. Therefore, the screen grid remains at a constant DC potential, regardless of the grid exciting voltage. It is due mostly to this constant potential on the screen that such a high plate impedance and high amplification factor are realized from the tetrode tube.

With constant screen-grid potential, the voltage on the plate of a tetrode may be varied over a wide range without causing any appreciable change in the plate current. This is evidenced from the characteristic curves for a type 24-A tube as shown in Fig. 6. With a negative grid bias of -3 volts, from Fig. 6 it is ascertained that the plate voltage may vary from 100 to 500 volts without causing more than 1.5 ma. change in plate current. At lower grid-bias voltages the plate becomes slightly more effective in producing a plate current change and with higher grid-bias voltage values, the plate is less effective. Even when a zero grid bias is used, it is seen from the characteristic curves that the plate current in a tetrode tube is practically independent of plate voltage variations. This means then, that the plate current is controlled almost entirely by the voltage variations applied to the control grid of the tube. It also signifies that the plate resistance of the tetrode is high in comparison to the plate resistance of a triode. As discussed in

Section 7 of Lesson 12, this characteristic of a vacuum tube is directly dependent upon the ability of the plate to cause a change in plate current.

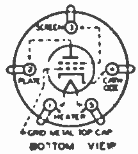
It was also learned in Lesson 12 that the amplification factor of a vacuum tube depends upon the ratio of the ability of the plate to the ability of the grid to cause a plate current change. In a tetrode tube, the plate is ineffective, whereas the grid exerts a pronounced ability to cause a plate current change due to the commanding position which it occupies.

In Fig. 1 it is seen that the control-grid winding is of small diameter; hence, it is directly in the midst of the space charge

Type 24-A

SCREEN-GRID RADIO-FREQUENCY AMPLIFIER

The 24-A is a screen-grid amplifier tube of the heater-cathode type for use primarily as a radio-frequency amplifier in a-c receivers. The 24-A may also be used as a screen-grid detector or audio amplifier.



CHARACTERISTICS

HEATER VOLTAGE (A. C. or D. C.)		2.5	Volts
HEATER CURRENT		1.75	Amperes
PLATE VOLTAGE*	180	250	Volts
SCREEN VOLTAGE (Maximum)	90	90	Volts
GRID VOLTAGE	−3	−3	Volts
PLATE CURRENT	4	4	Milliamperes
SCREEN CURRENT (Maximum)	1.7	1.7	Milliamperes
PLATE RESISTANCE	0.4	0.6	Megohm
AMPLIFICATION FACTOR	400	630	
MUTUAL CONDUCTANCE	1000	1050	Micromhos
GRID-PLATE CAPACITANCE (With shield-can)	0.007 max.		$\mu\mu f$
INPUT CAPACITANCE	5.3		$\mu\mu f$
OUTPUT CAPACITANCE	10.5		$\mu\mu f$

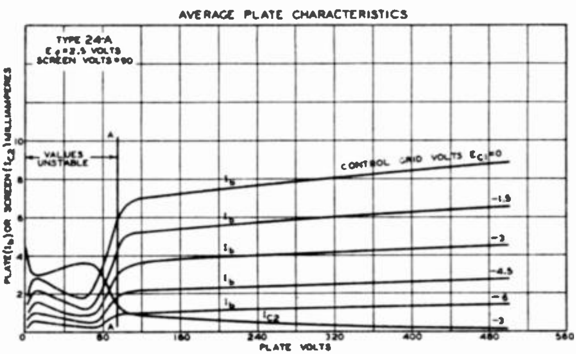


Fig.6 Plate voltage-plate current curves for a type 24-A tube.

surrounding the cathode. Also, the turns on the control-grid winding are spaced closely, thus providing it with an effective control on the plate current. These constructional features result in an amplification factor for the tetrode tube of about 400. When compared to the value of 5 to 15 for a triode, this is seen to be particularly advantageous.

Even though the amplification factor of a screen-grid tube is around 40 times as great as that possessed by a typical triode, it should be understood that an actual voltage amplification of 400 is not possible in practical circuit applications. This is due to plate circuit load limitations and the instability associated with high-gain amplifying stages. Even so, the total voltage amplification obtained from a tetrode is high in comparison with that secured from a triode; at least sufficient to warrant its use whenever possible.

9. SUPER-CONTROL TUBES. Tetrode tubes with a control-grid structure as shown in Fig. 1 are called "conventional" tubes. In a conventional tube, the control grid consists of a small coil of wire of uniform diameter and with uniform spacing between its turns. For convenience, a conventional grid is illustrated at A, Fig. 7.

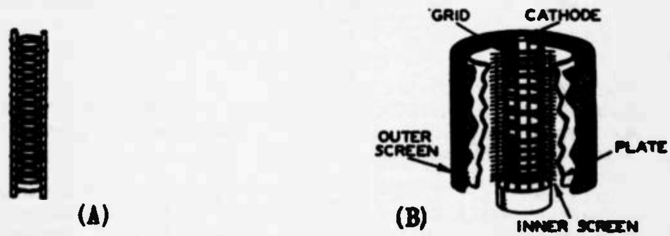


Fig.7 (A) Conventional grid. The spacing between the turns is uniform.
(B) Super-control grid. The spacing is close at the ends and open toward the center.

In a grid winding of this kind, every portion of it has an equal effect or control on the flow of electrons through its open spaces when placed around the electron-emitting cathode. The grid voltage-plate current characteristic curve for a tube of this type is shown by curve A in Fig. 8. It is observed that the E_g-I_p characteristic is practically a straight line, having only a very small curved portion at the lower end. From Fig. 8, when the grid of this tube is made approximately 9 volts negative with respect to the cathode, the plate current flow is cut off entirely. Tubes of this type are especially well adapted for use as grid-bias detectors, wherein they give excellent rectification and possess a high sensitivity.

In contract with the characteristics of a uniformly spaced grid, curve B in Fig. 8 represents the E_g-I_p characteristic of a super-control grid. It will be noticed that at low values of negative grid bias, the characteristic of the super-control tube is similar to that of the conventional tube. As the grid is made increasingly negative; however, the plate current is not decreased as rapidly

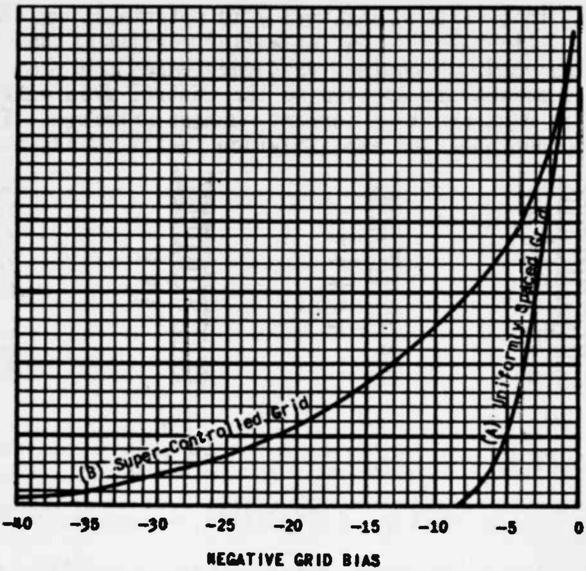


Fig.8 Eg-Ip curve to illustrate the difference between a tube having a uniformly spaced grid and a tube having a super-control tube.

and the plate current cutoff point is very remote, requiring approximately 44 volts negative potential to completely stop the plate current flow. The grid winding for a super-control tube is shown at B, Fig. 7. The turns are closely spaced at the two ends, then gradually taper toward the more open spaces at the center of the winding. This non-symmetrical method of winding the grid turns produces the "super-control" characteristics. On a tube of this kind, it is possible to vary the amplification factor and the transconductance by changing the grid-bias voltage.

Referring to Fig. 9, the small arrows to the right of the winding represent the passage of electrons through the spaces between the grid turns. At A, the conditions are illustrated when the grid bias is at a low value, such as -3 volts. When at this potential, the electron flow is through the entire grid winding, so the super-control grid has practically the same effect in controlling the electron flow as a conventional grid.

Sketch B in Fig. 9 shows the portion of the control grid through which electrons are permitted to pass when the grid-bias potential is made 8 volts negative. It will be noticed that electrons are no longer permitted to pass through the closely spaced turns at the two extreme ends of the winding. This is due to the strong negative fields established at these points. Since the turn spacing tapers toward the center, the negative field established around the more widely spaced turns is not sufficient to completely stop the passage of electrons. Reference to Fig. 8 shows that in a screen-grid tube with a conventionally wound grid (uniformly spaced), the plate current is cut off entirely at -9 volts. In the super-control tube, however, at this value of negative grid potential, the effect on the operation of the tube is that a smaller portion of the grid winding is now being used. Of course, when a decreased grid area is employed, the varying potentials applied to the control grid will not be as effective in causing plate current changes as before. This reduces the transconductance and amplification factor of the tube.

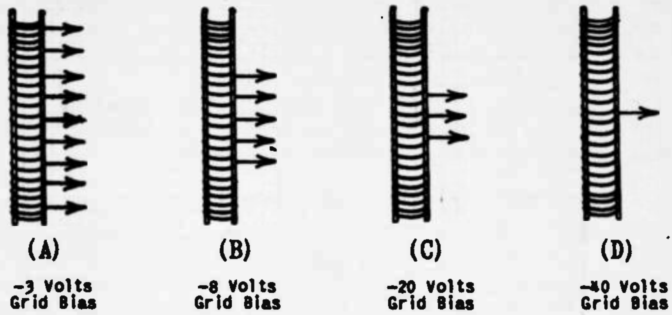


Fig.9 Drawing to show how the useful portion of the control grid is reduced as the negative grid bias is increased on the super-control tube.

At C, Fig. 9, the grid is made 20 volts negative with respect to the cathode. Now, the negative field established around the grid winding is sufficient to prevent the passage of electrons to the plate except near the center of the winding. It is only in this vicinity that the turns are spaced widely enough that the repulsion against the electrons is insufficient to block their passage. Since such a small portion of the entire grid winding is now being used, the transconductance and amplification factor of the tube have been reduced considerably, but it is still possible for a varying signal voltage applied to the grid to produce plate current changes and a little amplification.

Sketch D in Fig. 9 shows that at -40 volts grid potential, the repulsion against electrons in the space charge is sufficient to prevent their passage except at the exact center of the winding. The wide spacing between the two turns as the exact center permits a few electrons to pass; however, when in this condition, the plate current is extremely low, the transconductance is reduced to a very low value and the amplification produced is practically zero.

The desirable feature of a super-control tube is that the transconductance and amplification factor of the tube may be varied by changing the negative bias applied to the grid. In a typical super-control tube such as the type 35, the transconductance may be decreased from 1020 micromhos at 3 volts negative bias to 15 micromhos at 40 volts negative bias. This reduction is paralleled with a corresponding decrease in the amplification factor as the negative grid bias is increased. Due to the long and smooth curvature of the super-control E_g-I_p characteristic, there is no appreciable distortion produced when the tube is used as an amplifier and operated at a fairly high value of negative grid bias. If a small portion of the long, smooth curve is selected, it will be found fairly straight over a small distance to either side of the point selected, so it will give linear amplification when weak R.F. voltages are applied to the control grid. When the negative grid bias is increased on a conventional screen-grid tube, the curved portion is so abrupt that the tube will perform as a rectifier or detector rather than as a distortionless amplifier.

Since the Mu and Sm of a super-control screen-grid tube are decreased when the negative grid bias is increased, this is an excellent method of controlling volume on receivers incorporating tubes of this type. Volume control circuits applicable to these tubes will be discussed in the following lesson.

In modern receivers, super-control R.F. amplifying tubes are used extensively because the function of automatic volume control circuits is based on the variable-mu feature.

4. CROSS-MODULATION AND MODULATION DISTORTION. Two kinds of signal distortion which may occur in the R.F. stages of a receiver are known as "cross-modulation" and "modulation distortion". Super-control tubes are particularly effective in reducing both of these.

Modulation distortion is generally produced in the last R.F. amplifying stage; that is, the stage preceding the detector. It means a distortion of the modulated carrier wave which appears as A.F. distortion in the output of the detector. This is produced by an R.F. amplifying stage when the tube is operated near or on the curved portion of its characteristic and excited with a strong grid signal. Due to the sharp E_g-I_p cutoff of a conventional screen-grid tube, even though it may be operated at the negative grid bias specified by the manufacturer, after the signal has been amplified through all of the preceding stages of R.F. amplification, upon reaching the final R.F. amplifier, the grid voltage excitation may be strong enough to cause the plate current variations to decrease into the curved portion. Distorted amplification results and the waveform of the modulated R.F. signal is changed; hence, it is termed "modulation distortion".

If a super-control tube is used as the last R.F. amplifier, the strong grid signal voltages may be handled quite efficiently, even at high values of negative grid bias without producing modulation distortion. This is due to the long and smooth curvature in the E_g-I_p characteristic.

Cross-modulation generally occurs in the first R.F. amplifying stage of a receiver. It is defined as the effect produced in a radio receiver by an interfering station riding through on the carrier of the station to which the receiver is tuned. The interfering station actually combines with the carrier wave of the desired signal and both are heard in the output, regardless of the receiver's over-all selectivity. Cross-modulation is particularly noticeable when a receiver is operated close to a powerful broadcasting station. Even though the receiver may not be tuned near the local station, there will be sufficient energy picked up in the antenna to produce a signal voltage equal to or greater than the carrier to which the receiver is tuned on the grid of the first R.F. amplifier. Understand that this is not a problem of selectivity, because the first tuned circuit (if one is used) is not expected to prevent the passage of a strong local signal. The application of this strong local signal to the grid of the first R.F. amplifier, in addition to the weaker signal to which the receiver is tuned, results in composite plate current variations corresponding to both stations. The local station may be of sufficient strength to cause detection of its signal to occur in the first R.F. amplifier (with a conventional tube) and resultant A.F. currents are set up in the plate circuit. These A.F. currents, representing the modulation on the carrier of the local station, will, in turn, cross-modulate themselves on the carrier of the weaker signal (to which the receiver is tuned) and "ride" through the remaining tuned circuits to the detector. The selectivity of all the tuned circuits following the first R.F. amplifier will not be effective in preventing the cross-modulation because the carrier of the station to which the receiver's tuned circuits are adjusted is now being varied in amplitude not only by its own modulation, but also by the modulation on the strong local signal.

Satisfactory methods for preventing cross-modulation consist of (1) employing a trap circuit (wave trap) in series with the antenna lead to reduce the strength of the local signal, (2) by use of a pre-selector unit, or (3) to incorporate a super-control tube as the first R.F. amplifier. When a super-control tube is used, the long curvature of its E_g-I_p characteristic will not permit detection to occur regardless of the strength of the local signal; therefore, the A.F. currents representing the modulation of the local station cannot be produced in the plate circnit and cannot be cross-modulated onto the carrier of the desired signal.

5. APPLICATIONS OF SCREEN-GRID TUBES.

(A) The Screen-Grid Tube as an R.F. Amplifier. The screen-grid or tetrode tube finds its most extensive application in the amplification of high-frequency radio signals. In this respect it can be employed in a typical T.R.F. amplifier and is capable of producing a high gain in voltage per stage in addition to eliminating the necessity for neutralization. A typical two-stage, T.R.F. amplifier employing screen-grid tubes is shown in Fig. 10. The grid circuit of each R.F. amplifying stage is tuned with a resonant circuit to provide the necessary selectivity. The two tuning condensers are shown ganged so as to permit adjustment of the resonant circuits to the desired frequency by using only one control.

Transformer coupling is used in Fig. 10 for transferring the

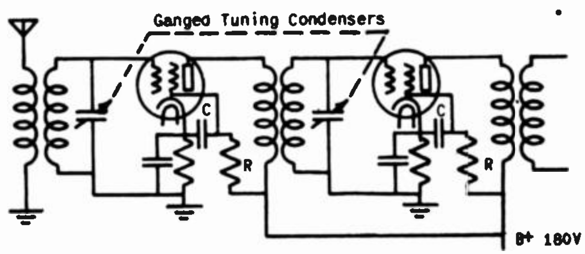


Fig.10 Typical two-stage transformer-coupled R.F. amplifier, using tetrode tubes.

amplified output of the first screen-grid tube to the grid circuit of the second stage. The primary winding of the R.F. transformer serves as the plate load impedance. The screen-grid voltage is secured from B+ through the dropping resistance R. By-pass condenser C serves to place the screen grid at R.F. ground potential. The size of the dropping resistance R should be such as to produce a potential difference between the cathode and screen grid of approximately 90 volts. The size of the series dropping resistance can be calculated by dividing the screen-grid current into the voltage drop desired. Let us assume that a 90-volt drop is necessary across R to reduce the screen voltage to one-half that of the plate voltage. Consulting the manufacturer's characteristics on a type 24-A tube, we find the screen current to be 1.7 ma. Upon dividing the 1.7 ma. into the 90-volt drop desired, it is found that the size of resistance R should be in the neighborhood of 50,000 ohms. A similar calculation can be carried out if a different voltage drop is desired or if the screen-grid current is more or less than 1.7 ma. The size of the by-pass condenser C is ordinarily .1 mfd. since a capacity of this value has an extremely low reactance to high radio frequencies.

The voltage amplification produced by a vacuum tube depends upon the amplification factor, the plate resistance and the plate load resistance. A formula by which the actual voltage amplification may be calculated is given in Section 13 of Lesson 12.

As given, the formula is:

$$V.A. = \frac{\mu \times R_L}{R_L + R_p}$$

Where: μ is the amplification factor
R_L is the load resistance
R_p is the plate resistance

From the formula it can be seen that the higher the amplification factor, the higher the load resistance, and the smaller the plate resistance of the tube, the greater the voltage amplification. Previous discussion of the screen-grid tube has shown that the amplification factor is high, but the plate resistance is also of high value. Hence, to obtain a high voltage amplification from a screen-grid tube, it is necessary to employ a plate load resistance in the neighborhood of 500,000 to 1,000,000 ohms. For R.F. amplification, a load impedance of this value is not practical, because it would force a considerable portion of the high-frequency signal energy in the plate circuit through the plate-to-screen-grid capacity of the tube and thus be lost. Nor is it possible to obtain an impedance of 1,000,000 ohms with the primary of an R.F. transformer. For these reasons, the actual load impedance on a screen-grid R.F. amplifier is somewhat less than that value necessary to produce extremely high voltage amplification. The primary winding, however, is designed to present as much load impedance to the plate circuit of the high-impedance tetrode as possible without causing excessive feedback into the grid circuit through inductive and capacitive coupling. Ordinarily, R.F. transformers are designed to produce a voltage amplification of 25 to 50 times per stage. In comparison with triode R.F. amplifiers, this amplification is very satisfactory since it is rather impractical to secure a voltage amplification of more than 5 times when using a triode.

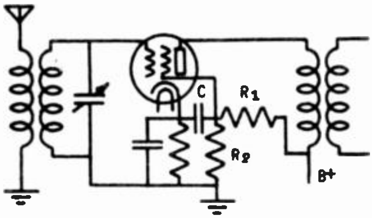


Fig.11 Tetrode R.F. amplifier stage wherein the screen voltage is secured by the voltage divider resistances R_1 and R_2.

An alternative means of securing the screen-grid voltage is shown in Fig. 11. The usual series dropping resistor is employed with the screen by-passed to the cathode. In addition, a second resistance R_2 is connected from the screen grid to ground. R_2 serves as a "bleeder" resistance and assists in maintaining the screen voltage constant at the desired value. Ordinarily, a value from 10,000 to 25,000 ohms is selected for R_2. To calculate the proper size for R_1, it is necessary to consider that both the bleeder current through R_2 and the screen current pass through it.

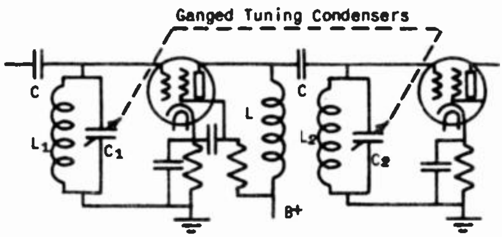


Fig.12 Impedance-coupled tetrode R.F. amplifier.

Another method of coupling screen-grid R.F. amplifiers is shown in Fig. 12. This is known as the "impedance-coupled" method and employs an R.F. choke as the load impedance in the plate circuit. The blocking condenser C prevents the high DC plate voltage from being applied to the grid and the resonant circuits L_1C_1 and L_2C_2 provide the necessary selectivity. The use of a properly designed R.F. choke instead of a transformer primary as the plate load impedance gives a higher voltage amplification per stage. The impedance of the choke cannot be made excessively high due to the shunting effect of the plate-to-screen-grid-capacity which would cause a considerable portion of the plate circuit signal energy to be by-passed to ground. The choke must have a low distributed capacity to assure best results. Particular care must be exercised in the shielding of all leads, the tuning inductances in the resonant circuit and the tubes themselves, when this method of coupling is used. Adequate selectivity is secured because the resonant circuits present a high impedance at the resonant frequency, but at off-resonant frequencies, the low impedance of the parallel tuned circuits places the grids at practically ground potential. Thus, grid excitation is secured only at the resonant frequency of the tuned circuit.

(B) The Screen-Grid Tube as an I.F. Amplifier. As we shall learn in Lesson 27, a superheterodyne receiver incorporates a fixed-frequency amplifier which amplifies radio signals at a rather low radio frequency. This low radio-frequency amplifier is commonly known as an I.F. (intermediate frequency) amplifier. In all modern superheterodynes, 4 or 5-element tubes are used in this amplifier. Triode tubes are not practical, because it is necessary to neutralize them and the gain per stage is low.

When amplifying at low radio frequencies, such as 175 kc., the feedback from the plate to the grid circuit through stray capacitive and inductive channels is not nearly so apt to occur. Also, the reactance of the tube capacities is much greater and less energy will be transferred through the elements. With the feedback problem of lesser consequence, it is possible to obtain a greater voltage amplification per stage without causing oscillations in the amplifier. This is done by inserting a higher load impedance in the

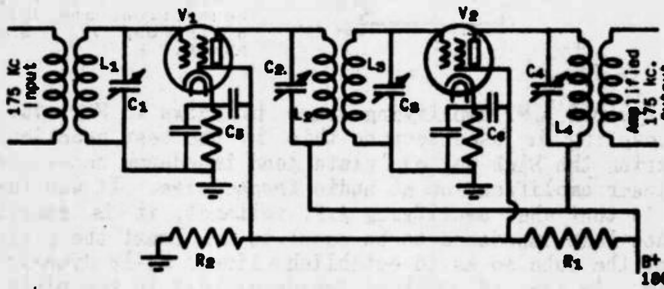


Fig.13 Typical two-stage I.F. amplifier with grid and plate circuit permanently tuned to 175 kc.

plate circuit of each stage. A parallel tuned circuit has a very high impedance at the resonant frequency and low impedance at off-resonant frequencies. Hence, if the plate and grid circuit of each amplifying stage is permanently tuned to the same frequency (for example, 175 kc.) as shown in Fig. 13, then that frequency will be amplified whereas other frequencies will not. Parallel resonant circuit L_2C_2 supplies the plate load for tube V_1 and L_4C_4 supplies the load for V_2. By proper design of these resonant circuits, the load impedance in each plate circuit may be made several hundred thousand ohms, thus making it possible to realize a voltage amplification through each stage of from 150 to 200 times. Careful shielding must be employed throughout when a gain per stage of this value is obtained to prevent the circuit from breaking into a state of oscillation.

These amplifiers are called I.F. amplifiers, because they amplify frequencies that are intermediate between audio frequencies and ordinary radio frequencies. The upper limit of the A.F. range is approximately 20 kc., and the lower frequencies in the broadcast range are around 500 kc., so those frequencies lying between are called "intermediate frequencies". Such amplifiers are always incorporated in superheterodyne receivers and their primary purpose is to obtain as high a voltage amplification per stage as possible.

(C) The Screen-Grid Tube as an A.F. Amplifier. The screen-grid tube can successfully be employed as an amplifier of weak A.F. voltages such as those from the output of a microphone, triode detector, or phonograph pickup. A.F. voltages greater than about 2 volts cannot be amplified properly by an ordinary screen-grid tube without distortion.

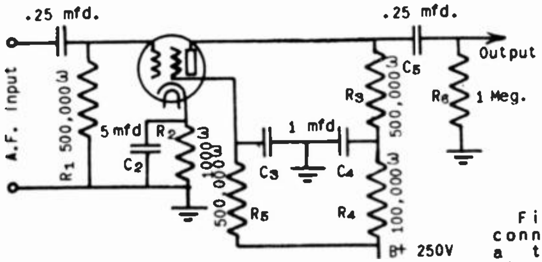


Fig.14 Typical circuit connections and values for a tetrode A.F. amplifier stage.

A typical A.F. amplifying stage is shown in Fig. 14. Resistance coupling is used because this is the best practical method of securing the high value of plate load impedance necessary to obtain linear amplification at audio frequencies. It was learned in Lesson 19 that when amplifying A.F. voltages, it is essential for the plate load impedance to be equal to at least the plate resistance of the tube so as to establish a linear E_g-I_p dynamic characteristic. In Fig. 14, the load impedance (R_3) in the plate circuit is 500,000 ohms, which, when compared to the plate resistance of the tube (from 250,000 to 400,000 ohms), will be sufficiently high to establish a linear dynamic E_g-I_p characteristic and obtain distortionless amplification. The 100,000-ohm resistance R_4 and the 1 mfd. condenser C_4 provide a decoupling or filter arrangement in the plate circuit to prevent motorboating. R_5 reduces the screen voltage from the high potential used for plate supply. R_5 is very high in value, this being necessary so as to reduce the screen voltage to a value less than 50 volts. Should the screen voltage be higher than this, the plate current drawn through the 600,000 ohms in the plate circuit will cause so much voltage drop that the actual plate voltage as measured from plate to cathode will be too low. The plate current in a screen-grid A.F. amplifier should not exceed a few tenths of a milliampere so the screen voltage must be fairly low. Grid bias developed across the cathode biasing resistor by this low plate current will also be low; hence, the signal input voltage to the grid circuit cannot be very high. If a high grid bias is used, the operating point moves down into the curved portion of the E_g-I_p characteristic in a tetrode A.F. amplifier. The over-all amplification will be in the neighborhood of 75 to 100 times. This surpasses the ability of any triode amplifying tube.

The amplified output of a screen-grid A.F. stage should not be fed into a succeeding screen-grid A.F. amplifier unless the original signal fed to the first stage was extremely weak. Ordinarily in circuits of this kind, a triode amplifier is used to follow the screen-grid A.F. amplifier.

(D) The Screen-Grid Tube as a Grid-Bias Detector. Conventional type screen-grid tubes are well adapted for grid-bias detector operation. The sharp plate current cutoff makes it possible to secure excellent rectification and a high A.F. output. The A.F. voltage output secured from a properly operated screen-grid bias detector is much greater than that possible from a triode bias detector, assuming the same modulated R.F. input signal voltage.

To operate a screen-grid tube as a bias detector, it is necessary to provide the plate circuit with sufficient load impedance so that the A.F. output will not suffer extreme distortion. Generally a .25 megohm to .5 megohm resistor is recommended as the plate load. Fig. 15 shows the circuit connections for a typical screen-grid, grid-bias detector circuit. The size of the cathode biasing resistor R_3 is considerably higher than the value necessary to work the same tube as an A.F. amplifier, because it must be operated on the curved portion of its E_g-I_p characteristic. Manufacturer's recommendations specify that the grid-bias voltage should be adjusted until only a few tenths of a milliampere of plate current is flowing when no input modulated R.F. signal is applied. The by-pass condenser C_1 must be sufficiently high in capacity so as not to degenerate the lower A.F. notes.

In Fig. 15, the resistor R_5 serves to drop the voltage from 250 to approximately 90 or 95 volts for the screen. The bleeder resistance R_4, connected from screen grid to ground, assists in reducing the voltage to this value and also maintains the screen voltage constant so as to insure good stability of operation.

It is not practical to use a super-control screen-grid tube as a bias detector. If the grid bias on a super-control tube is increased until it is operating with low plate current, then the transconductance and amplification factor are so low that it is impossible to secure much A.F. voltage from its output. When operated at a low negative grid bias, the smooth curvature of the E_g-I_p characteristic will not permit rectification; hence, the signal will only be amplified and not detected.

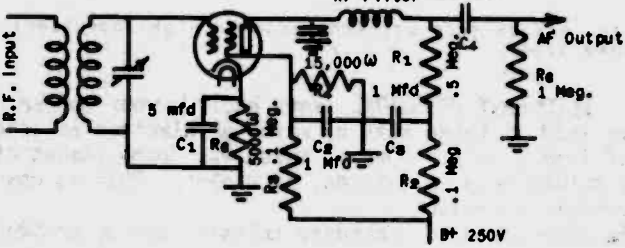


Fig.15 Typical circuit connections and values for a screen-grid, grid-bias detector.

When a screen-grid tube is used as a grid-bias detector, it is ordinarily followed by a triode audio-amplifying stage, or the A.F. output is fed directly to the grid circuit of a pentode power tube which, in turn, drives the loudspeaker. The A.F. output of a screen-grid detector is generally too strong for the grid circuit of a screen-grid A.F. amplifier, so for additional A.F. amplification, triode tubes are used.

The plate circuit of a tetrode bias detector is nearly always loaded with a resistor instead of a transformer primary. The load impedance must be high to match the plate resistance of the tube. For a transformer primary to have 500,000 ohms impedance would necessitate several thousand turns on an iron core; therefore, it would probably possess a high distributed capacity which, in turn, causes frequency distortion. Then, too, if the primary is wound with so many turns, to obtain a step-up in voltage to the secondary circuit, it would be necessary to wind two or three times as many turns on the secondary winding. Such a transformer would be physically impractical because of its size as well as unsatisfactory in electrical characteristics, due to its high distributed capacity.

Even though coupling transformers are not generally used with screen-grid detectors, some receivers have an iron-core choke as the plate load impedance. The A.F. output is then capacity coupled into the grid circuit on the first A.F. amplifier. These impedance chokes are designed especially for loading a screen-grid detector tube and may be used in receivers where the frequency response is not of paramount importance. They are wound with extremely small wire, ordinarily having a maximum current-carrying capacity of 8 ma. In a typical detector plate choke, when .5 ma. of current passes through the winding, the inductance is approximately 1,000 henries. An impedance-coupled screen-grid detector circuit is shown in Fig. 16.

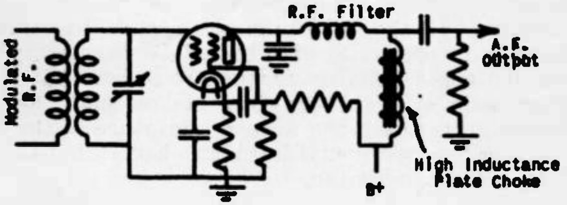
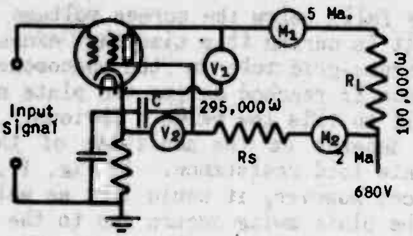


Fig.16 Screen-grid detector using a high-inductance choke for the plate load.

6. **SECONDARY EMISSION.** Very early in your course of training, you were told of three ways by which an electron emission could be obtained from a body.[1] One of these was "bombardment of a body by rapidly moving ions, electrons, or atoms". This is commonly known as "secondary emission".

The phenomenon of secondary emission has a decided effect on

[1] Lesson 7, Section 3.



Eg	Ip	Es	Ep
-3	5	90	180
-1	6	90	80
-5	4	90	280

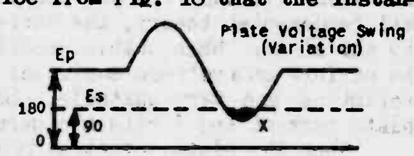
Fig.17 Tetrode amplifier stage to illustrate how the instantaneous plate voltage "swings" and falls below the screen voltage. Secondary emission then prohibits proper operation, so an excessive plate swing must be avoided.

the operation of a tetrode tube when the plate potential is allowed to fall near or less than the potential of the screen grid. In Fig. 17, a tetrode amplifying stage is shown using a resistive plate load of 100,000 ohms and operated with a plate voltage of 180 volts and screen voltage of 90 volts. The high supply voltage is used for the purpose of explanation; it does not represent typical operating conditions. The normal screen current of 2 ma. passing through R_s produces a voltage drop of 590 volts, which reduces the screen voltage to 90 volts as read on meter V_2. This screen current does not change during operation because the by-pass condenser C returns all variations directly to the cathode. Now, in the plate circuit the normal current of 5 ma. passes through R_L and produces a drop of 500 volts, allowing 180 volts to remain for plate potential as read on meter V_1.

With the bias voltage at -3 volts, let us proceed to learn how the plate voltage varies (swings) when an input signal is applied. On the positive alternation of the grid signal, the grid potential is made -1 volt and the plate current rises to 6 ma. As 6 ma. flows through R_L, the voltage drop produced is 600 volts, which reduces the instantaneous plate potential to 80 volts. *Notice that this is 10 volts below the screen-grid voltage.* On the negative alternation of the grid signal, the grid potential is made -5 volts, the plate current drops to 4 ma. and the voltage across R_L falls to 400 volts. At this instant, the actual plate voltage becomes 680 - 400 or 280 volts. *This is 100 volts higher than normal.* The table on the right of Fig. 17 tabulates these instantaneous conditions.

The point to be stressed is that the applied grid signal produces plate current changes and as the current changes occur through the plate load impedance, the instantaneous plate voltage varies over a wide range. Fig. 18 illustrates the variations of E_p in the example just given. The total change is from 180 up to 280, then down to 80 and back to 180 for one cycle of grid excitation. This is called the "plate swing". Notice from Fig. 18 that the instan-

Fig.18 Graph to show "plate swing". The plate potential is below the screen potential throughout the shaded portion marked X.



taneous plate voltage actually falls below the screen voltage over the shaded region marked X. It is during this time that excessive distortion is produced in a screen-grid tube by the phenomenon of secondary emission. The minimum E_p reached during the plate swing should not be permitted to fall to this low value. Obviously, the amplitude of the plate swing depends on the amplitude of the I_p changes and the value of the plate load resistance. In Fig. 17, the R_L consists of a pure resistance; however, it could just as well be an inductance, in which case the plate swing occurs due to the current changes through the inductive reactance. *The greater the plate swing, the higher the voltage amplification.* Since we are interested in obtaining as much undistorted voltage amplification as possible, let us see why the plate swing must be maintained within limits in a screen-grid tube.

Secondary emission occurs in all vacuum tubes when the rapidly moving electrons strike the plate. The electrons being attracted toward the plate from the cathode are accelerated to a very high velocity. They possess kinetic energy and, upon striking the plate material, cause not only the production of heat, but also the emission of additional electrons from the plate material. Those electrons attracted from the cathode to the plate are commonly known as "primary electrons", and those which have been knocked from the plate material are called "secondary electrons". It is possible for a single primary electron to cause the emission of several secondary electrons from the plate, depending on the plate material, the speed of the electron, and the temperature of the plate. In a triode vacuum tube, the secondary electrons emitted from the plate are attracted back to the plate and thus cause no detrimental effect on the operation of the tube. In a four-element tube (screen-grid), entirely different conditions exist.

The primary electrons are attracted from the space charge surrounding the cathode by the positive potential applied to the screen grid. Upon reaching the vicinity of the screen and finding no appreciable surface area, the primary electrons are attracted on through the screen-grid winding to the plate of the tube by its higher positive potential. Since the plate consists of a solid metallic body, the electrons strike it and cause the emission of secondary electrons. Even though the secondary electrons are not emitted from the plate at a tremendous velocity, it is quite possible that they will fly out from the plate sufficiently far to come into the field of attraction surrounding the positive screen grid. This will occur if the plate potential is equal to or less than the screen potential. In the event that this does happen, the secondary electrons emitted from the plate will constitute a steady electron flow to the screen grid which materially affects the tube's operation. Here we have a current flowing *from the plate* of the tube, whereas according to all fundamental theory, the current flow should be *from the cathode* to the plate. When in this condition, it is impossible for the tube to perform as a voltage amplifier because all of the tube's characteristics are very unstable. Secondary emission also lowers the plate current and limits the permissible plate swing.

When the plate potential is increased above that of the screen grid, the secondary electrons emitted from the plate will be attrac-

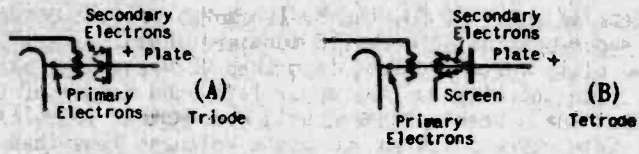


Fig.19 (A) Illustrating that the secondary electrons return to the plate in a triode.
(B) Due to the positive voltage on screen grid, the secondary electrons will be attracted to it unless the plate voltage is higher than the screen voltage.

ted back to it and therefore will not be permitted to reach the screen grid. The higher the plate potential relative to the screen-grid voltage, the less possibility there is for secondary electrons to reach the screen grid. When the plate is at least twice the potential of the screen grid, only a very, very few secondary-emitted electrons pass to the screen and proper operation of the tetrode as a voltage amplifier is thus assured. Increasing the plate potential to three to four times the screen voltage gives further assurance that correct operation will be maintained. Since plate potentials of greater than 250 volts are not practical, the screen grid is generally operated at a value somewhat less than 100 volts. Bear in mind that the screen-grid potential determines to a great extent the amplification factor and plate resistance of the tube, so it must not be reduced too low.

Drawings A and B in Fig. 19 illustrate the phenomenon of secondary emission in a triode and in a tetrode, respectively. No harm results in a triode because the secondary electrons return to the plate. When the plate potential is maintained higher than the screen potential in a tetrode, it, too, will amplify properly.

Increasing the plate voltage to a value above the screen voltage is one method of preventing the detrimental effects of secondary emission and placing an extra element called the "suppressor grid" between the screen grid and plate is another method. The addition of this fifth element forms a pentode tube.

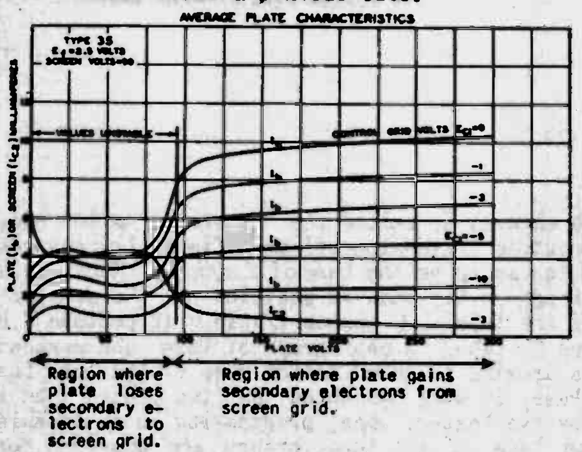


Fig.20 Plate voltage-plate current characteristic curves for a type 35 super-control R.F. amplifier.

Referring to Fig. 20, the E_p-I_p characteristic curves for a type 35 super-control screen-grid tube are shown. It will be noted that the plate voltage values less than 90 volts are marked "unstable". The notation in the upper left-hand corner of the graph states that the screen voltage is held constant at 90 volts; hence, all the plate current values at plate voltages less than 90 volts are rather uncertain and represent conditions unsuitable for amplification. These peculiar characteristics are caused entirely by secondary emission. After the plate potential is increased beyond 100 volts (the screen voltage remaining at 90), the plate current assumes a steady and stable relationship with the plate voltage and proper voltage amplification will be secured from the tube. These conditions also exist in a type 24-A screen-grid tube as shown on page 7.

7. **R.F. PENTODE AMPLIFIERS.** The greater voltage amplification secured from a tetrode in comparison to a triode is due to the addition of the screen grid. When an attempt is made to place the screen at a higher positive potential, the primary electrons from the cathode are speeded up to the extent that excessive secondary emission occurs. It is desirable to place the screen at a high potential in order to more thoroughly isolate the plate voltage from causing plate current changes and also to give the control grid more freedom in controlling the electron stream. If it were possible to place the screen and plate at the same potential without the detrimental effects of secondary emission, a much greater voltage amplification would be possible from the tetrode tube.

The introduction of a fifth element, situated between the screen grid and plate, effectively reduces the secondary emission and makes it possible to realize the maximum benefits from the screen grid.

(A)

Fig. 21 (A) Photograph of type 57 triple-grid R.F. amplifier. (B) Bottom view of tube base.

(B)

This fifth element is called the "suppressor grid" and, in most of the R.F. pentode (five-element) amplifiers, the suppressor grid is connected to a prong on the base of the tube. Thus, an R.F. pentode has six prongs on the base in addition to the control grid cap on the top of the tube. A common triple-grid pentode R.F. amplifier is the type 57 tube. A photograph of this tube is shown at A, Fig. 21, with a drawing to show a bottom view of the tube base at B. On the tube base, it will be noted that two prongs (the larger ones) are used by the heater; then, progressing in a clockwise direction around the base of the tube, prongs are provided for the plate, screen grid, suppressor grid and cathode. The control grid connection is to the metal top cap.

The suppressor grid in a pentode tube is so-called because of its effect on secondary emission. Its ability to regard or suppress the secondary emitted electrons and force them to return to the plate is responsible for its name. In practical operation, the suppressor grid is nearly always connected directly to the cathode of the tube; hence, it will be at a high negative potential with respect to the plate. Since the cathode is at R.F. ground potential, the suppressor grid is likewise, so the suppressor provides a grounded shield between the plate and screen grid. Since the suppressor grid is at the same potential as the cathode, it has practically no effect on the primary electrons that are passing from the cathode to the plate, but due to its high negative potential with respect to the plate, the secondary electrons are repelled and return to the plate rather than passing on through to the screen grid.

Fig.22 Electrode arrangement in a pentode tube.

Fig. 22 shows more definitely the electrode arrangement in the R.F. pentode tube. The primary electrons emitted from the cathode pass through the control grid, due to the attraction exerted by the positive potential on the screen grid, then are pulled on through the screen grid and suppressor grid to the plate. Upon striking the plate, the primary electrons cause the emission of secondary electrons. As these secondary electrons fly out from the plate, they immediately encounter the suppressor grid which is at a high negative potential with respect to the plate. Thus, they are forced to return to the plate and are not permitted to pass through to the screen grid. For this reason, the screen grid may be operated at a high positive potential without any detrimental effect caused by secondary emission.

Upon inspecting the operating characteristics of pentode R.F. amplifiers, it is found that when a low plate voltage is used, such as 100 volts, the screen voltage should be at the same potential as the plate. However, with higher plate potentials, such as 250 volts, the screen voltage should not be increased over 125 volts. With these operating voltages, the amplification factor of the tube increases to values from three to five times as great as that possible from an ordinary screen-grid tube and the transconductance also attains higher values. The plate resistance of the pentode tube is, of course, greater than that of the screen grid; however, when used for R.F. amplification, the higher value of plate resistance does not present any insurmountable difficulties. To properly load the plate circuits of these high-impedance tubes when they are used as R.F. amplifiers, specially designed R.F. transformers are nearly always employed. These transformers have an exceptionally high impedance primary winding which is not placed in inductive relationship with the secondary, but rather is wound on a small wooden dowel and set at right angles to it. The R.F. voltages developed across the primary are then coupled into the secondary circuit by a single loop of wire extending from the primary and encircling the top of the secondary winding. This single loop around the secondary winding forms sufficient capacity between the top of the primary and the grid end of the secondary to properly transfer the plate circuit energy into the grid circuit of the succeeding stage. On wiring diagrams, a transformer of this kind is often indicated as shown in Fig. 23.

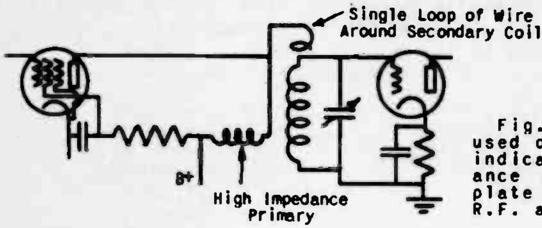


Fig.23 Symbol sometimes used on wiring diagrams to indicate the high-impedance primary used as the plate load for a pentode R.F. amplifier.

Considering the higher voltage gain acquired with pentode tubes, it is necessary to observe extreme precaution in the shielding throughout the entire R.F. amplifying circuit. Even though it is virtually impossible for sufficient R.F. to feed back through the interelectrode capacities from plate to control grid and cause oscillations, it is quite probable that stray magnetic and capacity coupling will cause oscillations to be established. Shielding, proper placement of the parts and careful wiring are all important points to take into consideration. On receivers incorporating these tubes, it will be found that care has been taken to shield all tubes, transformers and other parts of the R.F. system which might be affected.

The type 57 pentode tube was mentioned as a typical triple-grid R.F. amplifier. This tube has a conventional control grid; thus, its sharp plate current cutoff makes it very desirable for use as a grid-bias detector. The type 58 tube is the companion tube to the type 57, being similar in all respects except that it has a super-control grid. The type 58 tube is more widely used as an R.F. amplifier than the type 57 because its super-control feature prevents the possibility of cross-modulation when used as the first R.F. amplifier and modulation distortion when it is used in the last R.F. stage. The type 58, however, cannot be used as a grid-bias detector because of the remote plate current cutoff. A table of its characteristics is shown on the following page.

Other popular triple-grid R.F. amplifiers which should be inspected by the student are the types 77 and 78, both of which are similar to the 57 and 58 with the exception of the heater voltage. The types 6C6 and 6D6 are also companion tubes; the 6D6 has the super-control grid and the 6C6 has a conventional grid. These two tubes are similar to the 77 and 78 except that more careful shielding of the internal elements has been provided which makes them adaptable for use in all-wave receivers.

In the metal-tube line, the type 6J7 and the type 6K7 are both triple-grid R.F. amplifiers, the 6J7 having a conventional grid and the 6K7 a super-control. Additional tubes, similar in design to those mentioned, are available from various manufacturers with different type number designations. The complete tube chart provided at the end of this lesson should be consulted for this information.

Type 58

TRIPLE-GRID SUPER-CONTROL AMPLIFIER

CHARACTERISTICS

Heater Voltage (A. C. or D. C.)		2.5	Volts
Heater Current		1.0	Ampere
Plate Voltage	100	250 max.	Volts
Screen Voltage	100	100 max.	Volts
Grid Voltage (Minimum)	−3	−3	Volts
Suppressor	Connected to cathode at socket		
Plate Current	8	8.2	Milliamperes
Screen Current	2.2	2.0	Milliamperes
Plate Resistance	0.25	0.8	Megohm
Amplification Factor	375	1280	
Mutual Conductance	1500	1600	Micromhos
Mutual Conductance (At −40 volts bias)	10	10	Micromhos
Grid-Plate Capacitance (With shield-can)	0.007 max.		μμf
Input Capacitance	4.7		μμf
Output Capacitance	6.5		μμf

8. CALCULATING THE BIASING RESISTOR FOR TETRODES AND PENTODES. The chart on page 7 gives the manufacturer's characteristics for a type 24-A screen-grid R.F. amplifier. A circuit diagram showing this tube in a conventional R.F. amplifying circuit is shown in Fig. 24. Meters M_1, M_2 and M_3 are connected so as to measure the plate current, screen current and total (cathode) current, respectively. From the table of characteristics, it is found that with a plate voltage of 180 volts and a screen voltage of 90 volts, the

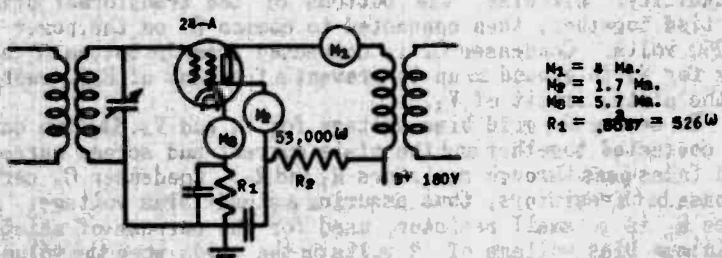
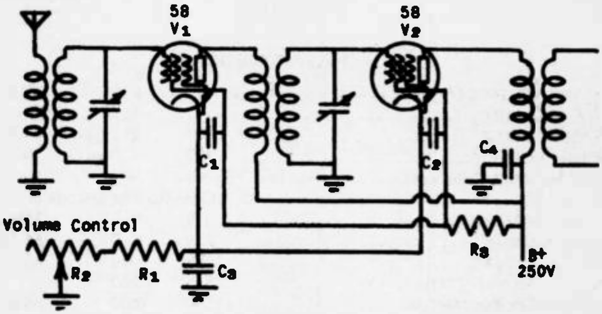


Fig.24 Typical tetrode amplifying circuit with meters inserted to measure the various currents.

plate current will be 4 ma. and the screen current 1.7 ma. Thus, the total cathode current as measured on meter M_3 will be 5.7 ma. According to the manufacturer's specifications, the grid bias voltage should be -3 volts. To calculate the size necessary for the grid-bias resistor R_1, it is necessary to divide the .0057 amperes total current into the 3 volts negative bias desired. This gives 526 ohms. This exact value is rather impractical, so a biasing resistor from 500 to 550 ohms will be found satisfactory.

This example is given because quite often when calculating the size of the biasing resistance for screen-grid or pentode tubes, there is a tendency to consider only the plate current and neglect the fact that the screen current must also pass through the biasing resistor.



	V_1	V_2	Total
Ip	8.2	8.2	16.4
Isg	2.	2.	4.
I total	10.2	10.2	20.4

$R_1 = \frac{3}{.0204} = 147\ \omega$

$R_2 = \frac{[illegible]}{.0204} = 10{:}000\ \omega$

Fig.25 Two-stage R.F. amplifier using pentode super-control tubes.

Fig. 25 shows a typical two-stage transformer-coupled R.F. amplifier, employing type 58 triple-grid, super-control tubes. In this diagram, the screen grid of V_1 is tied to the screen grid of V_2, then the common dropping resistance R_3 serves to reduce the screen voltage to the proper value for both tubes. Individual by-pass condensers C_1 and C_2 are employed to prevent possible circuit instability. Likewise, the bottoms of the transformer primaries are tied together, then connected to common B+ on the power supply of 250 volts. Condenser C_4 is connected from the bottom of the primary for V_2 to ground so as to prevent a feedback of R.F. energy into the plate circuit of V_1.

To secure the grid bias voltage for V_1 and V_2, the two cathodes are connected together and the plate current and screen current for both tubes pass through resistors R_1 and R_2. Condenser C_3 serves to by-pass both resistors, thus assuring a steady bias voltage. Resistance R_1 is a small resistor, used for the purpose of maintaining a minimum bias voltage of -3 volts on the grids when the volume control R_2 is set for maximum volume. A type 58 tube requires a grid bias voltage of -3 volts for maximum Mu and Sm. If only the rheostat R_2 were used to secure the grid bias, when turned completely to the right, the bias on each grid would be zero, with the plate current and screen current dangerously high. To calculate the size necessary for R_1 to maintain a minimum bias of -3 volts, we must find the sum of the screen current and the plate current drawn by both tubes because all this current will pass through R_1. Consulting the characteristics, with 250 volts plate voltage and 100 volts screen voltage, the plate current on each tube is found to be 8.2 ma. and the screen current 2 ma. Thus the total current flowing through the cathode circuit (at minimum bias) in V_1 is 10.2 ma. and likewise the total current passing through V_2 under the same conditions is 10.2 ma. The sum of these two currents, that is, 20.4 ma., passes through R_1. To calculate the size of R_1, .0204 amperes must be divided into the 3 volts negative bias desired. This gives a value of 147 ohms; hence, a resistor of 150 ohms would be the correct size to use, since 147 ohms is not a practical value.

The amplification factor and transconductance of a super-control tube are reduced when the negative grid bias is increased. Thus, increasing the negative grid bias of these tubes is a very convenient, effective and distortionless method of controlling the volume of the receiver. Resistance R_2 serves this purpose. When the movable arm on R_2 is adjusted to the extreme right, then the only bias voltage on the grids of V_1 and V_2 is the 3 volts developed across R_1. Under these conditions, the amplification factor and transconductance of each tube are maximum and the volume likewise maximum. Moving the arm on R_2 to the left increases the size of the biasing resistor, thus establishing a higher negative voltage on the grids of both V_1 and V_2. The amplification factor and transconductance of each tube is reduced accordingly and when the grid bias is at -40 volts, the transconductance has been reduced to 10 micromhos. The amplification factor, naturally, has been reduced to a correspondingly low value; hence, the voltage gain through the two R.F. stages is practically zero and the volume of the receiver at a minimum.

In calculating the size of R_2, we must take into consideration the fact that as the negative grid bias is increased, the plate current and screen current of each tube will decrease. We cannot assume that 20.4 ma. of total plate and screen current will be passing through R_2 when it is set for maximum value. Instead, it is quite probable that the total current will be reduced to a value in the neighborhood of 4 ma. Using this value and dividing it (changed to amperes) into the 40 volts negative bias desired, we find that the approximate size for R_2 is 10,000 ohms.

The method just outlined for controlling the volume on a receiver employing super-control R.F. amplifying tubes is not practical for use on a receiver which uses tubes of the conventional type. Increasing the negative grid bias on conventional tubes to a value in the neighborhood of 10 volts cuts the plate current off entirely; hence, the volume cannot be smoothly controlled without distortion. Instead, on tubes of this type, the screen-grid voltage is generally varied to obtain a control of the volume. A more complete description on various methods of controlling volume will be discussed in Lesson 26.

9. CHARACTERISTICS OF RECEIVING TUBES. Even though the lessons studied so far have not discussed in detail the construction and characteristics of all types of tubes which can be used in radio receivers, we feel that it is advisable to list the characteristics of the popular receiver tubes that are currently available. The student should inspect the following pages very carefully and become familiar with the various types of tubes.

These characteristics will be found of excellent reference value in all of the student's future work on radio receiver theory and radio servicing. The list is complete to the early part of 1937.

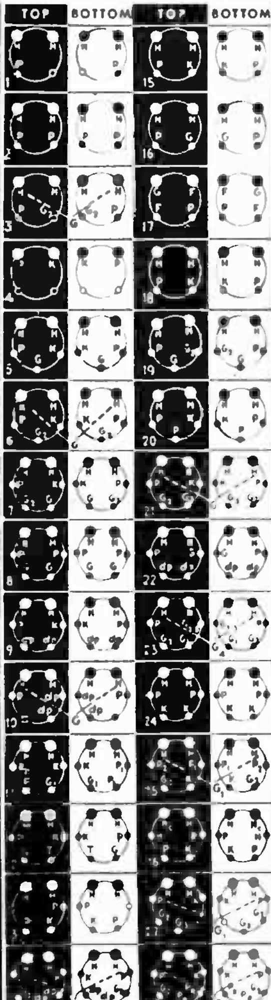
This entire list of tube characteristics and the following general information is reprinted in this lesson through the courtesy of P. R. Mallory & Co., Inc. We are indebted to P. R. Mallory & Co. for granting this privilege and for making such a complete list of tube characteristics available to the students of Midland Television, Inc. The pages are reprinted from the Mallory-Yaxley Radio Service Encyclopedia, a publication of the P. R. Mallory & Co., Inc. The Radio Service Encyclopedia is a 216-page reference and general information manual that will be found indispensable to anyone engaged in the radio servicing industry.

Radio Tube Characteristics

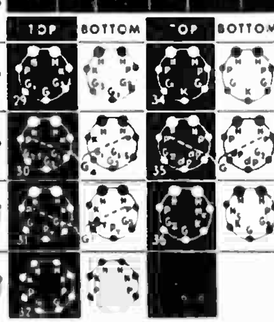
NUMBERING SYSTEM. The application of type designations to vacuum tubes was a haphazard process until the Radio Manufacturers Association set up a committee of engineers from the radio tube industry to handle the numbering of tubes and associated problems connected with the new types. From this committee came the present numbering system of: a numeral to indicate approximate filament or heater operating voltage; a letter to show the function of the tube; and a numeral to indicate the number of elements. Thus the 25Z5 tells by its first numeral group that the filament or heater operates at approximately 25 volts, by the letter Z that the tube is a rectifier and by the final numeral that the tube has five connected elements; that is, two plates, two cathodes and one common heater. Glass tubes designed to be interchangeable with the all-metal types can be subdivided into two general classifications. First of these is the "G" classification (or group) in which the tubes are glass, but are equipped with the octal base first introduced on metal tubes. These "G" tubes, except for the base, appear to be exactly like certain of the conventional glass tubes and indeed they are. For example, type 6K7G is a 78 with an octal base, and type 6A8G is type 6A7 with an octal base. When fitted with a "glove" shield, these tubes are practically interchangeable with the all-metal 6K7 and 6A8 types. The second group includes the "metal-glass" tubes. These MG tubes are the conventional glass types which correspond in characteristics to the all-metal tubes, but they are equipped with the octal-type base and are covered with a close-fitting sleeve cover of shield metal. In general they are designated with the same number used for the all-metal tubes followed by the suffix MG. In receivers of modern design, the MG tubes, like those in the G classification, can be substituted for all-metal tubes with small realignment or adjustments.

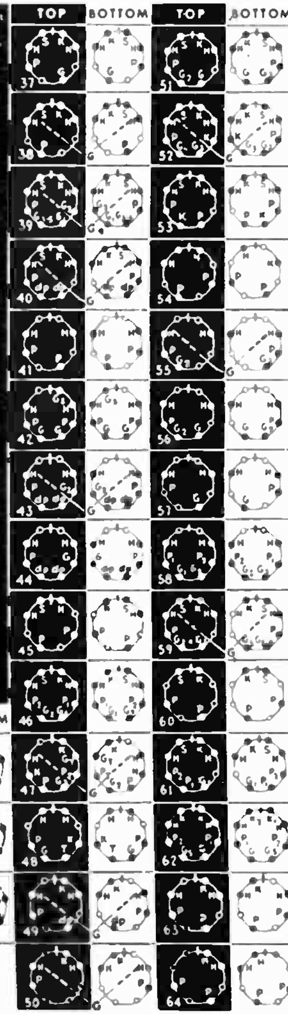
QUICK REFERENCE CHART

Showing Tube Socket Connections — Both Tops and Bottoms



Type	Socket	Type	Socket	Type	Socket
00A	16	6D6	21	30	6
01A	16	6D7	27	31	6-0
[illegible]A4	60	6D8G	39	32	3
1A4	3	6E5	87	33	29
1A6	23	6E6	34	34	3
1B4	3	6E7	52	35	6
1B5	22	6F5	38	36	6
1C6	23	6F6	31	37	5
1C7G	39	6F7	81	38	6
1D5G	55	6G5	12	39	6
1D7G	30	6H6	13	40	36
1E5G	55	6J5G	87	41	7
1E7G	42	6J7	12	42	7
1F4	19	6K5G	40	43	7
1F5G	56	6K6G	41	44	6
1F6	10	6K7	42	45	16
1F7G	43	6L5G	47	46	13
1H4G	57	6L6	1	47	13
1H6G	44	6L7	59	48	7
1J6G	58	6N5	48	49	18
1V	15	6N6	61	50	15
2A3	16	6N7	46	53	38
2A5	7	6P7	47	55	9
2A6	9	6Q6G	63	56	3
2A7	30	6Q7	45	57	21
2B6	40	6R7	40	58	[illegible]
2B7	15	6S7G	52	59	29
2E5	12	[illegible]	52	71	16
2G5	31	6X5G	63	75	9
[illegible]	12	6Y5	61	76	5
2S-4S	20	6Z5	25	77	21
[illegible]	1	10	25	78	21
5V4G	45	[illegible]	15	79	22
5W4	45	[illegible]	15	80	2
5X4G	61	12A5	35	81	3
5Y3	45	12A7	28	82	2
5Y4G	64	12Z3	16	83	2
5Z3	2	[illegible]	8	83V	3
5Z4	58	18	[illegible]	84	20
6A3	16	19	[illegible]	85	5
6A4	19	20	[illegible]	89	21
6A6	34	22	[illegible]	V99	17
6A7	30	24A	[illegible]	X99	16
6A8	39	25	2	182B	16
6B4G	37	25A6	5	183	16
6B5	11	[illegible]	6	485	5
6B6	40	[illegible]	1	950	19
6B7	35	[illegible]	6	BA	18
6B8	43	[illegible]	7	BH	18
[illegible]	43	[illegible]	2	BR	4
6C6	23	[illegible]	[illegible]	LA	19
6C7	11	[illegible]	10	RK[illegible]	32
6F[illegible]	37	27	[illegible]		





Some Servicemen Read TUBE SOCKET CONNECTIONS One Way, Some the Other. This New Chart Shows Both.

COMPLETE TUBE CHART

See Supplementary Chart on page 39

Type No.	Description: Type	Description: Cathode	Basing See Socket Connection Chart on Page 38	Fil. Current Amps.	Capacitances Micro-Microfarads: Grid Plate	Input	Output	Operating Conditions and Characteristics: When Used As	Plate Supply Volts	Screen Grid Volts	Grid Bias Volts (Neg.)	Plate Current MA.	Ampl. Factor	Plate Resis. Ohms	Mut. Cond. µMhos.	Max. Undist. Output Watts	Recomm. Load Resis. Ohms	Cut-Off Bias Volts
1.1 VOLT D.C. DETECTOR AND AMPLIFIER TUBES																		
WD-11	Triode	Fil.	4F Spec. 4 Pin	0.25	3.3	2.5	2.5	Grid Leak Detector	45		+A							
WX-12			4D Med. 4 Pin					Amplifier	90		4.5	2.5	6.6	15500	425	0.007	15000	
									135		10.5	3.0	6.6	15000	440	0.040	15000	
864	Triode	Fil.	4E Sm. 4 Pin	.25				Non-Microphonic Amplifier	90		4.5	2.9	8.2	13500	610		15000	
									135		9.0	3.5	8.2	12700	645		15000	
2.0 VOLT D.C. DETECTOR AND AMPLIFIER TUBES																		
15	Pentode	Heater	5F Sm. 5 Pin	.22				Detector-Oscillator	135	67.5	15	1.85	500	800000	750			
30	Triode	Fil.	4D Sm. 4 Pin	0.060	6.0	3.7	2.1	Bias Detector	180		18							
								Amplifier	135		9	3	9.3	10300	900	.07	20000	
									180		13.5	3.1	9.3	10300	900	0.13	20000	
31	Triode	Fil.	4D Sm. 4 Pin	0.130				Amplifier	135		22.5	8	3.8	4100	925	0.185	7000	
									180		30	12.3	3.8	3600	1050	0.375	5700	
32	Tetrode	Fil.	4K Med. 4 Pin	0.060	0.015 Max.	6.0	11.7	Detector	180	67.5	6						150000	
								Amplifier	135	67.5	3	1.7	610	.95M Ω	640			9
									180	67.5	3	1.7	780	1.2M Ω	650			9
33	Pentode	Fil.	5K Med. 5 Pin	0.260				Amplifier	180	180	0	10.5	60	50000	1200	0.30	7000	
									135	135	13.5	14.5	70	50000	1450	0.70	7000	
34	Remote Cut-Off Pentode	Fil.	4M Med. 4 Pin	0.060	0.015 Max.	6.0	12.6	1st Detector	67.5 to 180	67.5	5							
								Amplifier	135	67.5	3	2.8	360	0.6M Ω	600			27
									180	67.5	3	2.8	620	1.0M Ω	620			27
49	Double Grid Triode	Fil.	6C Med. 5 Pin	0.120				Class A	135		20	5.7	4.5	4000	1125	0.17	11000	
								Cl. B (Avg. 2 tubes)	180		0	4 to 30				3.0	9000 Min.	
19	Twin Triode	Fil.	6C Sm. 6 Pin	0.260				Complete Cl. B (Both Sections)	135		0	10 to 35				2.1	10000	
									135		3	4 to 35				1.9	10000	
1A4	Tetrode	Fil.	4K Sm. 4 Pin	0.060	0.007 Max.	4.6	11	Amplifier	180	67.5	3	2.3	720	0.90M Ω	750			30
1A6	Heptode	Fil.	6L Sm. 6 Pin	0.060	0.8	5	6	Oscillator Section	135		a50000 Ω b20000 Ω	2.3						
					0.25	10.5	9	Mixer Section	(a) 180	67.5	3	1.3		0.5M Ω	300	Conversion Conductance	Rg0.02M Ω	22.5
									(b) 180	45	−F	1.2		0.6M Ω	250			11
1B4	Tetrode	Fil.	4K Sm. 4 Pin	0.060	0.007 Max.	4.6	11	1st Detector	180	67.5	6							
951								Amplifier	180	67.5	3	1.7	780	1.0M Ω	650			9
1B5 / 25S	Duplex Diode Triode	Fil.	6M Sm. 6 Pin	0.060	3.6	2	3	Diode Detect. Triode Amplifier	135		3	0.8	20.0	35000	575			

1C6	Heptode	Fil.	6L Sm. 6 Pin	0.120	1.5	6	6	Oscillator Section	180		0.05M Ω	3.3				Conversion Conductance 0.5M Ω		
					0.3	10	10	Mixer Section	180	67.5	3	1.5		0.75M Ω	325	mhos		14
1F4	Pentode	Fil.	5K Med. 5 Pin	0.120				Amplifier	135	135	4.5	2.5	340	0.2M Ω	1700	0.34	16000	
1F6	Duo Diode Pentode	Fil.	6T Sm. 6 Pin	.060	.007	4	9	R. F. Det.-Ampli.	180	67.5	1.5	2.0	600	1 Meg.	650			12.0
								A. F. Det.-Ampli.	135	135 Res.	1.0	Plate Resistor .25 Meg.; Screen Resistor 1.1 Meg.						
2.5 VOLT A.C. DETECTOR AND AMPLIFIER TUBES																		
24A	Tetrode	Heater	5E Med. 5 Pin	*1.75	0.007 Max.	5.0	10.5	Detector	250	45	5						0.25M Ω	
								A. F. Amplifier	250	25	1	0.5	1000	2.4M Ω	380		0.1M Ω	
								R. F. Amplifier	180	90	3	4.0	600	0.4M Ω	1000			15
									250	90	3	4.0	600	0.6M Ω	1000			15
26	Triode	1.5V A.C. Fil.	4D Med. 4 Pin	1.5 V 1.05a	8.1	2.8	2.8	Amplifier	135		10	5.2	8.3	7000	1100	0.08	6000	
									180		14.5	6.2	8.3	7300	1150	0.18	10000	
27	Triode	Heater	5A Sm. 5 Pin	1.75	3.5	3.5	3.0	Bias Detector	250		30							
								Amplifier	135		9	4.5	9	9000	1000	0.08	12000	
									180		13.5	5.0	9	9000	1000	0.165	15000	
									250		21	5.2	9	9250	975	0.30	20000	
35 51	Remote Cut-Off Tetrode	Heater	5E Med. 5 Pin	1.75	0.007 Max.	5.0	10.5	1st Detector	250	90	7 App.							
								Amplifier	180	90	3	6.3	305	0.3M Ω	1020			50
									250	90	3	6.5	400	0.4M Ω	1050			50
45	Triode	Fil.	4D Med. 4 Pin	1.50				Single Amplifier	180		31.5	31	3.5	1650	2125	0.82	2700	
									275		56	36	3.5	1700	2050	2.0	4600	
								Push-Pull (Avg. 2 Tubes)	275		70	64 to 70				18	5060	
46	Double Grid Triode	Fil.	5C Med. 5 Pin	1.75				Class A	250		33	22	5.6	2380	2350	1.25	6400	
								Cl. B (Avg. 2 tubes)	300		0	8 to 70				16	5200 Min.	
									400		0	12 to 75				20	5800 Min.	
47	Pentode	Fil.	5B Med. 5 Pin	1.75				Amplifier	250	250	16.5	31	150	60000	2500	2.7	7000	
53	Twin Triode	Heater	7B Med. 7 Pin Lg. Pin Circle	2.0				Cl. A (Parallel Conn.)	294		6	7	35	11000	3200	0.37	20000	
								Complete Cl. B (Both Sections)	250		0	35 to 30				8	8000	
									300		0	35 to 30				10	10000	
55	Duplex Diode Triode	Heater	6G Sm. 6 Pin	1.0	2.0	2.0	4.0	Diode Detector	180		13.5	6	8.3	8500	975	0.16	20000	
								Triode Amplifier	250		20	8	8.3	7500	1100	0.35	20000	
56	Triode	Heater	5A Sm. 5 Pin	1.0	3.2	3.2	2.3	Bias Detector	250		20							
								Amplifier	250		13.5	5.0	13.8	9500	1450	0.35	47000	
57	Pentode	Heater	6F Sm. 6 Pin	1.0	0.007 Max.	5.0	6.5	Detector	250	100	2.0						0.25M Ω	
								Amplifier	250	100	3	2.0	2000	2.0M Ω	1225			7
58	Remote Cut-Off Pentode	Heater	6F Sm. 6 Pin	1.0	0.007 Max.	5.0	6.5	1st Detector	250	100	10							
								Amplifier	250	100	3	8.2	1280	0.8M Ω	1600			50
59	Triple Grid	Heater	7A Med. 7 Pin Lg. Pin Circle	2.0				Class A Triode	250		28	26	6	2300	2600	1.25	5000	
								Class A Pentode	250	250	18	35	100	40000	2500	3	6000	
								Cl. B Triode (Avg. 2 tubes)	400		0	26 to 75				20	6000 Min.	

Type No.	Description: Type	Description: Cathode	Base & Socket Connection Chart	Fil. Current Amps.	Capacitances: Grid Plate	Capacitances: Input	Capacitances: Output	When Used As	Plate Supply Volts	Screen Supply Volts	Grid Bias Volts (Neg.)	Plate Current MA	Amp. Factor	Plate Res. Ohms	Mut. Cond. Micromhos	Power Output Watts	Load Resistance Ohms	Cut-off Bias Volts
2.5 VOLT A.C. DETECTOR AND AMPLIFIER TUBES (continued)																		
2A3	Triode	Fil.	4D Med. 4 Pin	2.5				Single Amplifier	250		45	60	4.2	800	5250	3.5	2500	
2A3H	Triode	Heater	4Q	2.0				Cl. AB (2 tubes)	300	Self Bias	62	80 to 100				10	5000	
								Cl. AB (2 tubes)	300	Self Bias	62	80 to 150				15	3000	
2A5	Pentode	Heater	6B Med. 6 Pin	1.75				Pentode	250	250	16.5	34	220	0.1M Ω	2200	3	7000	
					No. 2 Gr. to Pl. Class AB Triode 2 tubes				350		38	45 to 90				20	3000	
2A6	Duplex Diode Triode	Heater	6G Sm. 6 Pin	0.8	2.0	2.5	4.0	Diode Detector	250		2	0.8	100	91000	1100			
								Triode Amplifier	250		2	0.1					0.25M Ω	
2A7	Heptode	Heater	7C Sm. 7 Pin	0.8	1.0	7	5.5	Oscillator Section	250		50000 Ω	4					Rs. 0.05M Ω	
					0.3	8.5	9	Mixer Section	250	100	3	4		0.36M Ω	500	Conversion Conductance		45
2B7	Duplex Diode Pentode	Heater	7D Sm. 7 Pin	0.8	0.007 Max.	3.5	10	Diode Detector	100	100	3	5.8	285	0.3M Ω	950			17
								R. F. Amplifier	250	100	3	4.5	800	0.65M Ω	1000			17
								Dia. Det. & A. F. Amp.	250	50	4.5	0.65					0.25M Ω	
3.3 VOLT D.C. DETECTOR AND AMPLIFIER TUBES																		
20	Triode	Fil.	4D Sm. 4 Pin	0.132				Amplifier	135		22.5	6.5	3.3	6300	525	0.110	6500	
V-99	Triode	Fil.	4E Spec. 4 Pin	0.063	3.3	2.5	2.5	Grid Leak Detector	45		+A	1.5	6.6	17000	370			
X-99			4D Sm. 4 Pin					Amplifier	90		4.5	2.5	6.6	15500	425	0.007	15500	
22	Screen Grid	Fil.	4K Med. 4 Pin	0.132	0.025 Max.	3.5	12	R. F. Amplifier	135	67.5	1.5	3.7	160	0.325M Ω	500			7.5
								Audio Amplifier	180	22.5	0.75	0.3	200	2.0M Ω	175		0.25M Ω	
5.0 VOLT D.C. DETECTOR AND AMPLIFIER TUBES																		
12A	Triode	Fil.	4D Med. 4 Pin	0.25	8.0	4.0	2.0	Amplifier	135		D.C. 9.0	6.2	8.5	5300	1600	0.13	9000	
									180		D.C. 13.5	7.7	8.5	4700	1800	0.285	10700	
71A	Triode	Fil.	4D Med. 4 Pin	0.25				Amplifier	135		D.C. 27.0, A.C. 29.5	17.3	3.0	1850	1650	0.40	3000	
									180		D.C. 40.5, A.C. 43.0	20	3.0	1750	1700	0.79	4800	
200A	Cs. Vapor Triode	Fil.	4D Med. 4 Pin	0.25	8.5	3.3	2.0	Grid Leak Detector	45		−A	1.5	20	30000	670			
01A	Triode	Fil.	4D Med. 4 Pin	0.25	8.1	3.1	2.2	Grid Leak Detector	45		+A	1.5	8.0	12000	670			
								Amplifier	90		4.5	2.5	8.0	11000	725	0.015	20000	
								Amplifier	135		9	3.0	8.0	10000	800	0.055	20000	
40	Triode	Fil.	4D Med. 4 Pin	0.25	8.0	3.4	1.5	Bias Detector	180		4.5	0.1					0.25M Ω	
								Audio Amplifier	180		3	0.2	30	0.15M Ω	200		0.25M Ω	

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6.3 VOLT A.C. OR D.C. DETECTOR AND AMPLIFIER TUBES

36	Tetrode	Heater	5E Sm. 5 Pin	0.30	0.007 Max.	3.7	9.2	Detector	100	67.5	6						0.25M Ω	
								Amplifier	100	55	1.5	1.8	470	0.55M Ω	850			7
									250	90	3	3.2	595	0.55M Ω	1080			7
37	Triode	Heater	5A Sm. 5 Pin	0.30	2.0	3.5	3.3	Bias Detector	250		30							
								Amplifier	90		6	2.5	9.2	11500	800	0.03	17500	
									250		18	7.5	9.2	8400	1100	0.34	20000	
38	Pentode	Heater	5F Sm. 5 Pin	0.30				Amplifier	100	100	9	7	60	80000	900	0.27	13300	
									175	135	13.5	9	100	0.1M Ω	1000	0.525	13500	
									250	250	25	22	120	0.1M Ω	1200	2.5	10000	
39 / 44	Remote Cut-Off Pentode	Heater	5F Sm. 5 Pin	0.30	0.007 Max.	3.5	10	1st Detector	90 to 250	90	7 App.							
								Amplifier	90	90	3	5.6	360	0.375M Ω	960			42
									250	90	3	5.8	1000	1.0M Ω	1050			42
41	Pentode	Heater	6B Sm. 6 Pin	0.40				Amplifier	100	100	13.5	12.5	150	81000	1850	1.5	9000	
									250	250	18	32	150	68000	2300	3.4	7600	
42	Pentode	Heater	6B Med. 6 Pin	0.70				Pentode	250	250	16.5	34	185	78000	2250	3	7000	
								Amplifier	315	315	22	42	220	0.1M Ω	2200	5	7000	
					No. 2 Gr. to Pl. Class A B Triode (2 tubes)				350		38	45 to 90				18	6000	
53	Double Grid Triode	Fil.	8C Med. 5 Pin	0.30				Class A	110		0	43	5.2	1750	3000	1.5	2000	
								Cl. B. (Avg. 2 tubes)	180		0	6 to 40				6	9000 Min.	
75	Duplex Diode Triode	Heater	6G Sm. 6 Pin	0.30	2.0	2.0	4.0	Diode Detector	250		2	0.8	100	91000	1100			
								Triode Amplifier	250		2	0.1					0.25M Ω	
76	Triode	Heater	5G Sm. 5 Pin	0.30	2.8	3.5	2.5	Oscillator	90		0							
								Amplifier	250		13.5	5.0	13.8	9500	1450	0.25	50000	
77	Pentode	Heater	6F Sm. 6 Pin	0.30	0.007 Max.	4.0	11	Detector	250	100	4.3							
								Amplifier	250	100	3	2.3	1500	1.5M Ω	1250			7.5
78	Remote Cut-Off Pentode	Heater	6F Sm. 6 Pin	0.30	0.007 Max.	4.0	11	1st Detector	250	100	10							
								Amplifier	250	100	3	7.0	1160	0.8M Ω	1450			42
79	Twin Triode	Heater	6H Sm. 6 Pin	0.60				Complete Cl. B Both Sections	250		0	20 to 60				8	14000	
85	Duplex Diode Triode	Heater	6G Sm. 6 Pin	0.30	2.0	2.0	4.0	Diode Detector	100		13.5	6	8.3	8800	975	0.16	20000	
								Triode Amplifier	250		20	8	8.3	7500	1100	0.35	20000	
89	Triple Grid	Heater	6F Sm. 6 Pin	0.40				Cl. A Triode	250		31	32	4.7	2600	1800	0.9	5500	
								Cl. A Pentode	250	250	25	32	125	70000	1800	3.4	6750	
								Cl. B. Triode (Avg. 2 tubes)	250		0	6 to 30				5	10000Min.	
6A3	Triode	Fil.	4D Med. 4 Pin	1.0				Single Amplifier	250		45	60	4.2	800	5250	3.2	2500	
								Class AB (2 tubes)	325	Self Bias	68	120 to 150				10	5000	
									325	Fixed Bias	68	140 to 200				15	3000	
6A4LA	Pentode	Fil.	5B Med. 5 Pin	0.30				Amplifier	100	100	12	22	100	4800	2200	1.4	8000	
								Class AB (2 tubes)	250	250	28	32	Self Bias R_{sg} = 700 Ω			4.8	16000	
12A5	Pentode	Heater	7F Sm. 7 Pin	6.3 V 0.6A 12.6 V 0.3A	0.5	6	8	Amplifier	100	100	25	17			1700	0.45	4500	
									180	180	27	30			2200	2.6	3000	

Type No.	Description: Type	Description: Cathode	Tube Size, Socket Connection Chart	Fil. Current Amps.	Capacitances: Grid-Plate	Capacitances: Input	Capacitances: Output	Use	Plate Supply Volts	Screen Volts	Grid Bias Volts	Plate Current MA	Amp. Factor	Plate Res. Ohms	Mut. Cond. Micromhos	Power Output Watts	Load Resistance Ohms	Cut-Off Bias
6.3 VOLT A.C. OR D.C. DETECTOR AND AMPLIFIER TUBES (continued)																		
6A6	Twin Triode	Heater	7D Med. 7 Pin Lg. Pin Circle	0.8				Cl. A Parallel Conn.	294		6	7	35	11300	3100	0.37	35000	
								Complete Cl. B	300		0	35 to 50				8.	8000	
								Both Sections	250		0	25 to 50				10	10000	
6A7	Heptode	Heater	7C Sm. 7 Pin	0.30	1.0	7	8.5	Oscillator Section	250		50000 Ω	4					[illegible]	
					0.3	8.5	9	Mixer Section	250	100	3	4		0.36M Ω	550	Conversion Conductance		45
6B5	Dual Triode	Heater	6AS Med. 6 Pin	0.80				Single Tube	Each 300		0	Out-Put 45, In-Put 5	58	24000	2400	4	7000	Volts Input 15
									Each 325		0	51, 9				5.2	7000	17
								Two Tubes	Each 250		0	38, 6.5				8.5	10000	30
									Each 325		0	61, 9				12.5	10000	45
6B7	Duplex Diode Pentode	Heater	7D Sm. 7 Pin	0.30	.005 Max.	3.5	10	Diode Detector	100	100	3	5.8	285	0.3M Ω	950			17
								R. F. Amplifier	250	100	3	6.0	800	0.65M Ω	1000			17
								Dir. Det. & A.F. Ampl.	250	50	4.5	0.65					0.25M Ω	
6C6	Pentode	Heater	6F Sm. 6 Pin	0.30	0.007 Max.	5.0	6.5	Detector	250	100	4.3						0.25M Ω	
								Amplifier	250	100	3	2.0	1500	1.5M Ω	1225			7
6D6	Remote Cut-Off Pentode	Heater	6F Sm. 6 Pin	0.30	0.007 Max.	5.0	6.5	Int Detector	250	100	10							
								Amplifier	250	100	3	8.2	1280	0.8M Ω	1600			50
6E5	Cathode Ray	Heater	6R Sm. 6 Pin	0.30				Tuning Indicator	With Plate 250V. (Thru 1M Ω) Target 250V. Ib=0.25 m.a. And Shadow Angle is 90° at Ec=0v., Angle is Zero At Ec = -8V. Approx.									
6E6	Twin Triode	Heater	7B Med. 7 Pin	0.60				Complete Cl. A	180		20	30	6.0	3150	2000	0.75	10000	
								Both Sections	250		27.5	36	6.0	1750	3400	1.6	14000	
6F7	Triode Pentode	Heater	7E Sm. 7 Pin	0.30	2.0	2.5	3.0	Triode Amplifier	100		3	3.5	8	16000	500			
					0.008 Max.	3.5	12	Pentode Int. Detect.	250	100	10							
								Pentode Amplifier	250	100	3	6.5	900	.85M Ω	1100			30
6G5	Cathode Ray	Heater	6R Sm. 6 Pin	0.30				Tuning Indicator	With Plate 250V. (Thru 1M Ω) Target 250V. Ib=0.25 m.a. and Shadow Angle is 90° at Ec=0v., Angle is Zero at Ec = -22V. Approx.									
6N7G	Twin Triode	Heater	8B Octal Med. Shell 8 Pin	0.80				Same as 6A6										
7.5 VOLT A.C. POWER AMPLIFIER TUBES																		
10	Triode	Fil.	4D Med. 4 Pin	1.25				Amplifier	350		31	16	8.0	5150	1550	0.9	11000	
									425		39	18	8.0	5000	1600	1.6	10200	
50	Triode	Fil.	4D Med. 4 Pin	1.25				Amplifier	300		63	45	3.8	1800	2000	2.4	4100	
									450		84	55	3.8	1800	2100	4.6	4350	

SERIES FILAMENT POWER AMPLIFIER TUBES

43	Pentode	Heater	6B Med. 6 Pin	0.3a.				Amplifier	95	95	15	20	90	45000	2000	0.9	4000	
				25V.					180	135	20	38	100	40000	2300	2.75	5000	
48	Pentode	Heater	6A Med. 6 Pin	0.4a.				Amplifier	95	96	19	52			2800	2.0	1500	
				30V.					125	100	20.5	56			3900	2.5	1200	
25A7	Pentode and Diode	Heater	7K Sm. 7 Pin	0.3a.				Amplifier	135	135	13.5	9	100	0.1M Ω	975	0.55	13500	
				12.6V.				Rectifier	125 RMS			20 Max.						

METAL DETECTOR AND AMPLIFIER TUBES

6A8	Heptode	Heater	8A Octal 8 Pin	0.3	1	7	4.5	Oscillator Section	250		50000 Ω	4						
					0.05	[illegible]	12.0	Mixer Section	250	100	3	4		0.36M Ω	550	Conversion Conductance		
6C5	Triode	Heater	6Q Octal 6 Pin	0.30	2.0	4.5	11	Oscillator	90		0							
								Amplifier	250		8	8	20	10000	2000			
6F5	Triode	Heater	5M Octal 5 Pin	0.30				Amplifier	250		2	0.9	100	66000	1500			
									250		2	0.1					0.25M Ω	
6F6	Pentode	Heater	7S Octal 7 Pin	0.70				Pentode Amplifier	250	250	16.5	34	125	80000	2500	3	7000	
								Triode (Sc. to P)	250		20	31	6.2	2700	2600	0.85	4000	
								Cl. AB Pentode	375	250	340 Ω Self	54				19	10000	
								Amplifier (2 tubes)	375	250	26 Fixed	34				19	10000	
6H6	Twin Diode	Heater	7Q Octal 7 Pin	0.30				Diode Detector	100 Max. AC			2 Max. Ea. Diode						
6J7	Pentode	Heater	7R Octal 7 Pin	0.30	0.005	5	10	Detector	250	100	3.2						0.25M Ω	
								Amplifier	250	125	3	4			1500			9
									250	100	3	2	2000	2.0M Ω	1225			7
6K7	Pentode	Heater	7R Octal 7 Pin	0.30	0.005	5	12	1st Detector	250	100	10							
								Amplifier	250	125	3	10.5	990	0.6M Ω	1650			30
									250	100	3	7	1100	0.8M Ω	1450			60
6L6	Tetrode	Heater	7V Sm. Oct. 7 Pin	0.9				Pen. Amplifier	250	250	14V	72	135	22500	6000	Scr. G. Current 5MA		
								Pen. Amp. (Fixed Bias)	375	125	9	34				4.2	14000	
								Pen. Amp. (Self Bias)	375	125	9	34				4.0	14000	
								Fixed Bias	375	250	17.5	57				11.5	4000	
								2 tubes Class AB (Fix. Bias)	400	300	20.0	88 to 100				40	6600	
								(Fix. Bias)	400	300	25.0	102 to 230				60	3800	
6L7	Heptode	Heater	7T Octal 7 Pin	0.30	[illegible]	[illegible]	20	Mixer	250	150	G1 6 G3 15	3.3	I_{sc} = 0.3	2.0M Ω	350	Conversion Conductance		G1 45
								Amplifier	250	100	G1 G3 3	5.3	650	0.6M Ω	1100			G1 22 G3 12
6Q7	Duplex Diode Triode	Heater	7V Octal 7 Pin	0.30	1.2	6	6.5	Diode Detector	100		1.5	0.35	70	0.058M Ω	900			
								Triode Amplifier	250		3	1.1	70	0.058M Ω	1200		0.25M Ω	
6R7	Duplex Diode Triode	Heater	7V Octal 7 Pin	0.30	2.0	6	4.6	Diode Detector Triode Amplifier	250		9	9.5	16	8500	1900	0.30	10000	
25A6	Pentode	Heater	7S Octal 7 Pin	0.3a.				Amplifier	95	95	15	20	90	45000	2000	0.9	4000	
				25.0V.					180	135	20	38	100	40000	2500	2.75	5000	

RECTIFIER TUBES

Type and Description					Fil. Amps.	Fil. Volts	Max. A.C. Volts Per Anode	Max. D.C. Out. Curr. (Amps.)	Max. Peak Inverse Volts	Max. Peak Plate Current	Min. Choke Before Filter Cond.	Max. Heater Cathode Bias	Max. D.C. Volts Del. to Filter (Nom.) Cond. Input	Choke Input
BA	Full Wave	Gas	Cold	4J M. 4 P.			350	0.350	1000	1.00				300
BH	Full Wave	Gas	Cold	4J M. 4 P.			350	0.125	1000	0.40				300
BR	Half Wave	Gas	Cold	4H M. 4 P.			300	0.050	850	0.30			300	
1V	Half Wave	High Vacuum	Heater	4G Sm. 4 Pin	0.3	6.3	350	0.050	1000	0.30		300	400	
80	Full Wave	High Vacuum	Fil.	4C Med. 4 Pin	2.0	5.0	350	0.125	1000	0.40			300	225
							400	0.110	1100	0.35			370	275
							550	0.135	1500	0.30	20 Henries			405
81	Half Wave	High Vacuum	Fil.	4B Med. 4 Pin	1.25	7.5	700	0.085	2000	0.40 Full Wave			700	500
82	Full Wave	Mercury Vapor	Fil.	4C Med. 4 Pin	3.0	2.5	500	0.125	1400	0.40			500	485
83	Full Wave	Mercury Vapor	Fil.	4C Med. 4 Pin	3.0	2.5	500	0.250	1400	0.80			500	400
83V	Full Wave	High Vacuum	Heater	4L Med. 4 Pin	2.0	5.0	400	0.200	1400	0.60			510	395
0Z3	Full Wave	Gas	Cold	5N Sm. 5 Pin			300	0.075 Max. 0.030 Min.	1200	0.20			405	300
0Z4	Full Wave	Gas	Cold	4R Octal 4 Pin			300	0.075 Max. 0.030 Min.	1200	0.20			405	300
5Y3	Full Wave	High Vacuum	Fil.	5L Octal Med. Shell 5 Pin	2.0	5.0	Same as Type 80							
5Z3	Full Wave	High Vacuum	Fil.	4C Med. 4 Pin	3.0	5.0	500	0.250	1400	0.75			400	350
6Z4 / 84	Full Wave	High Vacuum	Heater	5D Sm. 5 Pin	0.5	6.3	350	0.060	1000	0.20		500	405	400
12Z3	Half Wave	High Vacuum	Heater	4G Sm. 4 Pin	0.3	12.6	250	0.060	700	0.30		350	310	
25Z5	Rectifier Doubler	High Vacuum	Heater Heater	6E Sm. 6 Pin	0.3	25.0	125	0.100	700	0.60	Rectifier	300	130	
								0.100	700	0.30	Doubler	350	300	

METAL RECTIFIER TUBES

Type and Description					Fil. Amps.	Fil. Volts	Max. A.C. Volts Per Anode	Max. D.C. Out. Curr. (Amps.)	Max. Peak Inverse Volts	Max. Peak Plate Current	Min. Choke Before Filter Cond.	Max. Heater Cathode Bias	Cond. Input	Choke Input
5W4	Full Wave	High Vacuum	Fil.	5T Sm. Oct. 5 Pin	1.5	5.0	350	0.110					370	
5Z4	Full Wave	High Vacuum	Heater	5L Octal 5 Pin	2.0	5.0	400	0.125	1100	0.30			405	375
6X5	Full Wave	High Vacuum	Heater	6S Octal 6 Pin	0.6	6.3	350	0.075	1250	0.25		500	400	
25Z6	Rectifier Doubler	High Vacuum	Heater	7Q Octal 7 Pin	0.3	25.0	125	0.170	700	0.35	Rectifier	350	115	
								0.085	700	0.17	Doubler		250	

SPECIAL TUBES

Type No.	Filament Volts	Filament Amps.	Basing View	Basing Shield Conn. to	Characteristics Use and Dimensions
2S/4S	2.5	1.25	5D	Cathode Pin	Approximately 40 Ma. on each Diode Plate at 60 volts D.C.; Duplex Diode Detector.
24S	2.5	1.75	5E	Cathode Pin	Same as 24A
27S	2.5	1.75	5K	Cathode Pin	Same as 27
35/51S	2.5	1.75	5E	Cathode Pin	Same as 35
55S	2.5	1.0	6G	Cathode Pin	Same as 55
56S	2.5	1.0	5A	Cathode Pin	Same as 56
57S	2.5	1.0	6F	Cathode Pin	Same as 57
57AS	6.3	0.4	6F	Cathode Pin	Same as 6C6 except Heater Amps.
58S	2.5	1.0	6F	Cathode Pin	Same as 58
58AS	6.3	0.4	6F	Cathode Pin	Same as 6D6 except Heater Amps.
75S	6.3	0.3	6G	Cathode Pin	Same as 75
85AS	6.3	0.3	6G	Heater pin Adjacent to Cathode Pin	Similar to 85 except Amp. Factor =20, Mutual Cond. =1800; Plate Curr. = 3.5 Ma.; Plate Volts =250 V; Grid Bias = −9V.
182B	5.0	1.25	4D	No Shield	Similar to 45 except Fil. Volts, Amp. Fact. =5.0; Mutual Cond. =1500; Plate Curr. =18 Ma., Pl. Volts =250V; Gr. Bias = −35V.
183	5.0	1.25	4D	No Shield	Similar to 45 except Fil. Volts; Amp. Fact. =3.2 Mut. Cond. =1800; Pl. Curr. =25 Ma.; Pl. Volts =250V; Gr. Bias = −60V.
485	3.0	1.25	5A	No Shield	Similar to 27 except Heater Volts; Amp. Fact. =12.5; Mut. Cond. =1250; Pl. Curr. =6.0 Ma.; Pl. Volts =180V; Gr. Bias = −10V.
950	2.0	0.12	5K	No Shield	Similar to 33 except Fil. Amps; Pl. Curr. =7 Ma.; Power Output =0.45 Watts; Pl. & Scr. volts =135V; Max. Cont. Gr. Bias = −16.5V.
2A7S	2.5	1.0	7C	Cathode Pin	Same as 2A7
2Z2 / G84	2.5	1.5	4B	No Shield	Similar to 1V
6A7S	6.3	0.3	7C	Cathode Pin	Same as 6A7
6B7S	6.3	0.3	7D	Cathode Pin	Same as 6B7
6C7	6.3	0.3	7G	Separate Pin	Same as 85A-S
6D7	6.3	0.3	7H	Separate Pin	Same as 6C6
6E7	6.3	0.3	7H	Same as 6D6	Same as 6D6
6F7S	6.3	0.3	7E	Cathode Pin	Same as 6F7
6Y5	6.3	0.8	6J	Separate Pin	Similar to 6Z4/84
6Z5	12.6 / 6.3	0.4 / 0.8	6K	No Shield	Similar to 6Z4/84

COMPARISON CHART—Similar Characteristics

Octal Base Glass	Metal Glass	Metal	Glass
5Y3	5Z4MG		80
6A8G	6A8MG	6A8	6A7
6C5G	6C5MG	6C5	
6F5G	6F5MG	6F5	75 Triode
6F6G	6F6MG	6F6	42
6H6G	6H6MG	6H6	
6J7G	6J7MG	6J7	77
6K7G	6K7MG	6K7	78
6L7G	6L7MG	6L7	
6N7G	6N7MG		6A6
	6N6MG		6B5
6Q7G	6Q7MG	6Q7	
6R7G	6R7MG	6R7	
6X5G	6X5MG	6X5	
6B6	6B6		75
6P7	6P7		6F7
25A6G	25A6MG	25A6	43
25B6G	25B6MG	25B6	25B5

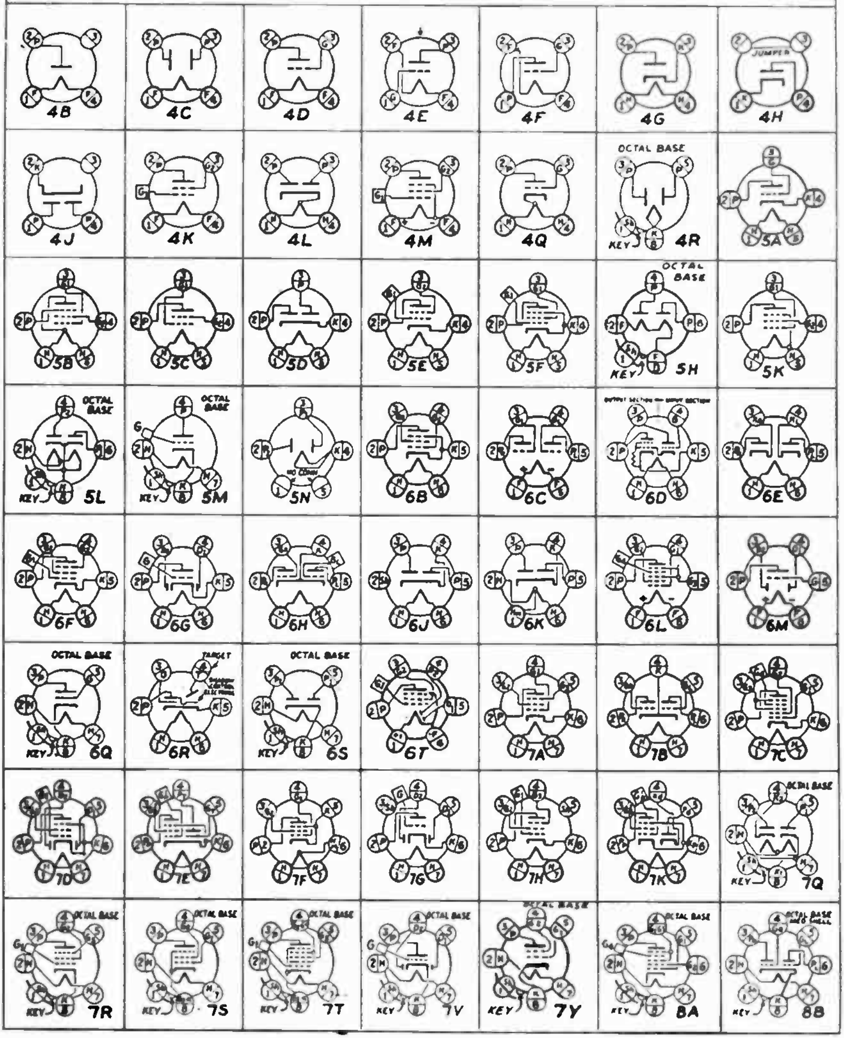
BASE CONNECTIONS—Octal Base 2-Volt Glass Tubes

Octal Base "G" Types	Equiv. Types	1	2	3	4	5	6	7	8	Top Cap
1C7G	1C6	NC	+F	P	G_3G_5	G_2	G_1	−F	NC	G_4
1D5G	1A4	NC	+F	P	G_2	NC	—	−F	NC	G_1
1D7G	1A6	NC	+F	P	G_3G_5	G_2	G_1	−F	NC	G_4
1E5G	1B4	NC	+F	P	G_2	NC	—	−F	NC	G_1
1F5G	1F4	NC	+F	P	G_2	G_1	—	−F	NC	—
1H4G	30	NC	+F	P	NC	G_1	—	−F	NC	—
1H6G	1B5/25S	NC	+F	P	D(+)	D(−)	G	−F	NC	—
1J6G	19	NC	+F	P_2	G_1	G_2	P_1	−F	NC	—

TABLE OF COMPARATIVE TYPES

Octal Base Glass	Metal Glass	Metal	Glass
5V4			83V
6L6G		6L6	
1C7G			1C6
1D5G			1A4
1D7G			1A6
1E5G			1B4
1F5G			1F4
1H4G			30
1H6G			1B5/25S
[illegible]			19

SOCKET CONNECTIONS—BOTTOM VIEW



See pages 29 and 42 for additional Socket Connections

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SUPPLEMENTARY TUBE CHART

See Complete Chart on Page 90

Type No.	Description: Type	Description: Cathode	Base Socket Conn. Chart on page 12	Fil. Current Amps.	Capacitances Micro-Microfarads: Grid-Plate	Input	Output	Operating Conditions and Characteristics: When Used As	Plate Supply Volts	Screen Grid Volts	Grid Bias Volts (Neg.)	Plate Cur. Ma.	Screen Cur. Ma.	Ampl. Factor	Plate Resist. Ohms	Mut. Cond. µMhos	Max. Undist. Power Output Watts	Recomm. Load Resist. Ohms	Cut-Off Bias Volts
2.0 VOLT D.C. DETECTOR AND AMPLIFIER TUBES																			
1C7G	Heptode	Fil.	2A Octal 8 Pin	0.120	0.3	6	6	Oscillator Section	180		0.5 Meg.	3.3						Rg = 0.05 Meg.	
						10	9	Mixer Section	135	67.5	3.0	1.3	2		0.55 Meg.	300	Conversion		
									180	67.5	3.0	1.5	2		0.75 Meg.	325	Conductance		
1D5G	Tetrode Var. Mu.	Fil.	6B Octal 7 Pin	0.060	0.007 Max.	4.8	11.5	Amplifier	180	67.5	3.0	2.3	0.8	705	1.05 Meg.	750			20
1D7G	Heptode	Fil.	2A Octal 8 Pin	0.060	2.8	5	6	Oscillator Section	135		0.5 Meg.	2.3							
					0.25	10.5	9	Mixer Section	135	67.5	3.0	1.3	2.3		0.4 Meg.	275	Conversion		
									180	67.5	3.0	1.3	2.4		0.5 Meg.	300	Conductance		
1E5G	Tetrode	Fil.	6B Octal 7 Pin	0.060	0.007 Max.	4.8	11	Plate Detector	180	67.5	3.0								
								Amplifier	180	67.5	3.0	1.7	0.4	780	1.5 Meg.	650			8
1E7G	Dbl. Pent.	Fil.	8C Octal 8 Pin	0.240				Amp. Push-Pull Both Sections	135	135	7.5	6.5	2.0				0.65	24000	
								Amp. Each Section	135	135	4.5	7.5	2.1	380	.35 Meg.	1600			
1F5G	Pentode	Fil.	6D Octal 7 Pin	0.120				Amplifier (Cl. A Pentode)	135	135	4.5	8.0	2.4	340	.2 Meg.	1700	.34	16000	
1F7G	Duo Diode Pentode	Fil.	8E Octal 8 Pin	0.060	0.007	4	9	R. F. Amplifier	180	67.5	1.5	2.0	0.5	650	1 Meg.	650			12
								A. F. Amplifier (Resis. Coupled)	135	135	2.0	0.65	0.24	62	Gain		22.2 V.	.25 Meg. Pl. Res.	
										Supply	0.8 Meg. Screen Resistor						Peak	0.5 Meg. Grid. Res.	
1H4G	Triode	Fil.	6Q Octal 7 Pin	0.060				Amplifier	135		9.0	2.0		9.3	10000	900			
									180		13.5	3.1		9.3	10000	900			
1H6G	Duo Diode Triode	Fil.	8G Octal 8 Pin	0.060	2.6	2	3	Triode Amplifier	135		0.0	0.8		20	35000	575			
1J6G	Twin Triode	Fil.	8M Octal 8 Pin	0.240				Amplifier Cl. B (Both Sections)	135		0.0	1.0	Static Plate Current for Two tubes. Max. peak plate current per plate, 50 Ma.				1.6	10000	
									135		3.0	4.0					1.9	10000	
									135		6	10.0					2.1	10000	
6.3 VOLT A.C. OR D.C. DETECTOR AND AMPLIFIER TUBES																			
6B8G	Duo Diode Pentode	Heater	8E Octal 8 Pin	0.300	0.007	3.3	9.5	R. F. or I. F. Ampl. and Detector	250	125	3.0	10.0	2.3	800	0.6 Meg.	1325			22
6L7G	Heptode	Heater	8T Octal 8 Pin	0.300	1.0	6.0	3.5	Oscillator Section	125		0.05 Meg.	Grid Leak							
									150 Thru 20000 Ohms		0.05 Meg.								
					0.3	8.0	11.0	Mixer Section	125	67.5	0.0	6.0	Total Cathode		0.4	325	Conversion		25
									250	100	3.0	12.0	Current		0.25 Meg.	300	Conductance		33.5
6C5G	Triode	Heater	6Q Octal 7 Pin	0.300	2.4	3.0	3.3	Amplifier	250		8.0	8.0		20	7700	2600			
[illegible]	Triode	Heater	8E Octal 7 Pin	0.300	2.0	2.4	2.4	Amplifier	250		2.0	1.1		70	0.05 Meg.	1600			

Type No.	DESCRIPTION Type	Cathode	Basing See Socket Conn. Chart on page 42	Fil. Current Amps.	CAPACITANCES Micro-Microfarads Grid-Plate	Input	Output	OPERATING CONDITIONS AND CHARACTERISTICS When Used As	Plate Supply Volts	Screen Grid Volts	Grid Bias Volts (Neg.)	Plate Curr. Ma.	Screen Curr. Ma.	Ampl. Factor	Plate Resist. Ohms	Mut. Cond. µMhos	Max. Undist. Power Output Watts	Recomm. Load Resist. Ohms	Cut-Off Bias Volts
6.3 VOLT A.C. OR D.C. DETECTOR AND AMPLIFIER TUBES (*continued*)																			
6L5G	Triode	Heater	8K Octal 6 Pin	0.150	2.7	3.0	5.0	Amplifier	135		5.0	3.5		17	11300	1500			11
									250		9.0	8.0		17	9000	1900			20
6N5	Cath. Ray	Heater	6A Sm. 6 Pin	0.150				Tuning Indicator	Plate Supply 135 Volts Thru 0.25 Meg. Target 135 Volts Ib = 0.5Ma. & Shadow 90° For Ec = 0. Shadow 0° for Ec = −12 V.										
6P7	Triode Pentode	Heater	8L Octal 8 Pin	0.300				Triode	100		3.0	3.5		8	10000	450			
								Pentode	250	100	3.0	6.5	1.5	900	.85 Meg.	1100			50
6Q6G	Sing. Diode Triode	Heater	8M Octal 6 Pin	0.150	1.0	2.5	5.2	Amplifier	135		1.5	0.9		65	.65 Meg.	1000			
									250		3.0	1.2		65	.62 Meg.	1050			
6S7G	Var. Mu. Pentode	Heater	8N Octal 7 Pin	0.150	.007 Max.	4.6	7.8	R.F. or I.F. Ampl.	135	67.5	3.0	3.7	0.9	850	.60 Meg.	1250			25
									250	100	3.0	8.5	2.0	1100	.63 Meg.	1750			38.5
954	Acorn Pentode	Heater	Special	0.150	0.007	3.0	3.0	R.F. or I.F. Ampl.	90	90	3.0	1.2	0.5	1100	1 Meg.	1100			
									250	100	3.0	2.0	0.7	2000	1.5 Meg.	1400			
								Detector	250	100	6.0							0.25 Meg.	
955	Acorn Triode	Heater	Special	0.160	1.4	1.0	0.6	Cl. A Amplifier R.F. or A.F.	90		2.5	2.5		25	14700	1700			
									135		3.75	3.5		25	13200	1900			
									180		5.0	4.5		25	12500	2000	.135	20000	
								Cl. C R.F. Power Amplifier or Osc.	180		35.0	7.0					0.5		
1603	Low Microphonic Pentode	Heater	6B Sm. 6 Pin	0.300	0.010	5.5	7.0	Pent. Ampl. Cl. A	100	100	3.0	2.0	0.5	1185	1 Meg.	1185			
									250	100	3.0	2.0	0.5	1500	1.5 Meg.	1225			
					2.0	3.0	11.5	Triode Conn.	180		5.3	5.3		20	11000	1800			
								Cl. A Amplifier	250		8.0	6.5		20	10500	1900			
2.5 VOLT A.C. OR D.C. POWER AMPLIFIER TUBES																			
2B6	Dual Triode	Heater	7A Med. 7 Pin	2.25				Input Section	250		24	4		7.2		600		8000	
								Output Section	250		+2.5	40		18		3500	4.0	5000	
6.3 VOLT A.C. OR D.C. POWER AMPLIFIER TUBES																			
6B4G	Triode	Fil.	8O Octal 8 Pin	1.0	16	7	5	Sing. Cl. A Ampl.	250		45	60		4.2	800	5250	3.2	2500	
								Push-Pull Class A Fixed Bias	325		68	40 Per Tube					15 Two Tubes	3000 P to P	
								Push-Pull Class A Self Bias	325	Bias Resist. 750 Ohms		40 Per Tube					10 Two Tubes	5000 P to P	
6D6	Triode	Heater	8P Octal 6 Pin	0.7				Single Cl. A	275		60	31		4.7	2250	2100	1.4	7200	
								Push-Pull Cl. AB	300		50	23 Per Tube					5	5300 P to P	
6K6G	Pentode	Heater	8Q Octal 7 Pin	0.4				Amplifier	100	100	13.5	10.5	2.0	150	81000	1850	1.5	9000	
									250	250	18.0	32	5.5	150	68000	2200	3.4	7600	

6.3 VOLT A.C. OR D.C. POWER AMPLIFIER TUBES (continued)

6N6G	Dual Triode	Heater	[illegible] Octal 7 Pin	6.3				Single Tube	Eb. 300		0	Output [illegible]	Input [illegible]	[illegible]	[illegible]	[illegible]	4.0	7000	
									Eb. 300		0	Output [illegible]	Input 9.0	35	24500	2400	5.2	7000	
								Push-Pull	Eb. 300		0	46	0				10.0	10000	
									Eb. 300		0	58	9.0				13.5	10000	
6N7	Twin Triode	Heater	[illegible] Octal 8 Pin	6.3				Cl. A Parallel Connection	300		6	6		35	11300	3100		20000 to	
									294		6	7		35	11000	3200		40000	
								Complete Cl. B Both Sections	300		0	14 Per Plate					8.0	8000 P to P	
									300		0	17.5 Per Plate					10.0	10000 P to P	

7.5 VOLT A.C. OR D.C. POWER AMPLIFIER TUBES

[illegible]	Low Mu Triode	Fil.	Med. 4 Pin Bayonet	1.25	7	4	3	Cl. A Amplifier	350		32	16		8	5150	1600	0.9	11000	[illegible] Ohms
									425		40	18		8	5000	1600	1.6	10000	2100 Ohms

Formerly Designated as [illegible]

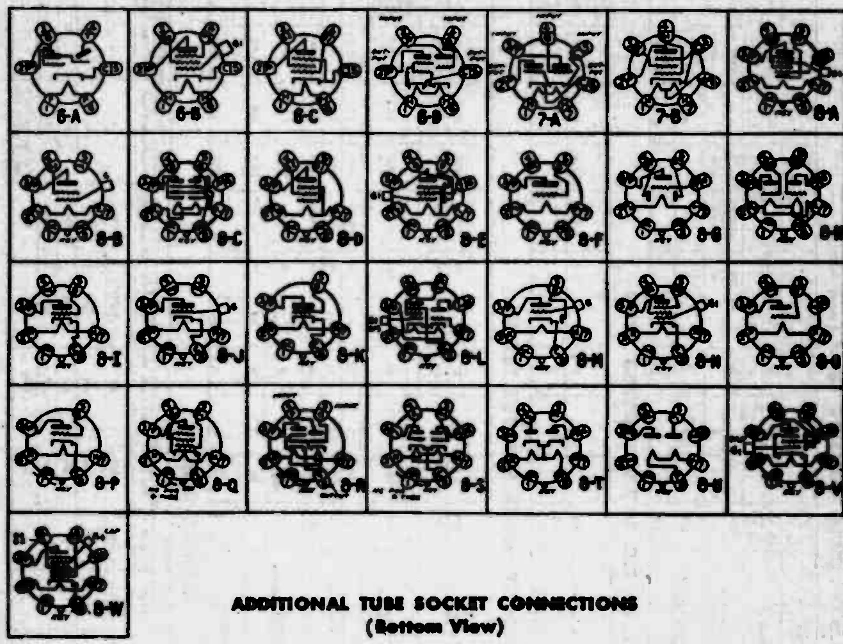
SERIES FILAMENT POWER AMPLIFIER TUBES

12A5	Pentode	Heater	[illegible] Sm. 7 Pin	[illegible] 12.6V. or 0.6a. 6.3V.				Amplifier Cl. A Pentode	100	100	15	17	3	70	50000	1900	0.85	4500	
									180	180	27	36	6	60	35000	2200	3.5	3300	
25	Pentode	Heater	6C Sm. 6 Pin	0.3a. 25V.				Amplifier Cl. A Pentode	250	250	16.5	36	7.5	105	75000	2500	3.0	7000	[illegible]
25A6G	Pentode	Heater	[illegible] Octal 7 Pin	0.3a. 25V.				Amplifier Cl. A Pentode	95	95	15	20	4	90	45000	2000	0.9	4500	
									135	135	20	37	2.5	90	45000	2000	2.0	4000	
									160	120	20	60	8	56	50000	2400	2.75	5000	
[illegible]	Dual Triode	Heater	[illegible] Med. 6 Pin [illegible] Oct. 7 Pin	0.3a. 25V.				Dynamic Coupled Amplifier	110	Input 110 Plate	0	45	Input 7 Plate	35	11400	2500	2.0	2000	
									180	180	0	46	5.8	35	10500	2000	3.8	4000	
[illegible]	Pentode	Heater	[illegible] Octal 7 Pin	0.3a. 25V.				Amplifier Cl. A Pentode	95	95	[illegible]	[illegible]	[illegible]			[illegible]	1.75	[illegible]	

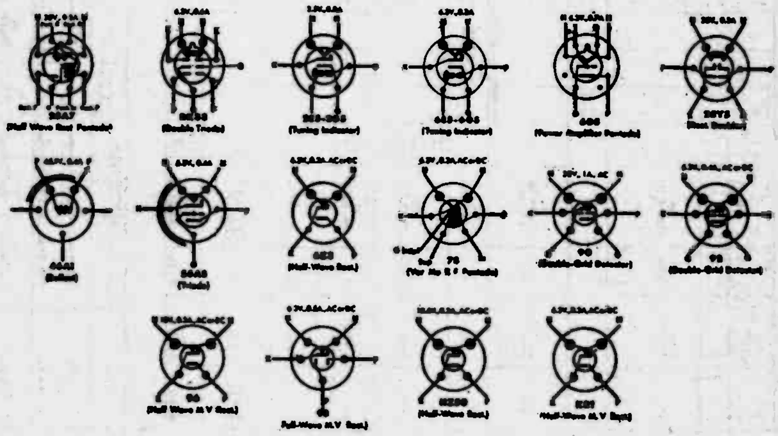
RECTIFIER TUBES

Type	Description		Cathode	Base	Fil. Amps.	Fil. Volts	Max. A.C. Volts Per Anode	Max. D.C. Output Curr. Ma.	Max. Peak Inverse Volts	Max. Peak Pl. Curr. Ma.	Max. Volts Delivered to Filter (Ohms): Condenser Input	Choke Input
5V4G	Full Wave	High Vacuum	Heater	[illegible] Octal 5 Pin	2.0	5.0	400	200	1100	700		
5X4G	Full Wave	High Vacuum	Fil.	[illegible] Octal 5 Pin	3.0	5.0	500	250	1400	780	400	340
5Y4G	Full Wave	High Vacuum	Fil.	[illegible] Octal 5 Pin	2.0	5.0	350	125	1000	400	300	235
							400	110	1100	350	370	375
							500	125	1550	500	For Choke Input [illegible]	425

SUPPLEMENTARY SOCKET CONNECTIONS BOTTOM VIEW



ADDITIONAL TUBE SOCKET CONNECTIONS
(Bottom View)



TYPE NUMBER	DESCRIPTION		FIL. CUR. AMPS.	CAPACITANCES MMFDS.			OPERATING CONDITIONS AND CHARACTERISTICS										
	TYPE	CATHODE		GRID PLATE	INPUT	OUT PUT	WHEN USED AS	PLATE SUPPLY VOLTS	SCREEN GRID VOLTS	GRID BIAS VOLTS	PLATE CURRENT MA.	AMPL. FACTOR	PLATE RESIS. OHMS	MUT. COND. µ MHOS.	MAX. UNDIST. OUTPUT	RECOMM. LOAD RESIS.	CUT OFF BIAS

This page is to be used by the student to record the characteristics of newer tubes not listed on the preceding pages. It is advisable to enter those most frequently encountered in your own work.

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UNIT NO. 1

METHODS OF VOLUME AND TONE CONTROL

LESSON NO. 26

DOLLARS, CENTS, AND LIFE

.......SUCCESS IS NOT MEASURED IN DOLLARS ALONE.

You have set out in the earnest quest of knowledge and practical experience which will enable you to earn a substantial living. You have recognized the necessity of preparing yourself for the kind of work which you will enjoy. That is one of the reasons why you have cast your lot with the Radio industry.

Naturally, you want to make money, for without it, you cannot hope to care for your loved ones. But there are several very important factors of which you must not lose sight in your quest for success.....factors which are equally as important as dollars and cents.

As you progress through life and rub shoulders with a world of realities, you will appreciate more and more the true value of unselfishness, consideration for others, conscientious service, and above all, honesty.

You must learn to consider the problems of your fellow men, just as you expect them to consider yours. You must be considerate of them just as you want them to be considerate of you. Tolerance, a winning smile, and a cheery disposition will bring you many true friends. And without friends, life at its best will be drab and monotonous. You expect your employer to be conscientious in his attitude toward you. Therefore, you must render conscientious service in return for the pay checks you receive. You expect those with whom you have business dealings to be fair and honest with you. So it is only proper that you, too, be fair and honest with others. In other words, never expect more than you give.

It's nice to have people say good things about you. It's comforting to know that your employer has complete confidence in you. So in your quest of money and success, take care to win the kind of success that will include every factor we have mentioned above!

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Lesson Twenty-Six

METHODS of VOLUME and TONE CONTROL

"Haven't you often wondered why various musical instruments sound differently? There is a very interesting reason for this and I am going to tell you of it in the first part of this lesson. I also point out the relation between musical notes and electric currents in an A.F. amplifier.

"A treatise on volume and tone controls constitutes the latter portion of this lesson. You all know of their importance in the design of a radio receiver and I'm sure you will be much concerned regarding their construction and theory of operation."

1. **SOUND.** Sound is the production of waves in an elastic medium caused by a vibrating body. By the term "elastic" is meant a substance which will contract when a pressure is applied to it and will expand when the pressure is released. The most familiar elastic substance, and the material in which most sound waves are created, is air. The vibrating body may be a pair of vocal cords used in speaking; a string used in the piano harp and violin; a reed used in the clarinet, French horn, trumpet, etc.; a column of air used in the flute, piccolo and pipe organ; or the cone of a loudspeaker used to reproduce a radio program.

The actual production of sound waves by a vibrating body is illustrated in Fig. 1. At the top of the figure is shown a loudspeaker cone at rest. The small black dots represent a number of air molecules surrounding the cone. At B, the cone has moved to the left and in so doing has pushed molecule 1 ahead of it toward 2; then 2 in turn pushes 3, and 3 pushes 4. The molecules in front of the cone are closer together than they were before the cone started moving and therefore the air immediately in front of the cone has been compressed. At the same time, molecules 5, 6, 7, and 8 have rushed in to fill the space left behind the cone when it moved forward. Since these molecules are farther apart than before, the air behind the cone has expanded or become less compressed than normal. They constitute what is known as rarefaction.

If the cone were left in this position, the compression wave formed in front would travel outward at the velocity of sound (1130 feet per second at 68° F.). Each molecule would move forward, strike the one in front of it and, having transferred its energy, would then stop. Likewise, the rarefaction wave formed at the rear of the cone would move to the right at the velocity of sound. Each molecule would move to the left to close up the space between it

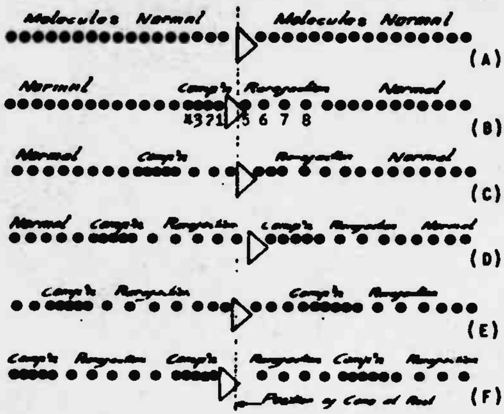


Fig.1 Illustrating the production of sound waves by the vibration of a loud speaker cone.

SOUND WAVES PRODUCED BY VIBRATING CONE

and its neighbor. Those molecules some distance away from the cone have not, as yet, moved; but as the compression and rarefaction waves expand outward from the cone, they also will be influenced. Although the waves travel relatively great distances, the molecules themselves move through very short paths.

The cone now moves back to its position of rest, and in its movement compresses the air molecules in back of it, and decompresses those in front. This is shown at C in the figure. Thus a compression wave is formed at its right and a rarefaction wave at its left. In moving back it does not stop at its rest position, but continues to travel to the right until it reaches the point shown at D in the figure. By this time the compression and rarefaction waves have reached their maximum; that is, the molecules to the right are as close together, and those at the left as far apart as they will become. From its maximum position to the right, the cone moves back to its rest position and then continues its to and fro motion, producing compression and rarefaction waves which travel onward until they reach our eardrums. Upon striking the eardrum, the compression waves cause it to move inward, while the rarefaction waves produce an outward motion. If the eardrum is caused to vibrate at a rate of at least 16 times a second, the brain perceives the disturbance as sound. The same principle is involved whether the vibrating body is a string of a violin or the lips of a whistler.

2. LOUDNESS. Whether a sound is perceived as loud or soft depends upon the amplitudes of vibration of the body creating the waves. If the cone in the preceding example moves only a short

distance from its rest position, the actual air pressure of the compression waves is not much greater than normal atmospheric pressure, while the pressure of the rarefaction waves is not much less than normal. Consequently, the eardrums do not vibrate through very large paths, and the sound is perceived as soft by the brain. If, on the other hand, the cone vibrates through relatively large amplitudes, the compression waves have a greater pressure and the rarefaction waves a lesser pressure. The eardrums vibrate through longer distances, and the sound appears loud.

The actual pressure of any compression wave, even when the sound produced is deafening, is only very slightly greater than normal. The same is true of the rarefaction waves; they are only a little less than normal air pressure. Thus, the difference in pressure between a loud and a soft compression wave may be very great, yet the actual change relative to atmospheric pressure is very small.

The same thing applies to the distances through which the cone moves. When reproducing a very loud sound, the cone moves a distance not exceeding three-eighths to one-half of an inch, probably less; and a vibration amplitude of a few thousandths of an inch will produce an average speaker volume.

3. PITCH. In addition to loudness or intensity, there are two other distinguishing properties which a sound may possess. The second of these is its pitch. Whether a note appears high or low in pitch depends upon the frequency of vibration of the body creating it. If the frequency is low, for example 32 vibrations a second, the sound has a pitch corresponding to that produced when the lowest bass note is struck on a piano. When the vibration frequency is several thousand cycles per second, the note is similar to that created when the highest treble key is struck. Middle C is produced by a body vibrating at a rate of 256 cycles per second. The low notes on a piano are generated by the vibration of long heavy wires, while the high notes are set up by short wires very light in weight. The amount of tension on the wire also determines the pitch of the note it will produce.

The pitch of the note created by a horn is varied by changing the length of the vibrating air column; this is done by depressing stops, thus opening or closing holes at will.

4. QUALITY OR TIMBRE. The third property of a sound is its quality or timbre. It is this property which enables us to distinguish the difference between the sound of middle C played on a piano and that produced by a violin. Both notes have the same frequency and may be of equal loudness, yet it is not difficult to determine which is which. Before we can intelligently discuss this subject, we must inquire into the generation of harmonics or overtones.

When the string corresponding to middle C on the piano is struck, it vibrates 256 times a second. In addition to vibrating as a whole, it is found that each half of the string is executing separate vibrations, and that their frequency is twice as great or 512 times per second. Fig. 2 shows a string vibrating as a whole, while Fig. 3 illustrates one in which each half is vibrating. The combined effect of both is shown in Fig. 4. Each third or each fourth of the string may produce its separate vibration, and the frequencies of the sounds created are respectively three and four times the original 256 cycles.

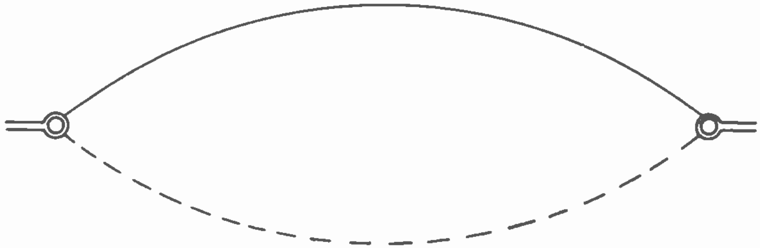


Fig. 2 A string vibrating as a whole.

Although the string is creating several frequencies, its pitch is still considered to be 256 cycles. The pitch of the sound produced by any vibrating body is determined by the lowest frequency that it will set up, or that created when it is vibrating as a whole. This frequency is called the fundamental. The other frequencies are known as harmonics or overtones. The term "harmonic" is used

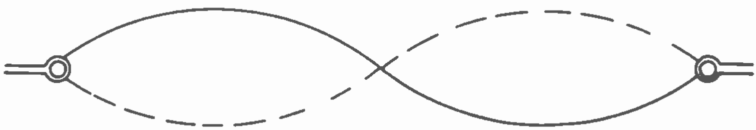


Fig. 3 A string in which each half is producing separate vibrations.

by the radio engineer, while the word "overtone" is a part of the musician's parlance.

That frequency which is twice as great as the fundamental is called the second harmonic, and those which are three and four times as great are respectively called the third and fourth harmonics. The ratio of any harmonic frequency to its fundamental is a

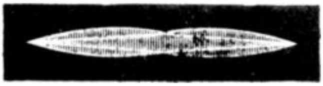


Fig. 4 A string vibrating as a whole and by halves. In this case the fundamental and second harmonic would be heard.

whole number. Thus, it is not possible for a body to vibrate at a frequency 1½ times its fundamental.

The number of harmonic frequencies which a vibrating body may have is theoretically unlimited. Actually, since the higher harmonics have smaller amplitudes, it is difficult for the ear to detect those above the fourth or fifth. That they exist, however, has been proved, for harmonics as high as the forty-second of the lower notes of the piano have been identified.

We are now ready to continue the discussion of timbre. The reason that a piano note and a violin note of the same frequency and loudness sound different to the ear is due to the fact that the number of harmonics present in each as well as their respective amplitudes with reference to that of the fundamental is different. The low notes of the piano have a large number of harmonics and the energy contained in them is greater than that possessed by the fundamental. The higher tones of the piano have few harmonics and most of the energy is contained in the second. A tuning fork has a loud fundamental and practically no harmonics. It is characterized by a peculiar tone which is rather sweet but flat and lifeless. The presence of harmonics add the richness and vibrant quality possessed by most musical instruments.

5. COMPLEX WAVE FORMS. The wave form of the tone produced by a tuning fork is sinusoidal, since it consists of just one frequency. Likewise, an alternating current of sine wave form will, when passed through a loud speaker, create a tone of one frequency. Most sounds, however, possess a series of harmonics as well as the fundamental frequency. Therefore, the voice currents corresponding to these sounds will be of several frequencies, and will not be sinusoidal. Such wave forms are known as complex waves and may assume a variety of shapes. The shape of the complex wave depends upon the ratio of the harmonics compared to that of the fundamental, the number of harmonics present, and their phase relative to the fundamental.

When the second harmonic is the only one present, is in phase with the fundamental, and has an amplitude equal to half of it, the complex wave has the form shown in Fig. 5. One cycle of the fundamental and two of the second harmonic are shown in dotted lines.

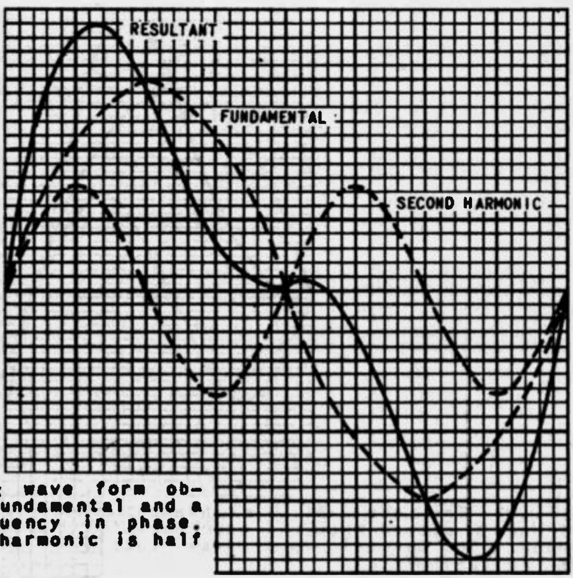


Fig.5 The complex wave form obtained by adding a fundamental and a second harmonic frequency in phase. The amplitude of the harmonic is half of the fundamental.

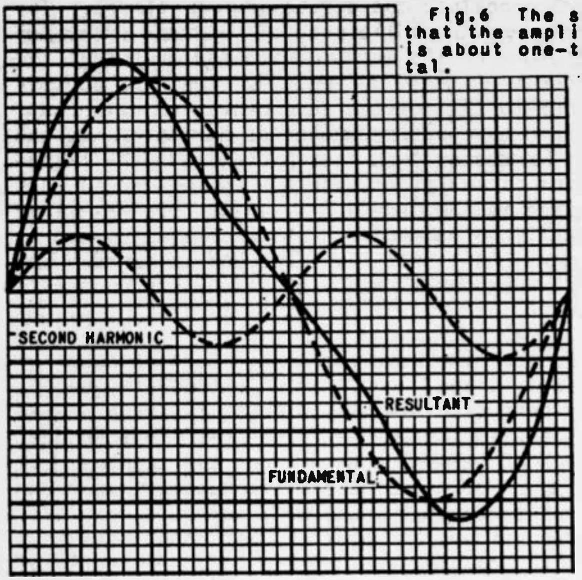


Fig.6 The same as Fig. 5 except that the amplitude of the harmonic is about one-third of the fundamental.

The combined wave form is shown as a solid line. The complex wave is obtained by adding the amplitudes of the fundamental and the harmonic at various points throughout the cycle. Suppose the frequency of the fundamental is 60 cycles and that of the harmonic, 120 cycles. The motion of the electrons producing this current is

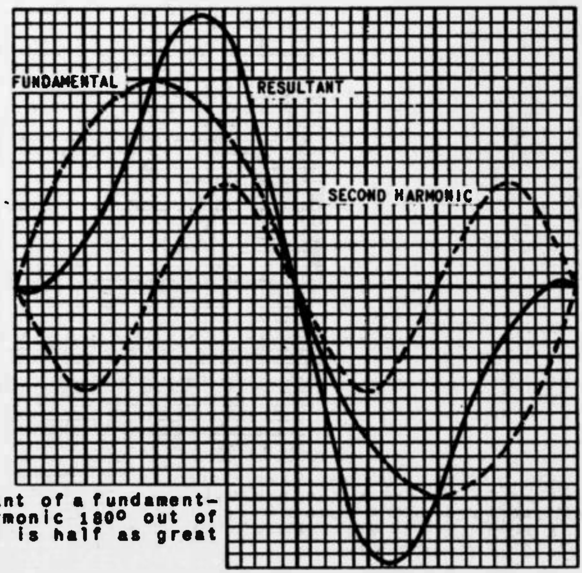


Fig.7 The resultant of a fundamental and a second harmonic 180° out of phase. The harmonic is half as great as the fundamental.

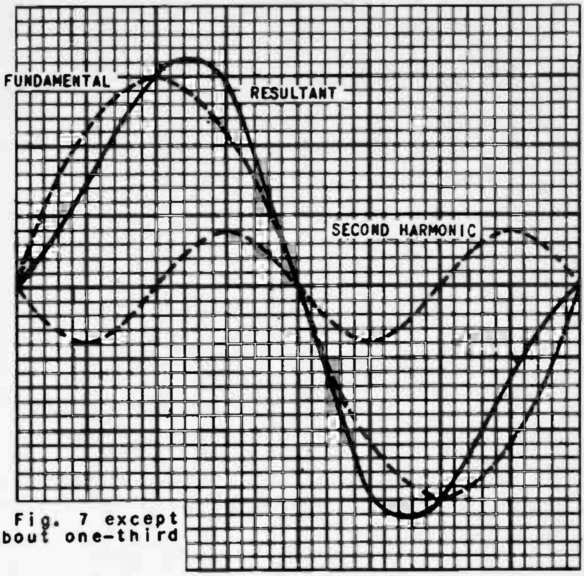


Fig.8 The same as Fig. 7 except that the harmonic is about one-third of the fundamental.

quite complex. The electrons do not oscillate at either 60 or 120 cycles. At every instant there are two voltages acting upon the electrons and their motion is the result of the combined influence of both. Thus, the complex wave is a true picture of their motion.

When the amplitude of the harmonic is reduced to about one-third

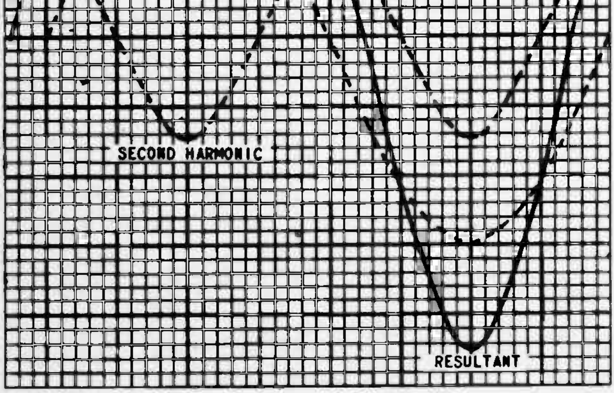


Fig.9 Wave form produced by a fundamental and a second harmonic with a phase difference of 90°. The harmonic is half of the fundamental.

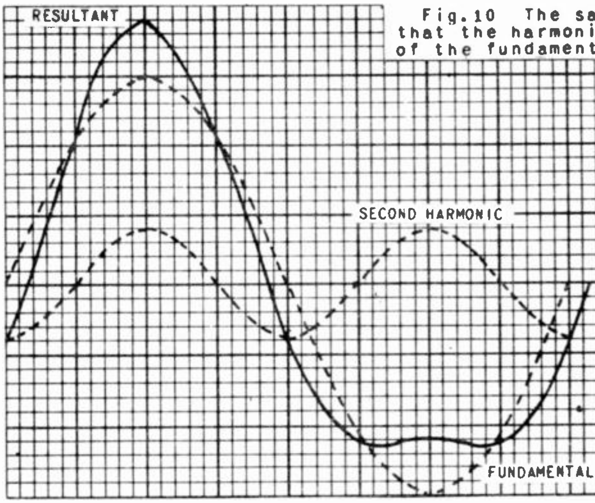


Fig.10 The same as Fig. 9 except that the harmonic is about one-third of the fundamental.

that of the fundamental, the resultant wave has the form shown in Fig. 6. If the second harmonic is 180° out of phase with the fundamental, the combined wave is of the form shown in Figs. 7 and 8. In the first case, the amplitude of the harmonic is one-half of the fundamental, and in the second, it is about one-third. A phase difference of 90° produces a wave form as shown in Figs. 9 and 10. The two cases correspond to the same amplitudes as in the previous graphs.

A third harmonic and a fundamental create the wave forms given in Figs. 11 and 12. In these figures, the harmonic is in phase with the fundamental. In Figs. 13 and 14, the harmonic is 180° out of phase with the fundamental, while a 90° difference between the two is shown in Figs. 15 and 16.

When a complex wave contains only the fundamental and odd har-

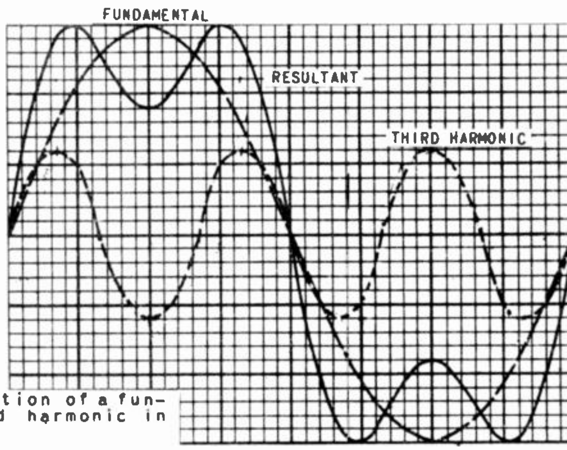


Fig.11 The combination of a fundamental and a third harmonic in phase.

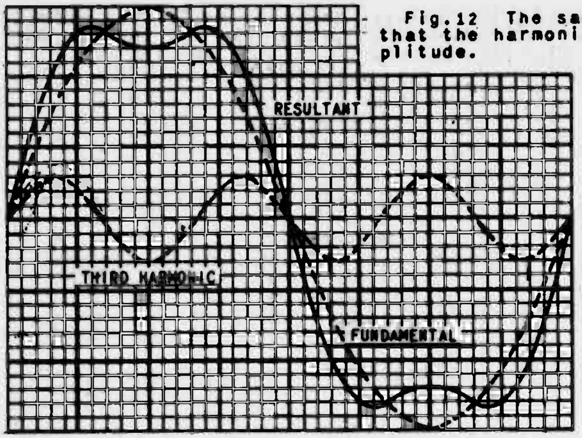


Fig.12 The same as Fig. 11 except that the harmonic has a smaller amplitude.

monics; that is, third, fifth, seventh, etc., and none of even degree, it has perfect symmetry. The negative alternation is exactly like the positive. If the negative alternation could be rotated about the zero axis until it was above the zero line, it would be an exact duplicate of the positive alternation. This is not true when the second harmonic or any even harmonic is present. From

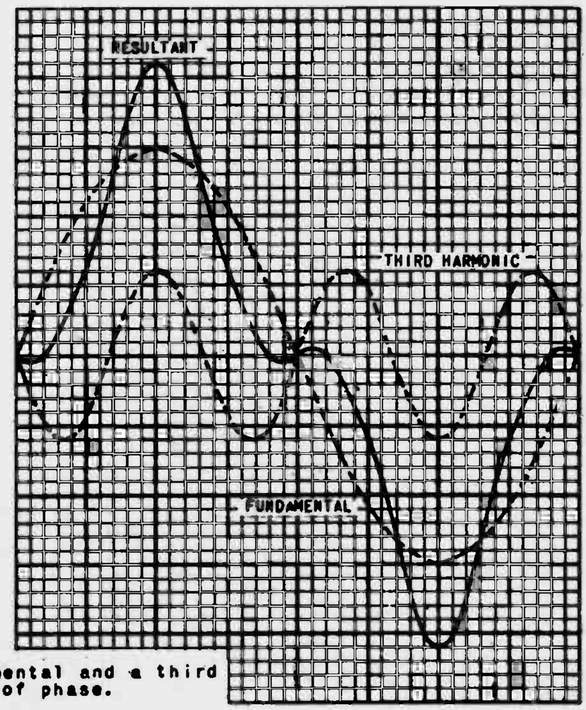


Fig.13 A fundamental and a third harmonic 180° out of phase.

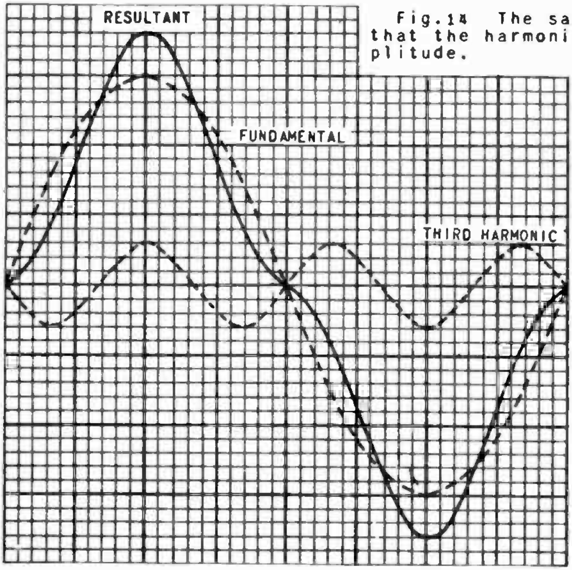


Fig.14 The same as Fig. 13 except that the harmonic has a smaller amplitude.

Figs. 5 and 6, it may be seen that the two alternations of the complex wave appear to be symmetrical even though the wave has a second harmonic; however, if the negative alternation is rotated about the zero axis, it is found that it is not an exact duplicate of the positive alternation, but is a mirror image of it. Such a wave is said to have mirror symmetry, and may be produced by a fundamental

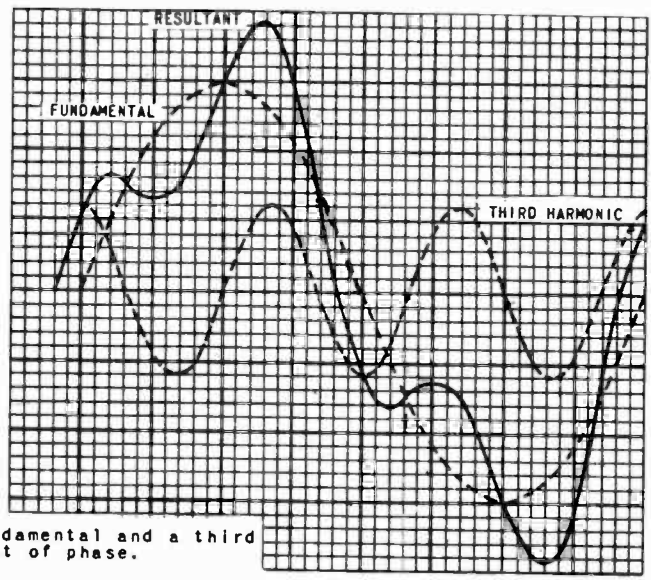


Fig.15 A fundamental and a third harmonic 900 out of phase.

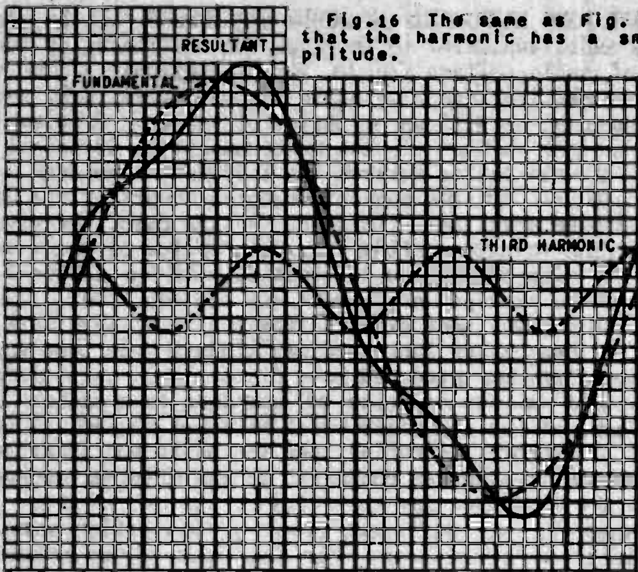


Fig.16 The same as Fig. 15 except that the harmonic has a smaller amplitude.

and an even harmonic of a particular phase. True symmetry on the other hand is only possible when the wave has no even harmonics.

The wave forms of the note middle C as played on a cello organ pipe, a trombone organ pipe, a piano, and the syllable "ah" sung at this pitch are shown in Fig. 17. Notice that all the waves are similar yet each has its individual characteristics. Each has a fundamental of 256 cycles, but the number and amplitudes of the harmonics present in each are different. It is this difference in the harmonics that makes the voice of one person distinguishable from all others. Curiously enough, the phase of the harmonics with respect to each other, or with respect to the fundamental, have no bearing upon the quality or timbre of the sound. Thus the totally different wave forms of Figs. 5, 7, and 9 would sound exactly alike to the ear.

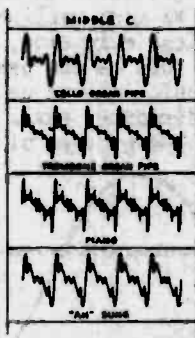


Fig.17 Wave forms of the audio tone middle C, as produced by various instruments.

6. **WAVE FORM DISTORTION IN AUDIO AMPLIFIERS.** It is the purpose of the audio amplifier to increase the amplitudes of the complex wave of audio voltage fed to its grid circuit. The signal voltages representing speech or music are of complex form, and contain a fundamental as well as a series of harmonic frequencies of greater or lesser value. If the audio amplifier is ideal, there will be no discrimination between the fundamental or any of its harmonics, and all of the many frequencies composing the complex wave will receive equal amplification. In this case, the wave form of the amplified voltages will be an exact replica of the wave form of the input voltages, and no distortion will be produced. If, however, through improper adjustment of the amplifier, the wave form of the output voltages differs from the input wave form in any respect other than having increased amplitudes, it is then apparent that the amplifier has produced some distortion. This distortion manifests itself in the creation of harmonic frequencies in the output voltages of the amplifier which were not present in the input. It is, therefore, essential that the audio amplifier amplify all the harmonic frequencies contained in the original production, but that it not introduce any harmonics of its own accord.

In Lesson 19, the different types of distortion possible in audio amplifiers were discussed. For simplicity it was assumed that the input to the audio amplifier was a pure sine wave, and whenever the wave form of the output differed from a sine wave, distortion had taken place in the amplifier. One type of distortion was caused by insufficient grid bias, thereby allowing the grid to become positive. This action caused the output wave to have the form shown in Fig. 18. When this wave is compared to that of Fig. 10, it is seen to be very similar. Fig. 10, however, was produced by adding a fundamental and a second harmonic with a phase difference of 90°. Therefore, is it not logical to assume that the output wave of the amplifier contains a second harmonic frequency? That such is the case has been definitely proved. Any wave form, no matter how complex, nor how much it differs from a sine wave, may be resolved into its component frequencies, which consist of a pure sine wave fundamental and a series of harmonics of sine wave form. Or it may be stated that changing the shape of a sine wave in any manner whatsoever produces harmonic frequencies.

We must realize that these harmonics do not have a separate physical existence, yet the fact that the distorted wave has the same form as one produced by adding a fundamental and some of its harmonics allows us to say that harmonic frequencies are present in the distorted wave.

The process of resolving a complex wave into its fundamental

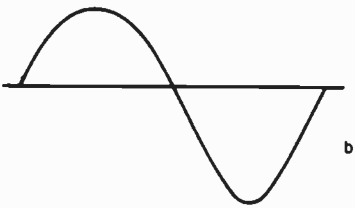


Fig. 18 Type of distortion produced by insufficient grid bias.

and harmonics is similar to that of analyzing a pulsating DC into a pure DC and an alternating current, which was explained in Lesson 14. The actual mechanics of the method, however, are much more complicated and require a knowledge of the integral calculus. It is not necessary for you to be able to do this, but you should remember that it can be done.

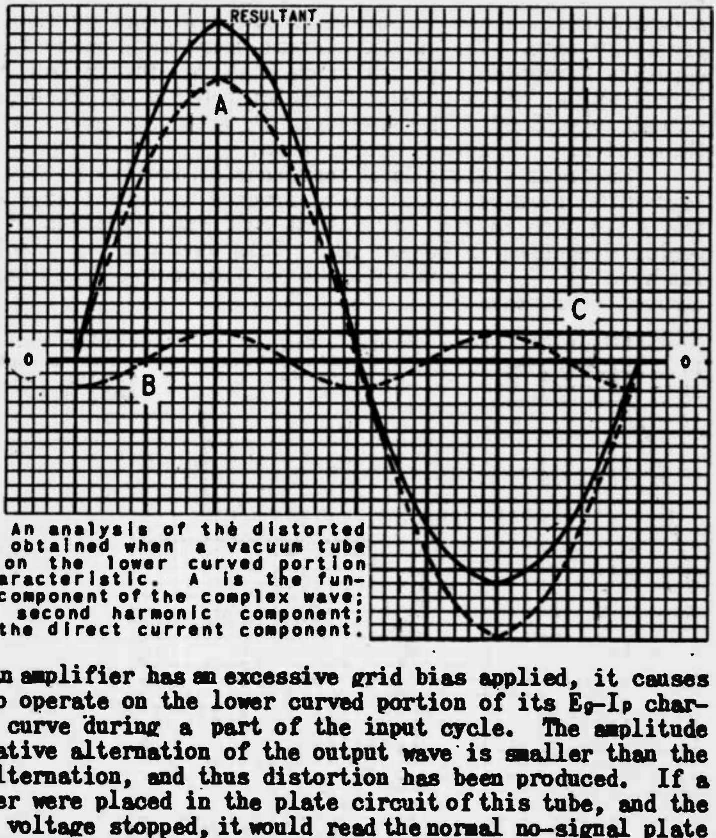


Fig.19 An analysis of the distorted wave form obtained when a vacuum tube operates on the lower curved portion of its characteristic. A is the fundamental component of the complex wave; B is the second harmonic component; and C is the direct current component.

When an amplifier has an excessive grid bias applied, it causes the tube to operate on the lower curved portion of its E_g-I_p characteristic curve during a part of the input cycle. The amplitude of the negative alternation of the output wave is smaller than the positive alternation, and thus distortion has been produced. If a milliammeter were placed in the plate circuit of this tube, and the excitation voltage stopped, it would read the normal no-signal plate current. Then when the excitation is applied, the reading of the of the meter should not change if no distortion is present. Such will be the case when the two alternations of the AC component of the plate current have the same amplitude, for then the increase in plate current above normal is equal to the decrease below normal. With excessive grid bias, however, the increase is greater than the decrease and the meter shows an increase in plate current when the signal voltage is applied.

Fig. 19 gives an analysis of this distorted wave. The output wave is shown as a solid line. Its components are a fundamental frequency, A; a second harmonic frequency, B; and a direct current, C. The direct current component, C, adds to the normal no-signal plate current and thereby increases the reading of the DC milliammeter. The second harmonic frequency is transferred along with the fundamental to the following tube, and causes the output from the loud speaker to sound fuzzy or blurred.

When the amplifier has insufficient grid bias, the positive alternation has a lower amplitude than that of the negative and the plate current meter shows a decrease below the normal no-signal value. It may be proved that the components of the output wave are a fundamental, a second harmonic, and a direct current, as in the preceding case. The direct current component, however, is in the opposite direction, and therefore must be subtracted from the no-signal value. This causes the meter reading to decrease when the signal is applied. The waveforms in this case would be the same as those of Fig. 19 turned upside down.

Sometimes a plate load impedance of too low a value will, when used with a push-pull amplifier, produce an output wave as shown by the solid line in Fig. 20. (Push-pull amplification will be thoroughly discussed in Lesson 28.) This wave may be resolved into a fundamental, A, and a third harmonic frequency, B; it has no direct current component.

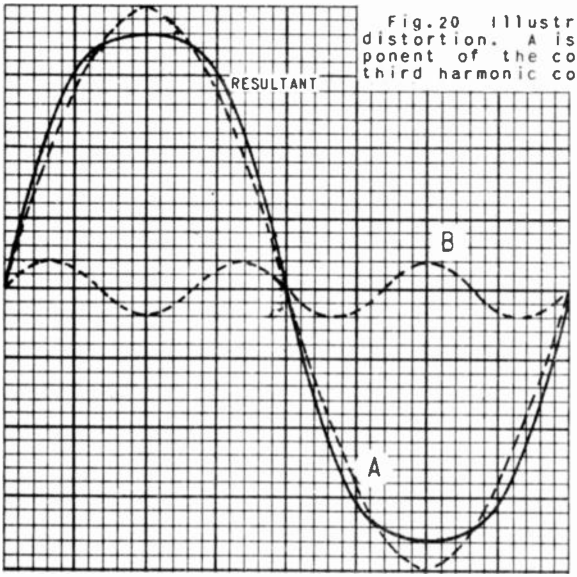


Fig. 20 Illustrating third harmonic distortion. A is the fundamental component of the complex wave; B is the third harmonic component.

From the foregoing discussion, it is easy to see why waveform distortion is often called harmonic distortion. Any change in the wave form will introduce harmonic frequencies. This type of distortion may also be caused when the no-signal plate current of a tube is large and is allowed to flow through the primary of an audio transformer. The DC plate current saturates the iron core; that is, it produces so much magnetism that the relation between the current flowing through the coil and the amount of magnetism created is no longer linear. When the plate current increases on the positive alternation, the increase in magnetism is not as great as the decrease on the negative alternation. Thus, the amount of magnetism does not exactly follow the amount of plate current, and the voltage it induces in the secondary is distorted. The waveform of the distorted voltage is practically the same as that of Fig. 18.

Now that we have a fair understanding of the nature of sound, harmonics and distortion in audio amplifiers, it is time that we discussed two other important adjuncts necessary for the convenient operation of any radio receiver. They are volume controls and tone controls.

7. **REQUIREMENTS OF A VOLUME CONTROL.** It is of prime importance to design any amplifier, either R.F. or A.F. to produce a maximum gain so that a large amount of amplification will be available when necessary. When receiving very weak signals, the total amplification will probably be used; however, most of the radio stations to which we listen possess a moderately large field strength in our vicinity, and some means must be provided to vary the amount of amplification until the volume of the sound issuing from the loudspeaker is neither too loud nor too soft.

To be satisfactory, a volume control must have the following characteristics:

1. The control of volume must be smooth; that is, there should be no sudden changes from soft to loud as the control is varied. Instead, there should be a gradual increase from no volume to maximum volume as the control is rotated from one end to the other.
2. The control should not produce any detuning effect upon the receiver. When the position of the volume control is changed, it should not be necessary to retune the receiver.
3. The fidelity of the receiver should not be affected as the control is changed from one position to another.
4. The control should be so placed that at no position is any stage overloaded.
5. When the control is in the maximum-volume position, there should be no loss of the received signal.

Volume control methods have undergone a series of changes throughout the past ten years. Each change has been an attempt to satisfy more closely the foregoing requirements. We shall now discuss the various methods that have been used, from the very earliest to those employed in modern receivers.

8. **CONTROL OF FILAMENT VOLTAGE.** Before 1927, all receivers were battery operated and the control of volume was obtained by varying the filament voltage. A three-tube receiver consisting of a detector and two stages of audio amplification is shown in Fig. 21. In the filament circuit there is connected a rheostat by means of which the filament voltage may be changed from a very low value to the maximum available from the A battery. When the sliding arm of the rheostat is at the right, all the resistance is in the circuit, and a large part of the voltage of the A battery is dropped

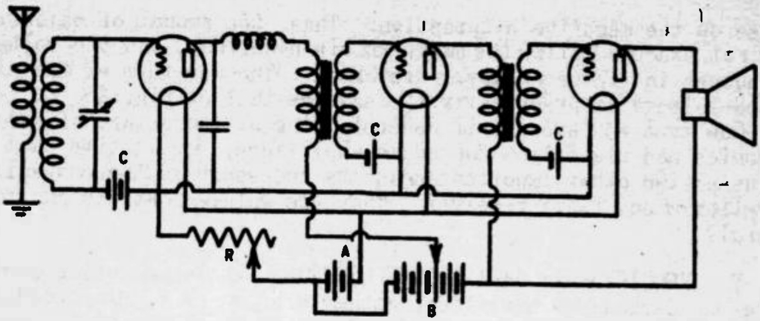


Fig.21 Controlling volume by varying the filament voltage by means of a rheostat R.

across the rheostat, leaving very little for the filaments. Under this condition, the emission from the filaments is very low and practically no electrons are able to reach the plates; therefore, little or no amplification is possible. As the slider is moved to the left, the resistance is cut out of the filament circuit, a higher voltage is applied to the filaments, and a greater emission takes place. This results in greater amplification and more volume from the loudspeaker.

In the earlier sets, a separate rheostat was used for each filament and the volume could be changed by varying the position of any one or all of them. One disadvantage possessed by this method is the fact that the voltage applied to a thoriated tungsten filament is rather critical. The recommended filament voltage for an 01A tube (the type used in all the early receivers) is 5 volts. When this voltage is used, electrons are emitted from a very thin layer of thorium atoms which covers the surface of the filament. This surface gradually evaporates, and is replenished by the diffusion of thorium from the inside of the filament. If the tube is operated at a filament voltage below normal for any great length of time, the temperature of the filament is so low that the process of boiling the thorium from the interior of the filament is greatly retarded. When this occurs, the thorium atoms cannot be replaced on the surface as fast as they are evaporated and the emission layer is slowly depleted.

When the filament voltage is above normal, the evaporation of the thorium atoms is rapidly accelerated, and the emission layer is again used up as the diffusion process is unable to maintain a sufficient supply. Despite this disadvantage, this system was almost universally used until the advent of the AC-operated filament.

When the first AC-operated tubes were used, the same system of controlling volume was attempted. It was, however, found to be entirely unsatisfactory. The types 26 and 71 tubes (which were the first ones used) possessed heavier filaments than the 01A; this was necessary so that the temperature of the filament would not change appreciably during the time that the alternating filament current was at zero, as a change would have introduced excessive hum. Thus, when the filament voltage was lowered in an attempt to reduce the volume, 5 to 10 seconds would elapse before the filaments cooled enough to actually produce a change in volume. Several attempts were, therefore, necessary before the volume could be set at a satisfactory level.

With cathode type tubes, this delay was even more pronounced and some other method had to be devised.

9. CONTROL OF PLATE AND SCREEN VOLTAGES. The next method used to control the volume was to vary the plate voltage of the amplifier stages. A rheostat is connected in the plate circuit and by varying its position, the voltage applied to the tube or tubes may be changed. Increasing the plate voltage naturally increases the amplification which the stage will produce, and thereby causes the volume to be louder. A diagram of a circuit using this method is shown in Fig. 22.

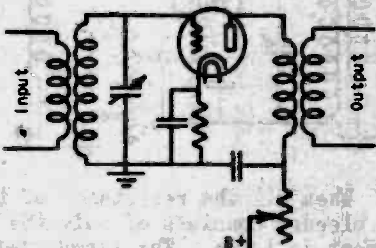


Fig.22 Varying the plate voltage to control volume.

This method cannot be used with screen-grid tubes, as the plate voltage might be reduced below the screen voltage and secondary emission would take place. If this occurs, the plate current variations do not exactly follow the grid voltage changes and severe distortion results. Changing the plate voltage is not entirely satisfactory

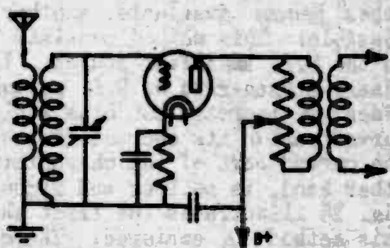


Fig.23 Another plate volume control.

even with triodes, as such a change moves the operating point and it is wholly possible that a lowered plate voltage would cause the tube to operate on the bottom curved portion of its grid voltage-plate current characteristic curve.

Another method which was once used is shown in Fig. 23. A potentiometer of approximately 10,000 ohms is connected across the primary of the R.F. transformer, and the plate voltage is applied through the sliding arm. This gives a somewhat smoother control of volume, but it possesses the same defects as the preceding arrangement.

Since the transconductance of a screen-grid tube depends upon the voltage applied to the screen, it is possible to control the amount of amplification a screen-grid stage will produce by varying the screen-grid voltage. Such a circuit is illustrated in Fig. 24. The combination of the rheostat R_1 and the fixed resistor R_2 constitutes a bleeder resistance connected from the screen to ground. When all of the resistance of the rheostat is in the circuit, the current flowing through the bleeder is low. Since this current must flow through R_3 to reach the bleeder, this small amount of current will not produce a very large voltage drop across R_3 and the screen-grid voltage will be high.

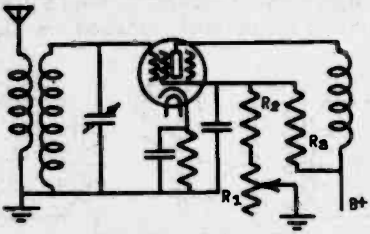


Fig.24 Controlling volume by varying the screen-grid voltage.

When all the resistance of the rheostat is out of the circuit, the bleeder consists of only the fixed resistor R_2 and the bleeder current is large. The large amount of current flowing through R_3 to reach the bleeder produces considerable voltage drop across R_3 and as a result, the screen-grid voltage is low.

The high value of screen-grid voltage causes greater amplification and louder volume, whereas the low screen-grid voltage produces opposite effects.

10. CONTROL OF GRID BIAS. When variable-mu or super-control tubes became available, another type of volume control was made possible. This method consists of varying the grid bias applied to the R.F. amplifier stages. If the grid bias applied to an ordinary screen-grid or R.F. pentode is changed, distortion results, since an increase in bias will cause the tube to operate on the curved part of its characteristic and partial detection will occur. The curved part of the characteristic of variable-mu tubes, on the other hand, is so long and gradual that detection is not possible. Fig. 25 illustrates the first three tubes of a receiver in which this method is employed. The cathodes of the two R.F. tubes are connected together, and in series with this common cathode circuit there is connected a fixed resistor R_1 and a rheostat R_2. The sliding arm is connected to ground, as are the grid return circuits and B minus. The plate currents of these tubes flow from B minus to ground, up through the slider, through that part of the rheostat connected in the circuit, and through the fixed resistor to the cathodes. Thus, the cathodes are placed at a positive potential with respect to ground equal to the voltage dropped across the two

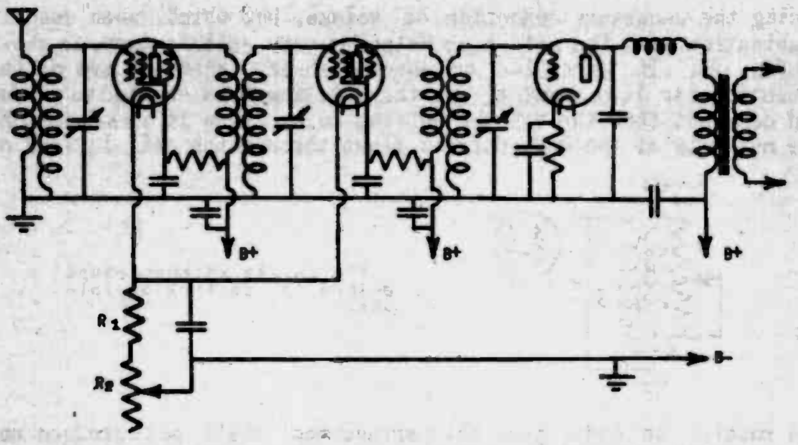


Fig.25 Controlling volume by variation of the grid bias of the variable-mu tubes.

resistors.

Since the grids are grounded as far as DC is concerned, this voltage constitutes the grid bias, and any change in the position of the rheostat will consequently change the bias value. When all the resistance of the rheostat is cut out, the grid bias is lowered and the tubes operate on the straight part of their characteristics, producing the maximum amount of amplification and the loudest volume.

Moving the slider downward will increase the bias, and cause the tubes to operate on the long, curved part of their characteristics, at which point a smaller amplification will be obtained. This is due to the fact that the amplification factor of the tubes is reduced when the bias is increased.

The fixed resistor R_1 is necessary to insure that the tubes have some bias even when all the resistance of the rheostat is out of the circuit.

11. OTHER METHODS. On receivers which do not employ automatic volume control, it is not advisable to place the control entirely in the audio stages, for in this case the R.F. stages or the detector may be overloaded by a strong signal and thereby produce distortion.

It is easily possible for the strongest signal that strikes the antenna to be 250,000 times as great as the weakest that is able to be received. Thus, the volume control must be capable of reducing the amplification 250,000 times if both signals are to be received with equal volume. In addition, no signal should be heard when the control is in the minimum-volume position; therefore, the control must further reduce the amplification so that none of the strong signal is able to produce a sound in the speaker. This requires that the total reduction in amplification be at least 1,000,000.

A volume control system which in itself is not capable of producing the necessary reduction in volume, but which, when used in combination with the grid-bias method is very satisfactory, is shown in Fig. 26. It is called an antenna shunt. When the arm of the potentiometer is at point A, all the R.F. input is shunted to ground and does not flow through the antenna coil. When it is at point B, the majority of the R.F. current flows through the coil instead of

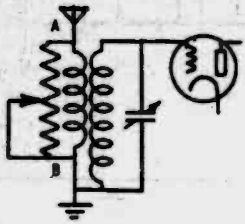


Fig.26 An antenna shunt method for control of volume.

the shunt. In order that this arrangement shall not produce any loss of the signal, the total resistance of the potentiometer must be quite large; it should be at least 4 or 5 times as great as the impedance of the antenna coil. It is not possible to completely cut off a very strong signal by this method, unless the R.F. transformers are well shielded, as a strong local station may induce enough voltage directly into the first tuned circuit to produce loud speaker volume.

A more satisfactory type of control is the so-called "antenna-bias" method. It consists of a combination of the antenna shunt and the bias control. Fig. 27 shows a circuit with this method. A movement of the arm toward A increases the shunting effect, and at the same time, increases the bias on one or more R.F. amplifier stages. When the arm is moved in the opposite direction, less R.F. current flows through the shunt, and the bias is decreased, which, of course, produces an increase in volume.

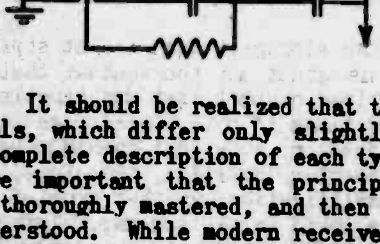


Fig.27 A combination antenna-bias control method.

It should be realized that there are many types of volume controls, which differ only slightly in their arrangement. To give a complete description of each type would not be desirable. It is more important that the principles underlying each general type be thoroughly mastered, and then the many variations may be easily understood. While modern receivers do not use the methods of volume control previously discussed in this lesson, it is necessary that the general classifications be learned, since many of the sets still in use employ one of these methods.

12. AUDIO CONTROLS. Practically all modern receivers have automatic volume control. This system, which will be explained in detail in a later lesson, makes the output volume from the loud speaker independent (within limits) of the voltage induced in the antenna. Thus, when a weak signal is being received, the full sensitivity of the set is used, while a strong local signal automatically reduces the sensitivity until the volume is the same as before. Naturally a manual volume control is also necessary to adjust the volume level to that desired under different conditions. While it will usually not be necessary to change the position of the manual control when tuning from a local to a distant station, it is essential that one be incorporated in the receiver so that the volume level may be reduced when the music from the set is to be used as a "background" during general conversation and thus not disturb the listeners.

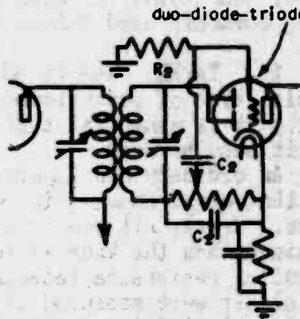


Fig.28 An audio volume control used in a diode detector circuit.

These controls are usually located in the audio amplifier, since there is no danger of a strong signal overloading any stage, as long as the automatic volume control system is functioning. One type of control often used in present-day receivers is shown in Fig. 28. The receiver has a diode detector, and the diode load is a potentiometer. The slider is connected through a condenser to the grid of the triode section of the duo-diode-triode. The triode section is the first audio amplifier. The voltages built up across the tuned circuit alternately make the diode plate positive and negative with respect to the cathode. When it is positive, current flows from the cathode to the diode plate, through the tuned circuit, through the potentiometer back to the cathode. In flowing through the potentiometer, this current produces a rectified voltage across it. The high-frequency variations are by-passed by the condenser C_1, and the voltage across the load is of audio frequency. By sliding the arm of the potentiometer, any part of this voltage may be applied to the grid of the triode section, and thus the volume level of the receiver may be set. The condenser C_2 is used to prevent the DC component of the voltage across the load from being applied to the grid. R_2 is the grid leak.

Another type of control which is occasionally used in receivers, and is widely used in public address system amplifiers, is illustrated in Fig. 29. It consists of a potentiometer connected across the secondary of an audio transformer. The sliding arm connects to the grid of the tube, and by moving the slider, any part of the voltage produced across the secondary may be applied to the tube.

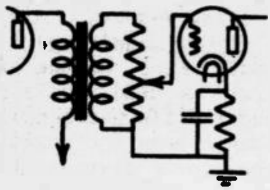


Fig.29 Another type of audio volume control.

As we shall learn in a later lesson, the presence of the potentiometer affects the value of the load resistance into which the preceding tube is working. In order for this effect to be negligible, the total resistance of the potentiometer must be rather high; commonly used values range from 100,000 to 2,000,000 ohms.

13. TAPER. Nearly all types of volume controls require a special type of potentiometer or rheostat, known as a tapered control. It is essential that we learn what a tapered control is and why it must be used.

An ordinary non-tapered or linear potentiometer is so constructed that equal changes in rotation produce equal changes in resistance. Nearly all controls are arranged so that maximum volume is obtained when the knob is rotated all the way to the right. If the amount of resistance between the left end of the potentiometer and the slider were measured at different amounts of rotation, and the results plotted in graphical form, the curve shown in Fig. 30 would be secured. For convenience, we have assumed that the total resistance of the control is 100,000 ohms. When the arm is at the extreme left end of its rotation, the resistance between it and the left end is zero. Then when the arm has been moved through 10% of its rotation, 10,000 ohms are included between it and the left end. At 50% rotation, half of the total resistance, or 50,000 ohms are between the arm and the left end, etc. Each 10% of rotation produces a change of 10,000 ohms.

That such a potentiometer is not desirable for the control of volume may be seen from the following example. Consider the circuit shown in Fig. 31. The letters L, R, and S indicate the left end, the right end, and the slider respectively. When the slider is at point R, the total voltage across the secondary is applied to the grid of the tube, and maximum volume is obtained. Let us now change the position of the slider until the volume sounds only half as loud, and then measure the voltage applied to the grid. You would probably say that this voltage is just half as great as when the maximum volume was secured, but you would be wrong. Incredibly enough, we find that under the condition of half volume, the voltage applied to the grid is only one-tenth of the total voltage across the secondary.

This unusual situation is caused by a peculiar characteristic

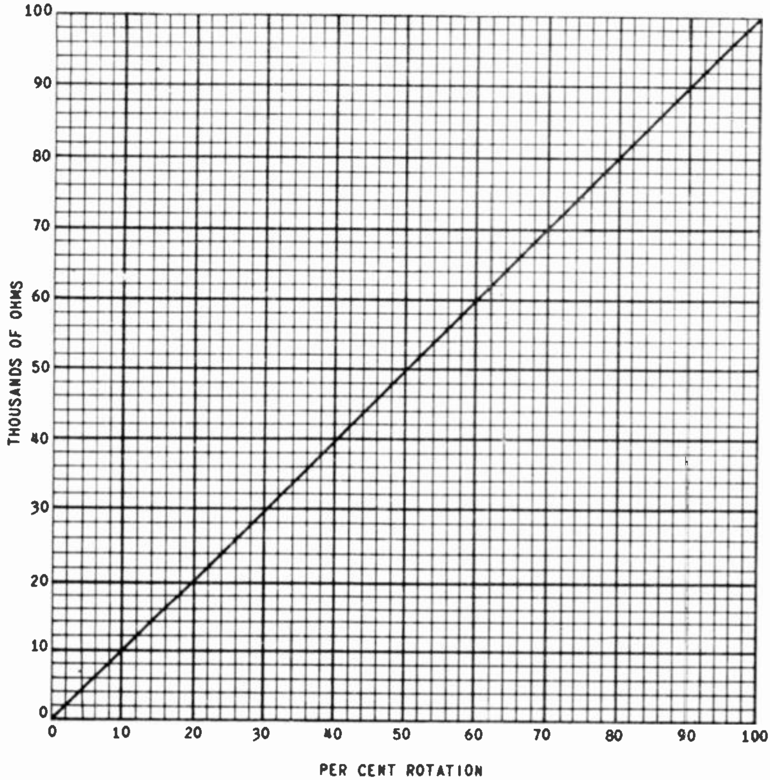
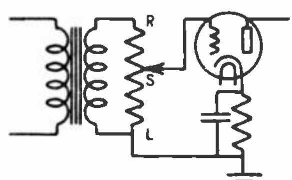


Fig.30 Plot of per cent of rotation against the resistance of an ordinary linear volume control.

of the human ear. In order for one sound to be perceived as twice as loud as a second, the first must have approximately ten times the intensity of the second. Or if it requires a certain sound pressure to produce a given volume of sound, it will require ten times as much pressure to produce twice this volume.

Fig.31 Circuit used to show the need for tapered controls.



The volume control should be constructed so that a rotation of 50% produces a volume one-half of the maximum. At half volume, only one-tenth of the total voltage across the secondary is needed,

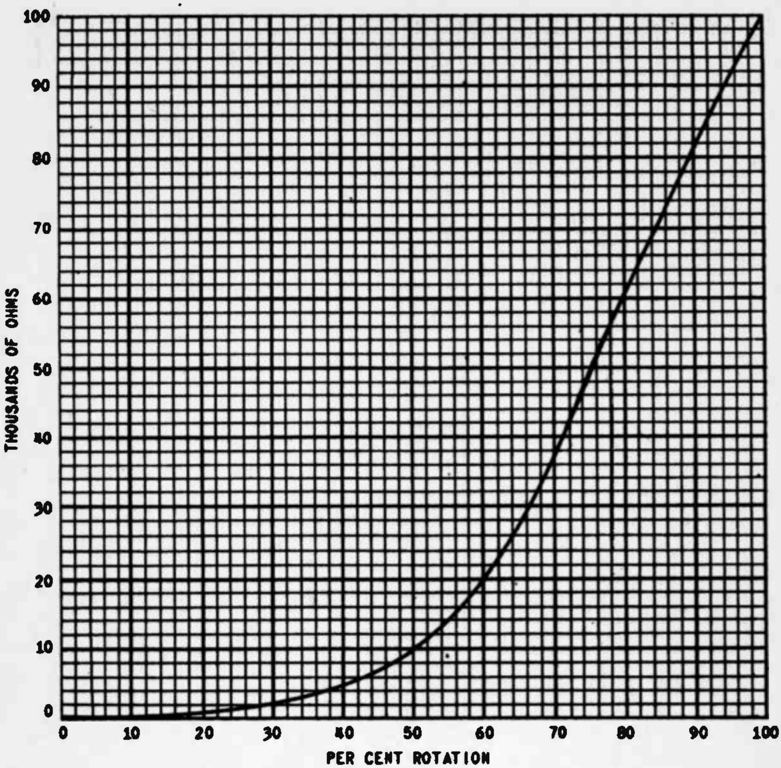


Fig.32 Plot of the per cent of rotation against the resistance of a control having the correct taper for the circuit shown in Fig. 30.

therefore the resistance between the arm and the left end should be one-tenth of the total; that is, there should be 10,000 ohms resistance between the arm and the left end of the potentiometer when the control has been rotated through half of its maximum. This is illustrated in Fig. 32. Notice that the first 25% of the rotation produces very little change in the resistance. At 50% rotation, the resistance is 10,000 ohms, and at 75%, it is 50,000 ohms. The taper is designed to produce 10% of the maximum volume, when the per cent of rotation is 10%; 20% of maximum volume when rotation is 20%; etc. The amount of volume is directly proportional to the per cent of rotation.

Since the left hand of the control has its resistance tapered out, this control is said to have a left-hand taper. Controls used in bias, and antenna-bias circuits have a right-hand taper. In right-hand tapers, the first few degrees of rotation produce a large change in the amount of resistance, while the last few degrees produce very little change. The graph shown in Fig. 33 gives

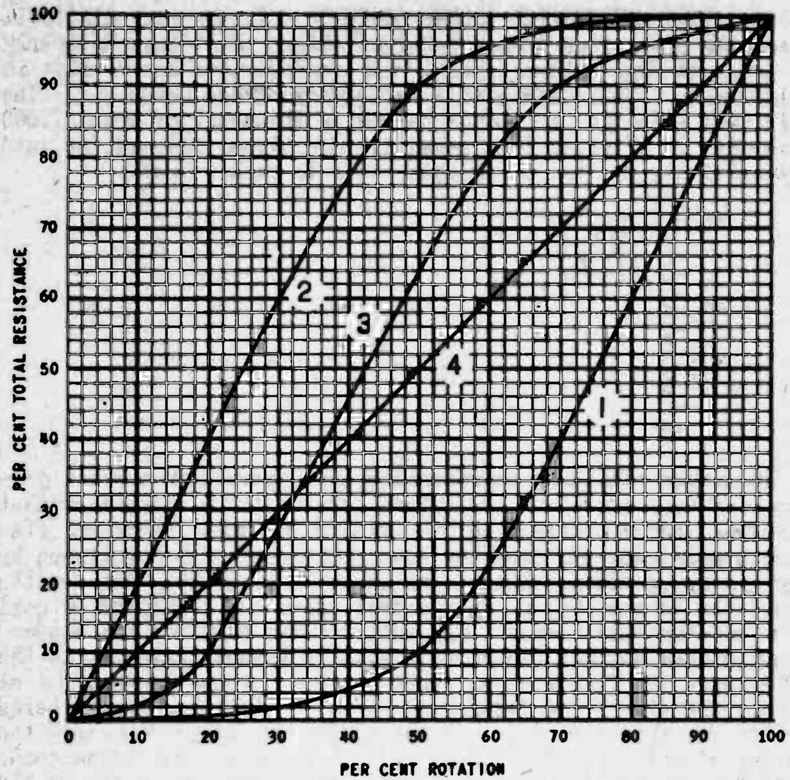


Fig.33 Curves showing the tapers of the more common types of volume and tone controls.

the taper curves of all the more popular types. No. 1 is a left-hand taper; No. 2 a right-hand taper; No. 3 a combination taper; and No. 4 is a linear control. Tapers other than these are manufactured, but they are seldom used, and are not important enough to be included.

Fig.34 The symbol used to indicate a tapered control.

When replacing a volume control, always make sure that the new control has the same taper as the old one; otherwise smooth control of the volume will not be secured. The symbol sometimes used to denote a tapered control is shown in Fig. 34.

14. **TONE COMPENSATED VOLUME CONTROLS.** It is very difficult to hear the bass notes from a receiver unless the volume is nearly full on. At low volume levels, the reproduction has a thin or shallow sound. This is due to a deficiency of the human ear. The ear is most sensitive to sounds having a frequency of about 1,000 cycles; it is slightly less sensitive to higher frequencies, and its sensitivity to the low or bass notes is rather small.

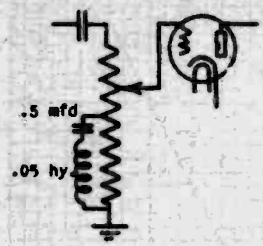


Fig.35 A tone compensated volume control.

In order that the reproduction shall have the correct proportion of bass notes at low volume levels, it is necessary that the volume control attenuate the middle and high range of frequencies more than it does the low. This may be accomplished by using a tapped volume control as shown in Fig. 35. Between the tap and the bottom end of the control there is connected a coil and a condenser in series. The value of the coil and the condenser are chosen so that the circuit will be broadly resonant to the middle range of frequencies. When the arm of the control is at the top, the signal is fed to the grid of the tube without being affected by this circuit. As the slider is moved downward, the shunting effect of the resonant circuit becomes more pronounced. The middle frequencies are attenuated more than the highs or the lows, and the correct proportion of bass notes is maintained.

The resonant frequency is usually about 1,000 cycles; common values for the coil and the condenser are .05 henry and .5 mfd. About 25% of the total resistance is connected between the terminals of the coil and the condenser.

A few controls have two taps as shown in Fig. 36. From the lower tap there is connected a condenser and a resistor in series. The resonant circuit attenuates the middle range of frequencies, while the condenser and resistor attenuate the highs. C_1 and L_1 have the same values as in the preceding case; C_2 is .5 mfd., and R_1 is approximately 800 ohms. In this case, the top section of the

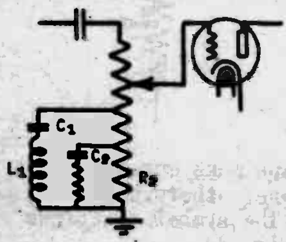


Fig.36 A more elaborate tone compensated volume control.

potentiometer was 30,000 ohms; the middle section, 7,000 ohms; and the bottom section, 7,000 ohms.

In a few cases, no attempt is made to attenuate the middle range of frequencies. A condenser is connected from the tap on the volume control directly to ground. No resistor is used. The same principle applied as in the preceding cases. The condenser tends to by-pass the higher frequencies without having an appreciable effect upon the low or middle range of frequencies.

15. TONE CONTROLS. The tone control first made its appearance about 1930. At that time, the frequency response of the average radio receiver was rather poor. It was able to reproduce middle frequencies and a few of the highs, but its bass response was especially bad. This caused the reproduction to sound tinny.

In order to compensate for this deficiency in the low notes, the tone control was devised. By its use, a portion of the high frequencies are by-passed around the loudspeaker, and there is an apparent increase in the low frequencies. Actually, there is no increase in the volume of the low frequencies present in the output of the speaker, but the lack of high frequencies causes what lows there are to be more noticeable. In addition, many static noises are of a high-frequency character and by turning the tone control to the bass position, they may be partially eliminated.

When the tone control is in the bass position, it is usually necessary to increase the volume as the tone control by-passes a part of the audio energy. Modern receivers have excellent fidelity and tone controls are no longer as important as they once were. They are, however, usually included in present-day sets as many people prefer to hear reproduction having a predominance of bass notes.

In order to partially by-pass the high frequencies and not affect the lows, condensers must be used. Since the capacitive reactance of a condenser decreases as the frequency is raised, it offers a low impedance to currents of high frequency and a high impedance to those of low frequency. It would be possible to connect a variable condenser between the grid of any one of the audio stages and ground and, by varying the capacity of the condenser, by-pass any amount of the high frequencies so desired. A variable condenser, however, requires considerable room and, therefore, this method is not used. One type of tone control consists of three condensers with one terminal of each grounded. The other terminals are connected to a switch having four contacts, the first contact being left blank. The rotating arm of the switch is connected to the grid of one of the audio amplifiers. Such an arrangement is shown in Fig. 37. When the switch is in the first position, none of the condensers is in the circuit, and the tone control is not functioning. The second switch position connects the condenser of low capacity between the grid and ground and a small portion of the high frequencies are by-passed through this condenser. When the switch is in the third position, a condenser of somewhat larger capacity is connected between the grid and ground, a larger part of the high frequencies are by-passed and the bass notes present in the output of the speaker become more noticeable. The fourth position connects a condenser of still larger capacity between the grid and ground and a very large percentage of the high frequencies are by-passed through it.

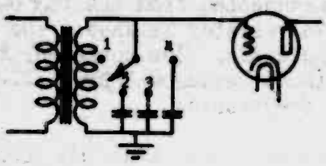


Fig.37 A tone control using three fixed condensers.

Average values for these three capacities are .003, .006 and .009 mfd. respectively.

A type of tone control used far more widely than the preceding one is shown in Fig. 38. It consists of a condenser and a rheostat connected between the grid of an audio amplifier stage and ground. The total resistance of the rheostat has an average value of 500,000 ohms and the condenser an average value of .002 mfd. When the sliding arm of the rheostat is at the bottom end, the 500,000 ohms of resistance is in series with the .002 mfd. condenser. Under this condition, there is practically no by-passing of any of the frequencies. Let us take, for example, a 100-cycle note, a 1,000-cycle note and a 5,000 cycle note, representing a low frequency, a middle frequency and a high frequency respectively. The capacitive reactances of the .002 mfd. condenser at these three frequencies are 795,000 ohms, 79,500 ohms and 15,900 ohms respectively.

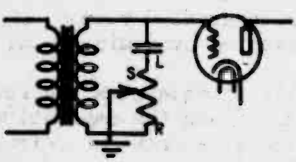


Fig.38 A tone control using a condenser and a rheostat.

The total impedance of the condenser and the rheostat is 939,000 ohms at 100 cycles, 510,000 ohms at 1,000 cycles and approximately 500,000 ohms at 5,000 cycles. All of these values are so large that there will be little, if any, by-passing of any of the frequencies contained in the audio signal.

As the sliding arm of the tone control is moved upward, more and more of the resistance of the rheostat is cut out of the circuit. When the resistance remaining in the circuit is 50,000 ohms, the total impedance between the grid and ground is 795,100 ohms at 100 cycles, 95,200 ohms at 1,000 cycles and 52,400 ohms at 5,000 cycles. It may be seen that very little, if any, of the 100-cycle frequency will be by-passed through this condenser-resistor combination. A part of the 1,000-cycle frequency will be by-passed and much more of the 5,000-cycle frequency. When the sliding arm has been moved to the top end of the resistor, only the condenser remains in the circuit and practically all frequencies above 1,000 cycles are by-passed through it and are not amplified by the tube. Thus the output will seem to have more low frequencies in it than before, although actually, they are only more noticeable due to the lack of the highs.

Tone controls may be placed in either the grid or the plate circuit of any of the audio-amplifier stages. Those used in the plate circuit usually have a smaller resistance in the order of 20,000 to 50,000 ohms, and the condenser a value of about .02 mfd. In addition, the condenser must be able to withstand the total applied plate voltage.

Nearly all tone controls use left-hand tapers. An easily remembered rule regarding tapers which should be observed when one is replacing a tone control is as follows: If the bass position is to the left-hand side of the knob, use a left-hand taper, and if it is to the right side of the knob, a right-hand taper should be employed. The taper curve ordinarily used for a tone control is the one marked No. 1 in Fig. 33.

16. CONSTRUCTION OF VOLUME AND TONE CONTROLS. There are two general types of controls, the wire wound and the carbon. The wire wound consists of many turns of high-resistance wire wound around a flat insulating strip. The strip is bent into the shape of a circle. It should be flat in order that the control will have as little inductance as possible. The sliding arm moves along from turn to turn across one edge of the strip. The carbon-type control consists of a molded carbon piece shaped in circular form. Each type has its advantages and disadvantages.

The advantages of the wire wound control are:

1. Absolute accuracy of resistance value is maintained throughout the life of the control. Wire wound controls can be manufactured to within a tolerance of 2% .
2. High current-carrying capacity is easily obtained. The average wire wound control is capable of dissipating at least 5 watts.
3. Low resistance values are easily obtainable. Wire wound controls having a total resistance of .5 ohm are available.

The disadvantages of the wire wound control are:

1. Difficulty of obtaining taper. A taper curve of a wire wound control is not a true curve, but is a series of broken lines. Thus the taper change is rather abrupt.
2. A slight amount of noise is generated when the arm moves from one turn of wire to another. This noise is caused by the voltage drop per turn of the resistance wire.
3. Wire wound controls have a limited resistance value. Resistance wire of less than one-thousandth of an inch in diameter is very fragile. It is very difficult to manufacture wire wound controls having a total resistance in excess of 150,000 ohms and still keep them compact in size.

The advantages of the carbon type of control may be listed as follows:

1. Any taper curve may be easily obtained.
2. They are silent in operation because the resistance change is progressive and does not take place by minute steps as in the case of the wire wound control.
3. Very high resistance values may be obtained in compact form. Carbon type controls having a total resistance of several megohms are not uncommon.

The disadvantages of the carbon type control are:

1. They are subject to a variation of resistance caused by humidity and age. A carbon control has a tendency to change its resistance, especially if it is overloaded for any length of time. It is also difficult to manufacture a carbon type control with a tolerance limit approaching that obtained in the wire wound types.
2. Carbon type controls have a low current handling capacity. The average dissipation is approximately 1 watt.
3. Low resistance carbon controls are impracticable. It is almost impossible to successfully make a carbon control with a total resistance lower than 500 ohms.

It may thus be seen that each type of control has its own uses. To be on the safe side, it is always best to replace a wire wound control with a wire wound control and an original carbon control with a carbon type control. It is possible that there would be a few cases where it would be desirable to change the type of control, but such a matter should be weighed cautiously. Unless the advantages to be gained are much greater than the disadvantages which will be introduced, it is best not to make this change.

MELTING CURRENTS FOR WIRES

Owing to the influence of various factors which control the rate of loss of heat energy, the following values can be considered only as approximations.

GAUGE NO. A.W.G.	DIAMETER INCHES	MELTING CURRENT IN AMP.			
		COPPER	ALUMINUM	IRON	FUSE WIRE
43	0.0021	1	...	....	.....
41	.0026	...	1	....	.....
39	.0035	2	...	....	.....
38	.0040	...	2	....	.....
37	.0045	3	...	1	.....
35	.0056	4	3	....	.....
34	.0063	5	4	....	.....
33	.0071	...	...	2	.....
32	.0080	...	5	....	.....
30	.0100	10	...	3	1.7
28	.0126	15	10	....	.....
27	.0142	...	...	5	.....
26	.0159	20	15	....	.....
25	.0179	25	...	....	.....
24	.0201	30	20	10	4.9
23	.0226	35	25	....	.....
22	.0253	40	30	....	.....
21	.0285	45	35	15	.....
20	.032	60	40	....	9.0
19	.036	70	50	20	11.3
18	.040	80	60	25	13.3
17	.045	100	70	30	.....
16	.051	120	90	35	19.8
15	.057	140	100	45	.....
14	.064	160	120	50	25.4
13	.072	200	160	60	32.
12	.081	225	180	70	39.1
11	.091	275	200	90	.....
10	.102	...	225	100	54.1
9	.114	...	275	120	63.1
8	.128	...	...	140	81.1
7	.144	...	...	160	90.6
6	.162	...	...	200	110.7
5	.182	...	...	225	132.1
4	.204	...	...	275	154.7

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UNIT NO. 1

SUPERHETERODYNE RECEIVERS

LESSON NO. 27

MAKE HASTE SLOWLY

.......A RULE YOU SHOULD ALWAYS FOLLOW

You have probably visited a museum sometime during your life, but have you ever had the opportunity of roaming through an exhibit of modern science and industry? It is one of the most absorbing tours a young man can take.

You can spend hours there...hours that you will not soon forget. You see models of every conceivable kind of mechanical and electrical device, from simple gears to elaborate radio sets, all arranged in the correct order of their development.

To you, the electrical units would be most interesting. You trace the development of the modern Radio and Television set back to the original inventions and discoveries which made it possible. You see, right before your eyes, how man literally groped his way from step to step. You almost feel the same surge of emotion that came over the discoverer or inventor upon the completion of his experiment.

Those first steps were little, when viewed from your eyes. Thousands of men spent their lives in patient research to develop each one of the hundreds of steps in the radio receiver of today. Over many hundreds of years, great minds had to puzzle out facts about magnets, condensers, the peculiarities of electricity, and the multitude of other details which are involved. Hundreds of years.....entire lives spent.....so that Radio could send a message around the earth in the wink of an eye!

This may be the age of Speed.....but Speed itself was never produced in haste. The designers of the fastest airplanes worked slowly and painstakingly. The telegraph, the airplane, the high-speed rifle...all were developed slowly, involving many steps and connecting links, like a chain.

Some of us get the idea that we must be in a hurry, because we live in an age of speed. We high-pressure ourselves into trying to absorb too much at one time. In our haste to get a thing done, we may overlook an important step or fact which would seriously retard us later on.

"Make Haste Slowly" is a good rule to follow. Don't say "I must get through this lesson in a hurry", but instead say "I want to know all the facts in this lesson thoroughly!

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Lesson Twenty-Seven

SUPER-HETERODYNE RECEIVERS

"Practically all modern radio receivers incorporate the superheterodyne principle of reception. While this principle has been known for many years, it has only been since about 1930 that this type of receiver has experienced more popularity than the older T.R.F. type.

"If you are to have a thorough understanding of modern receiver practice, unquestionably you must understand the superheterodyne's principle of operation. I am sure you will find the theory divulged in this lesson extremely helpful when constructing your own superheterodyne receiver during your laboratory experiments."

1. THE SUPERHETERODYNE PRINCIPLE. The objective foremost in the minds of all radio set manufacturers is to produce a receiver which fulfills the requirements of selectivity, sensitivity and fidelity as closely as possible, consistent with economy. The success in this respect depends largely on the design of the radio frequency amplifying portion of the receiver. The detector, audio amplifier, and power supply must, of course, fulfill certain requirements as pointed out in previous lessons. The detector should be designed so as to produce a minimum of distortion. The type of A.F. amplification used and the component parts of the amplifier should be selected so as to minimize frequency and harmonic distortion. As will be explained in Lesson 29, the loudspeaker also affects the fidelity of a receiver to a great extent.

The design of these latter portions of a receiver is rather conventional and seldom presents much difficulty to the constructing-engineer. By following well-established rules, it is possible for him to secure satisfactory operation through these parts of a radio receiver. The design of the R.F. amplifying section, however, presents additional problems, some of which were discussed in Lesson 24. The method of signal amplification as explained in that lesson up to the detector stage is known as T.R.F. (tuned radio frequency). In a T.R.F. amplifier, the incoming radio signal is amplified at its own frequency by adjusting the tuned circuits throughout the amplifier to the frequency of that signal. Each time recep-

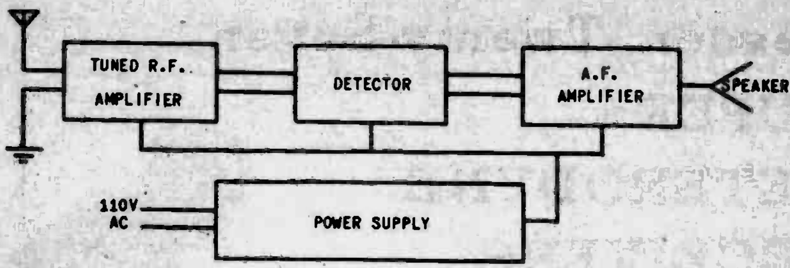


Fig. 1 Block diagram of T.R.F. receiver.

tion of a radio station operating on a different frequency is desired, it is essential to readjust the resonant circuits to coincide with the frequency of the new desired signal. A block diagram illustrating the main portions of a T.R.F. receiver is shown in Fig. 1. In a receiver of this design, if reception is desired from a station operating on 1500 kc., the tuned circuits in the T.R.F. amplifier are adjusted to that frequency. Then, when reception is desired at a different frequency, say 600 kc., all the tuned circuits must be readjusted to permit a signal of that frequency to pass through the amplifier. Altering the tuned circuits in this manner over the frequency range to be covered does not permit the sensitivity nor the selectivity exhibited by the receiver to be constant over the entire tuning range. When the same tuned circuit is used to resonate at all frequencies from 550 to 1600 kc., its characteristics will be quite different at one end of the band than at the other; hence, broadcasting stations will not be received with the same degree of satisfaction over the entire dial.

The total gain (voltage amplification) and selectivity of an R.F. amplifier is improved considerably when a constant load is maintained in the plate circuits of the R.F. amplifying tubes at all frequencies. This condition is realized to a higher degree of satisfaction when a preselector unit is employed ahead of an untuned R.F. amplifier as shown by the block diagram in Fig. 2. The design of preselector units was discussed in Lesson 24. Therein it was found that such a device consists of several tuned circuits coupled in such a manner that the incoming signal must pass through each

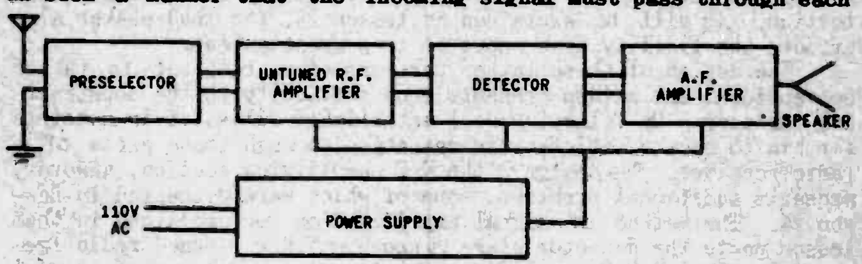


Fig. 2 Block diagram of preselector-untuned R.F. receiver.

of them. In so doing, selectivity is obtained; that is, the desired signal is permitted to pass, whereas the undesired signals are rejected. Following the preselector unit, an untuned R.F. amplifier is satisfactory. The selected frequency will then be amplified by the vacuum tube stages in the untuned R.F. amplifier and fed to the detector stage where it is demodulated. In a receiver of this kind, a more constant gain with uniform selectivity is secured over a normal frequency range when compared to the conventional T.R.F. amplifier, mainly because the selecting and amplifying portion are separated into two individual units. Some difference may exist at the two ends of the frequency range covered, but it will be found slight in comparison to those conditions existing in a T.R.F. amplifier.

Since no amplification is secured while the signal is being selected, there is, naturally, some loss in signal energy through the preselector unit. This means, then, that the strength of the signal delivered to the untuned R.F. amplifier is much weaker than that which would be delivered to the input of a T.R.F. amplifier (considering the same input voltage) and hence more untuned amplifying stages are generally necessary to obtain equal sensitivity in the two types of circuits. The weaker signal is also objectionable in that it is closer to the atmospheric noise level, thus making distant reception difficult without considerable static and interference.

These disadvantages of the T.R.F. amplifier and the preselector-untuned R.F. amplifier are solved to a great extent by the superheterodyne method of signal reception. In a superheterodyne, the selecting and amplifying portions of the receiver are not entirely separated, but the principle of operation enables the greater part of the amplification to be obtained at *one certain frequency* for all incoming signals. This overcomes the major difficulties of the T.R.F. amplifier wherein the signal amplification was conducted at the frequency of the incoming signal. The selectivity in a superheterodyne is distributed throughout the R.F. portion of the receiver in such a manner that it does not seriously interfere with the sensitivity when receiving different stations.

The superiority of a superheterodyne receiver to the other methods of signal reception is time proved and practically all modern receivers are now of this type. The block diagram in Fig.

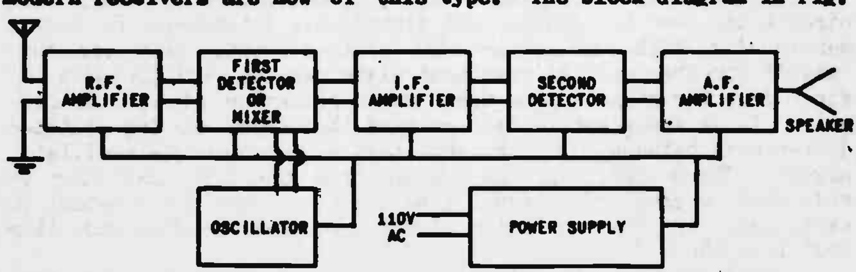


Fig.3 Block diagram of superheterodyne receiver.

3 illustrates the essential portions of a superheterodyne receiver. By comparison with Figs. 1 and 2, it is seen that considerable difference exists in the stage layout and general design. Let us briefly review the purpose of the various stages in a superheterodyne receiver, then, after establishing a general idea of its operation, we shall discuss each portion of the receiver independently and thoroughly.

2. THE SUPERHETERODYNE'S STAGES.

(A) The R.F. Amplifier. The signal voltage induced in the antenna is fed to the input of an R.F. amplifier. This amplifier nearly always consists of a one-stage, high-gain circuit with its grid circuit tuned to the frequency of the incoming signal. This single R.F. stage is not for the purpose of obtaining adjacent channel selectivity, but, rather, for off-channel selectivity. This means that it is to prevent the reception of strong radio signals which are a few hundred kilocycles away from the one desired and is not expected to prevent the passage of radio signals 10 or 20 kilocycles from resonance. Amplification is obtained as the desired signal passes through this stage; however, it is not anticipated to be of appreciable magnitude in comparison to the amplification to be secured further on.

(B) The Oscillator Stage. The purpose of the local oscillator in a superheterodyne is to generate a constant-amplitude (undamped) R.F. voltage. This R.F. voltage is always maintained a few hundred kilocycles above the frequency of the desired radio signal. The tuning condenser for the oscillator is ganged on the assembly that is rotated by the tuning knob and adjusted so as to maintain a definite frequency difference with respect to the incoming signal throughout the tunable range of the receiver. For example, if the receiver dial is adjusted to 600 kc., the oscillator might be tuned to 875 kc. Then, maintaining this frequency difference of 275 kc., when the receiver dial is tuned to 1500 kc., the oscillator will be 1775 kc.

(C) The First Detector or Mixer Stage. From the block diagram shown in Fig. 3, it is seen that the output of the R.F. amplifier and the output of the local oscillator are both fed into the first detector or mixer stage. This, of course, is a vacuum tube circuit and the two independent signals are introduced in such a manner that both will affect the plate current. They are thus "mixed" together and the resultant plate current variations in the first detector stage depend upon the combination of the two signals. It is important to bear in mind that there are two distinct differences between the R.F. amplifier signal and the oscillator signal. These are: (1) The signal from the R.F. amplifier is modulated, whereas the signal from the oscillator is constant in amplitude. (2) The oscillator signal is higher in frequency than that from the R.F. amplifier.

Combining these two signals in the mixer produces a new frequency in its plate circuit. It is called the "beat frequency" or "intermediate frequency." The words "intermediate frequency" are abbreviated "I.F." The intermediate frequency is equal to the *difference* between the oscillator frequency and the desired signal frequency. The plate circuit of the mixer is permanently tuned to this value. Permanent tuning can be employed because an equal difference is maintained between the oscillator and the incoming signal over the entire tuning range. The intermediate frequency will have the original modulation of the incoming signal impressed on it; that is, the amplitude variation will not be lost in the frequency conversion process.

The first detector, then, is that stage in a superheterodyne receiver which accepts a modulated R.F. signal voltage and a constant amplitude voltage, then produces, in its plate circuit, a modulated I.F. signal voltage equal in frequency to the difference between the incoming R.F. signal and the local oscillator. It performs the process of detection, but not to the extent that A.F. currents flow in the plate circuit.

(D) The I.F. Amplifier. The I.F. amplifier is a high-gain circuit permanently tuned to the frequency difference between the oscillator and the incoming signal. The modulated I.F. signal is produced in the plate circuit of the first detector, then fed directly to the input of the fixed-tuned I.F. amplifier. Since all incoming signals are reduced to the same frequency by the first detector and oscillator stages, this amplifier operates at only one frequency; therefore, the tuned circuits may be permanently adjusted and each stage in the I.F. amplifier adjusted for maximum amplification. One, two or three stages may be used in the I.F. amplifier, depending upon the design of the receiver. When amplifying at this low, fixed frequency, it is possible to obtain a voltage gain per stage far surpassing that which could be secured from a single stage in a T.R.F. amplifier using the same type of tube. The high amplification attained through the I.F. amplifier is largely responsible for the excellent sensitivity possessed by most superheterodynes. Also, the fact that each stage is tuned with either one or two resonant circuits accounts for the superheterodyne's sharp selectivity.

(E) The Second Detector. The amplified, modulated I.F. signal voltage is delivered to the input of the second detector. In this stage, the amplitude variations are converted into corresponding A.F. voltages. The function of the second detector is similar in every respect to the other detector circuits discussed in previous lessons.

(F) The A.F. Amplifier. The A.F. amplifier employed in a superheterodyne is the same as in other types of receivers. Likewise, the loudspeaker and the power supply are no different than in other receivers. The essential difference between the superheterodyne circuit and the other methods of signal reception lies only in the design of the circuit up to the demodulating stage.

Throughout the remainder of the lesson, it is necessary to keep in mind that in a T.R.F. receiver, the signal is amplified at its *own carrier frequency,* whereas in a superheterodyne, the incoming signal is *changed to the intermediate frequency.* The exact requirements as well as the superheterodyne's advantages and disadvantages will be pointed out as the individual stages are discussed in detail.

3. PHENOMENON OF BEAT FREQUENCIES. The operation of a superheterodyne receiver depends upon the mixing of two R.F. voltages so as to produce a third voltage known as the beat or intermediate frequency. This phenomenon of beat frequencies has many applications in all fields of radio work. Therefore, it is quite essential that the student understand it thoroughly.

Common examples of beat frequencies are found in acoustical (sound) work. For example, if two audible sounds differing slightly in frequency are heard at the same time and their intensities are practically the same, a third audible beat note will also be heard. When the two original sounds are sustained or continuous, a new sound will be heard that varies in intensity. This beat frequency is heard because the phase relation between the two original sounds is such that at one instant the two sounds aid each other, thus producing a more intense or stronger sound, while at other instants, the phase relationship is such that they buck against each other and tend to neutralize, thus decreasing the intensity of the sound. Sustained audio notes that beat against each other in this manner produce a wavering sound because of this reinforcement and cancellation at various instants of phase relationship. This wavering sound is the beat frequency and the rate at which its intensity rises and falls depends upon the relative frequency of the two original sounds. In actual value, its frequency will be equal to the difference between them. To produce a beat note in this manner, it is necessary that the two original sounds be of approximately the same intensity because if one falls below a certain level, the beat note will be too weak to be heard.

As an example, suppose that a sustained 300-cycle note is produced by a first tuning fork and that a sustained 350-cycle note is produced by a second tuning fork. Assuming the intensity of the two audio notes to be approximately the same, a beat note will be heard that is equal in frequency to the difference between the two; that is, 350 - 300 or 50 cycles.

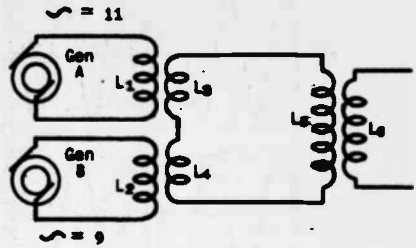
(A) Beat Frequency Produced by Two Unmodulated Voltages. In electrical circuits, this same beat frequency phenomenon is found to be applicable in all cases. When two electrical voltages or currents differing in frequency are mixed together or beat against each other, a third frequency equal in numerical value to the difference between the two will be produced.[1]

To demonstrate beat frequencies in an electrical circuit, let us refer to Fig. 4. Here two AC generators are shown, each loaded with an individual inductance. Generator A is delivering its current through inductance L_1 and generator B is working into inductance L_2. L_1 is inductively coupled to L_3 and L_2 is inductively coupled to L_4. Then, to complete these secondary circuits, L_3 and L_4 are placed in series and primary coil L_5 is connected across both

[1] In addition to the difference in frequency, there will also be another current or voltage produced equal to the sum of the two original frequencies. In practical applications, this sum frequency is seldom used; so it will be disregarded in explanations to follow.

L_3 and L_4. The resultant voltage output from the combination is developed across the secondary L_6.

Fig.4 Circuit to combine the output voltages of two generators operating at different frequencies.



For explanation, let us assume that the voltage output of generator A has a frequency of 11 cycles per second and the output of generator B is 9 cycles per second. Sine waves representing the two separate voltages are shown at A and B in Fig. 5. Whereas it is not absolutely essential for the amplitudes of the two voltages to be exactly the same, for explanation, we are assuming that this condition is true. In Fig. 5, a dotted line L-L' is extended down the left side of the drawing. This indicates that the two generators are started at the same time and in phase with each other. Since generator A is running slightly faster than generator B, when generator A has completed about 2¾ cycles, it is completely out of phase with generator B. This instant is indicated by the vertical dotted line M-M'. Now let us refer to curve C which is drawn directly beneath the sine waves illustrating the voltage output of the two generators. The positive alternation of the first cycle of C is shown to be quite high in amplitude. This high amplitude is determined by the addition of A and B at that instant. Since they were started in phase with each other, their voltages on the first positive alternation will naturally add to a value closely approaching the exact sum. The first negative alternation in C is not as high in amplitude as the first positive alternation, because in the short time that has elapsed, generator A has moved slightly ahead of B; hence, the negative alternations of A and B are not as near in phase with each other. Likewise, the positive alternation on the second cycle of C is lower in value than the positive alternation of the first cycle. The reason for the decrease is the same as before; that is, a greater phase difference exists between A and B. The negative alternation of the second cycle at C is shown to be considerably less and the next positive alternation is practically zero. A complete cancellation of the two voltages occurs immediately following the third positive alternation. Also, the phase of the resultant voltage C is reversed 180° at this instant which accounts for the two positive alternations without the intervening negative alternation. After the complete cancellation, generator A is moving further ahead of generator B and therefore is coming back into phase again. The fourth, fifth and sixth positive alternations at C are shown to be rising in amplitude (negative amplitudes likewise rise) and when the instant is reached as designated by the vertical dotted line N-N', the two generators are again in phase with each other and

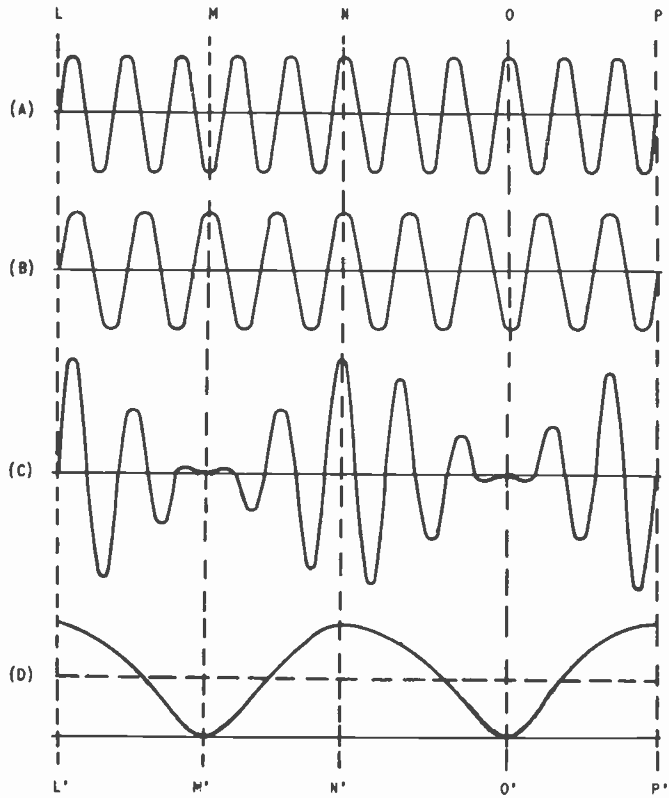


Fig.5 (A) Sine-wave output of 11-cycle machine.
(B) Sine-wave output of 9-cycle machine.
(C) Resultant voltage obtained from A and B. This is 10 cycles.
(D) Beat frequency (2 cycles) secured when C is applied to a non-linear device such as a detector.

adding together to produce the second high positive peak.

The entire action then repeats itself; that is, the two generators become completely out of phase at O–O', then back into phase at P–P' on the right side of the drawing. Throughout the entire 11 cycles of A and 9 cycles of B, it will be noticed that the amplitude of C has been decreased and increased twice. The amplitude variation of C is shown as a solid line at D, Fig. 5. D represents the beat frequency produced by the 9 and 11-cycle generators. The beat frequency exists as an amplitude variation of the resultant voltage changes (C); therefore, in electrical circuits, the resultant voltage C must be applied to a non-linear device, such as a detector, to secure the beat frequency.

There are 10 cycles in the resultant voltage[1] at C in Fig. 4. These 10 cycles are produced because it is the average between the 9 and 11 cycle generators. It should be understood that the beat frequency is not the average frequency produced when two voltages are beat against each other, but rather is the amplitude or cyclic variation of the average frequency. *To secure the beat frequency, it is necessary to demodulate the average frequency.*[2] In a superheterodyne receiver, this takes place in the first detector stage.

In Fig. 4, then, the actual voltage output across the terminals of L_6 will have a frequency numerically equal to 10 cycles, but will vary in amplitude at a 2-cycle rate. Should this voltage be demodulated, the resultant beat frequency of 2 cycles would be obtained from the combination of the 9 and 11-cycle voltages.

Whereas this example deals with low frequencies, it could just as well represent A.F. or R.F. voltages of any frequency. For example, suppose that generator A were producing a frequency of 1100 kc. and generator B producing 900 kc. These two R.F. voltages would periodically reinforce, then cancel each other the same as shown at C, Fig. 5, except that it would occur 200,000 times a second and thus the beat frequency produced (after detecting) would be the difference frequency of 200 kc.

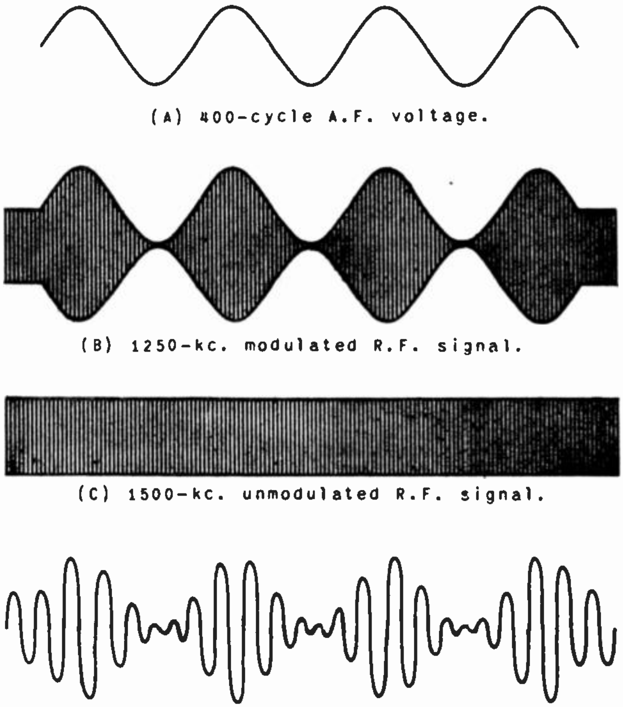
Two radio frequencies could likewise be beat against each other to produce an audio frequency; for example, if one generator is set to 1,000 kc. and the other to 1,001 kc., the beat note produced would be 1 kc. or 1,000 cycles, which is an audio frequency. Commercial beat-frequency audio oscillators operate on this principle.

(B) Beat Frequencies Produced When One Signal is Modulated and the Other Unmodulated. The explanation just given is not a complete picture of the action that really takes place in a superheterodyne receiver. As stated previously, the signal from the R.F. amplifier into the first detector is modulated, whereas that from the oscillator is unmodulated. The process of mixing these two signals in the first detector circuit is very similar to that just described except that the modulation introduces an additional consideration.

A graphical analysis of the conditions existing at high radio frequencies with one signal modulated is rather impractical, so we shall assume values to convey the necessary information. At A in Fig. 6, three cycles representing a 400-cycle A.F. voltage are shown. This 400-cycle note is then modulated on a 1250 kc. carrier wave and the resultant signal appears as shown at B. Let us assume that a signal voltage of this nature is delivered to the input of the first detector from the R.F. amplifier. At C in Fig. 6, the 1,500 kc. unmodulated R.F. signal from the local oscillator is shown. This is mixed (heterodyned) in the input circuit of the first detector with the modulated signal shown at B. The modulated R.F. signal has a frequency 250 kc. lower than that of the oscillator. The beat or intermediate frequency as produced in the plate circuit will then be 250 kc. *This I.F. signal voltage will be modulated in direct ac-*

[1] Due to 180° phase shift at points of cancellation, the 10 cycles are determined by counting the alternations (20), then dividing by 2.

[2] The human ear has a non-linear response. Thus, it is capable of detecting the beat frequency produced by two sound waves.



(A) 400-cycle A.F. voltage.

(B) 1250-kc. modulated R.F. signal.

(C) 1500-kc. unmodulated R.F. signal.

(D) 250-kc. modulated I.F. signal.

Fig. 6

cordance with the 400-cycle modulation originally impressed on the 1250 kc. carrier. The actual waveform of the average voltage produced when the modulated and unmodulated signals are mixed together is extremely complex and beyond representation or analysis by graphical means. It should be visualized, however, that the average frequency of 1375 kc. [(1250 + 1500) ÷ 2] actually varies in amplitude at a rate of 250 kc. per second; this is the same as shown at C in Fig. 5 where the average of 10 cycles varied in amplitude at a rate of 2 c.p.s. The 250 kc. beat frequency then varies in amplitude at the rate of 400 c.p.s., which is the frequency of the audio modulation.

While discussing the operation of the first detector tube, it is well to point out that various frequency components are produced in its plate circuit. Five of them are sufficiently important to bear recognition. First, there will be plate current variations produced by the modulated R.F. signal voltage. Then, the second component will be those plate current variations resulting from the steady oscillator voltage. Third, there will be the average of these two frequencies (the modulated and unmodulated signals), then as the fourth component, there will be plate current variations in accordance with the difference between the two frequencies and, fifth, another equal in numerical value to the sum of the two frequencies. With all these plate current components, it appears upon first glance that it might be difficult to select the one desired; that is, the beat or difference frequency. This is easily done, however, by the use of a parallel tuned circuit as the plate load impedance. This parallel resonant circuit is tuned exactly to the beat frequency (difference between the unmodulated and modulated signal voltages), so an oscillating current is established in the tuned plate load at that frequency. All other components of the plate current variations are lost in the plate circuit because there is no appreciable load on the tube at these frequencies. The student should recall from previous explanations that the amount of voltage amplification depends largely upon the magnitude of the plate load impedance; hence, *if the plate circuit is loaded only at the beat or intermediate frequency,* then only that component of the plate current will be amplified to any appreciable extent. The other components merely pass through the low impedance of the parallel tuned circuit and return to the cathode.

4. IMAGE FREQUENCY INTERFERENCE. The problem of image frequencies in superheterodyne receivers is one of no little consequence. Unless provision is made in the design of a receiver, image frequencies will be responsible for peculiar reception conditions. Let us explain what is meant by the phrase "image frequency". To produce the intermediate or beat frequency in a superheterodyne receiver, it is necessary to adjust the oscillator frequency to a value different than that of the incoming signal. The oscillator frequency may be made greater or less than the frequency of the incoming signal. For example, suppose it is desired to receive a broadcast station operating on 800 kc. and that the intermediate frequency of the receiver is 175 kc. To produce the I.F. of 175 kc., the oscillator frequency may be set to 975 kc., or to 625 kc. In either case, it differs from the incoming signal by 175 kc., so the proper I.F. will be produced in the plate circuit of the mixer stage.

Let us first assume that the oscillator frequency is set to 975 kc. (above the frequency of the incoming signal) to produce the I.F. of 175 kc. The 800 kc. station will then be received as desired. If the signal from a broadcast station operating on 1150 kc. is also reaching the grid circuit of the first detector stage, then that signal will beat against the oscillator frequency and produce an I.F. of 175 kc. Under these conditions, not only will the 800 kc. station be received, but also the station operating on 1150 kc., since both frequencies beat against the 975 kc. oscillator to produce the I.F. of the receiver. The 800 kc. station is the one to which the receiver is tuned, but since the 1150 kc. station is also being received, it is called the "image frequency signal". It is quite necessary that some means be provided in the design of the receiver to exclude this image frequency from the first detector circuit.

If the oscillator frequency had been placed 175 kc. below the frequency of the desired signal, a similar condition would exist. Again, assuming the desired signal to be 800 kc. and the I.F. 175

kc., then to receive the station, the local oscillator would be set to 625 kc. If a signal from a government, aeronautical or marine station operating on 450 kc. is also permitted to reach the first detector, it will beat against the oscillator and produce the 175 kc. I.F., the same as the desired signal. Both stations will then be heard in the output and the 450 kc. signal is called the "image frequency".

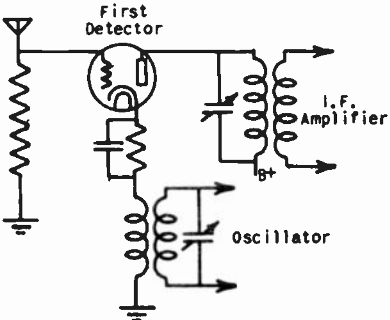


Fig.7 Antenna connected directly to the grid of the first detector. Image frequency interference is certain to occur.

Fig. 7 shows a resistance input circuit with the antenna connected directly to the grid of the first detector. With this design, all antenna signals, desired and undesired, are applied directly to the first detector and image frequency interference is certain to result. A preselector or R.F. amplifier inserted between the antenna and first detector is the most effective means of suppressing image frequency interference. A single R.F. stage will generally do the job quite efficiently, because if its grid circuit is tuned to the frequency of the desired station, the signal from an "image" station will certainly be excluded or at least diminished greatly in strength. If the "image" signal happens to be a strong local station, difficulties are apt to be encountered even though this R.F. stage is employed. Suppose for example that the desired signal is very weak in the antenna and that the local station which is apt to cause image-frequency interference induces a strong antenna voltage. Even if the R.F. amplifying stage increases the strength of the desired signal and at the same time reduces the strength of the local image station, both of them may reach the grid circuit of the first detector with practically the same strength and beat against the oscillator frequency to produce the I.F. In such a case, a parallel resonant circuit, known as a "wave trap", should be tuned to the local station and connected in series with the antenna lead so as to diminish its strength into the R.F. amplifier. This is shown in Fig. 8.

Some manufacturers employ a series of tuned circuits known as a "preselector" between the antenna and first detector input to prevent image frequency interference. A preselector satisfactory for this purpose is shown in Fig. 9. Such a unit may or may not be entirely successful in eliminating image frequency signals over the complete tuning range, depending upon the locality in which the receiver is used. It has been determined that to satisfactorily eradicate image frequency interference, the strength of the image frequency signal should be less than .1% of the desired signal. When this signal ratio is maintained, there is little doubt that the image frequency signal will be entirely excluded from the I.F. amplifier.

Fig.8 A wave trap L_1C_1 connected in series with the antenna lead to retard the passage of a strong local station.

Superheterodyne receivers with a separate dial for tuning the oscillator have long been obsolete. In all modern sets, the oscillator tuning condenser is ganged on the same assembly with the condenser used for tuning the R.F. and first detector grid circuits. An image frequency signal can, therefore, appear at nearly any setting of the tuning dial. The exact difference between the frequency of the dial setting and the image frequency can be determined from the I.F. used in the design of the receiver. The image frequency will always be found to differ from the setting of the tuning dial by an amount equal to exactly twice the intermediate frequency. This image signal is always above the dial setting in modern superheterodynes, because the oscillator frequency is always

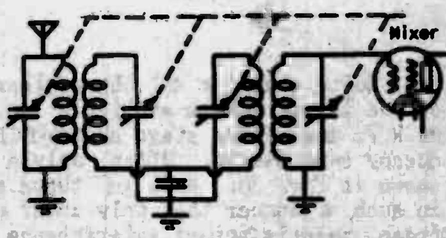


Fig.9 A four-circuit preselector.

made higher than the frequency of the incoming signal. For example, assume that the dial reading is 600 kc. and that the intermediate used in the set is 275 kc. To receive the 600 kc. station, it is necessary for the oscillator to be set at 875 kc. and the image frequency on the upper side of the oscillator frequency which could also produce an I.F. of 275 is equal to 875 + 275 or 1150 kc. This image frequency is seen to be above the dial setting by an amount equal to twice the I.F.; that is, 2 × 275 = 550. Then, 550 + 600 = 1150 kc.

At the high-frequency end of the broadcast band, the image frequencies fall in the amateur and police bands. Thus unless effectively suppressed, it is possible to receive such stations when the receiver is tuned for high-frequency broadcast stations. For example, if the tuning dial is set to 1500 kc. and the I.F. of the set is 460 kc., then a police station operating on 2420 kc. could produce an image signal. The frequency of the image signal is determined by adding twice the I.F. to the dial setting; that is, 460 × 2 = 920; 1500 + 920 = 2420 kc.

The use of a high intermediate frequency is particularly effective in reducing image frequency interference throughout the entire broadcast band. It will be found that most manufacturers employ an intermediate frequency in the neighborhood of 460 kc. at the present time. Using a value this high for the I.F., it is seen that the majority of signals which could cause image frequency interference are well above the broadcast band. Most of the amateur and police radio signals are somewhat weaker than those of broadcasting stations; hence, unless the receiver is used in a locality close to one of these stations, they are not so apt to cause interference.

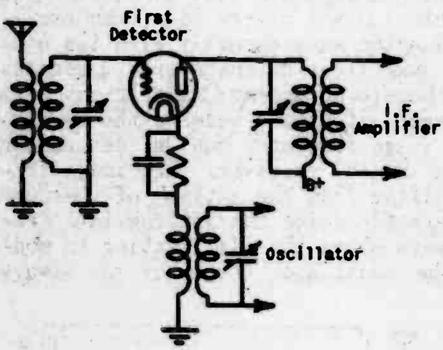


Fig.10 Antenna signal coupled to the grid of the first detector through a single tuned circuit.

Quite a number of the smaller superheterodynes and even some of the larger models available on the market today do not employ an R.F. amplifying stage ahead of the first detector for image frequency suppression. Often, only a single tuned circuit is used as shown in Fig. 10. Most of these receivers, however, are designed in such a manner that only under unusual conditions will any extreme, unsatisfactory interference arise. They all use a high I.F. and are sometimes provided with an extensive input tuning circuit of such design that its off-channel selectivity is sufficient to suppress ordinary image frequency signals. These sets also use an I.F. that is not evenly divisible by 10, such as 465, 456, 462.5, etc. Intermediate frequencies of these values do not coincide exactly with a possible image frequency signal in the broadcast band, because all broadcast stations are separated by 10 kc. Thus, if a 462.5 kc. intermediate is used, a possible image frequency signal would be 925 kc. above the dial setting. If the dial is set to 550 kc., then the image frequency falls at 1475 kc. There is no radio station operating on exactly this frequency; however, if a strong local station on 1470 or 1480 kc. is present, the image interference is apt to still occur.

Another source of image interference is known as "intermodulation interference". This is caused by two undesired signals, whose frequencies differ by exactly the I.F., beating against each other in the antenna circuit and producing an intermediate frequency on which is impressed the modulation of both the strong stations. If no R.F. amplifier or preselector is employed, it is possible for this dual-modulated beat frequency to pass through the first detector and into the I.F. amplifier. Both these stations will then be heard in conjunction with the station to which the receiver is tuned. The output from the loudspeaker under these conditions will be unintelligible.

Harmonic frequencies produced by the oscillator in a superheterodyne are also apt to be the source of image frequency interference. Prior to this time, we have assumed that the oscillator is generating only the single frequency to which it is tuned; however, all vacuum tube oscillators produce some harmonic content in their output. These oscillator harmonics may beat against a high-frequency station in the antenna circuit and thus produce the I.F. of the set and cause interference.

Suppose, for example, that a receiver using an I.F. of 260 kc. is tuned to 900 kc. The oscillator is tuned to 1160 kc. at the same time so as to beat against the 900 kc. station and produce the modulated I.F. of 260 kc. The second harmonic of the oscillator is 2 × 1160 or 2320 kc. Any signal in the antenna differing from 2320 kc. by 260 kc. and sufficiently strong to pass through the preselector or R.F. amplifier will produce a beat frequency against the oscillator's second harmonic and thus cause image frequency interference. Aircraft, commercial, and police stations operate along in this band; thus, if there is a station situated locally operating on a frequency of 2060 kc. or 2580 kc., this station could be heard from the speaker along with the regular broadcast station to which the receiver is tuned.

Another source of interference which, at first thought, may be attributed to image frequencies is that resulting from local code stations operating on frequencies below 500 kc. These are generally aircraft-beacon or marine stations, some of which possess fairly high power. If it so happens that the fundamental frequency on which a code station is operating is exactly equal to the I.F. of the superheterodyne, it is possible for that signal to feed directly through the circuits and reach the I.F. amplifier without beating against any other signal. In such a case, the local code station would be heard in conjunction with the regular broadcast station. This, obviously, is not an image frequency problem, so the most effective way to suppress it is to place a parallel tuned circuit directly in series with the antenna lead to the receiver, the circuit tuned exactly to the I.F. of the receiver. Some manufacturers incorporate such a tuned circuit in the design of the set. It is connected internally between the antenna post and the primary of the first R.F. transformer. It is commonly known as a "wave trap" and is very beneficial in some localities.

5. **THE PRESELECTOR OR R.F. AMPLIFIER.** Having learned the necessity for a selective circuit between the antenna and the input to the first detector stage, let us investigate the design requirements for this portion of a superheterodyne receiver.

A typical input circuit is shown in Fig. 11. Here, a single screen-grid R.F. amplifying stage is used, transformer coupled into the first detector. A screen-grid or pentode tube should be used because it does not need to be neutralized and a high voltage gain will be secured. The greater the voltage amplification obtained at the frequency of the desired signal, the less the possibility for image frequency interference. The adjacent channel selectivity of the R.F. amplifier is not so important, because after the desired signal is beat against the oscillator, the selectivity provided by the permanently tuned I.F. amplifier is sufficient to exclude those signals operating on adjacent channels.

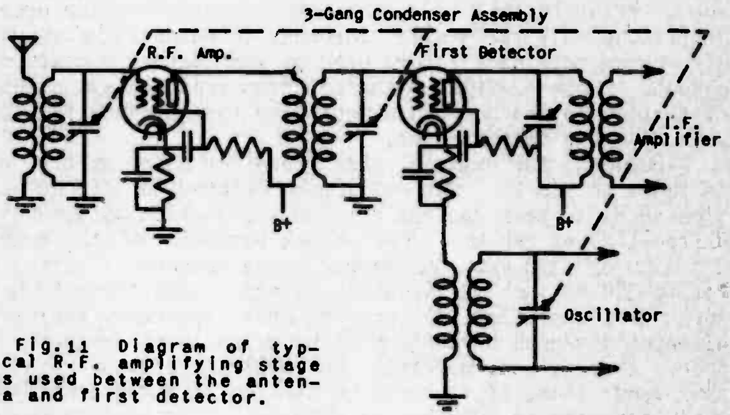


Fig.11 Diagram of typical R.F. amplifying stage as used between the antenna and first detector.

In those receivers where an R.F. amplifying stage is not used, wave traps or preselector units are generally employed to decrease the strength of the image frequency signal on the mixer grid. A four-circuit preselector unit was shown in Fig. 9. Since the desired signal passes through four tuned circuits before reaching the grid of the mixer tube, it will no doubt be considerably stronger than any image frequency signal which might be successful in passing through. The operation of the preselector unit shown in Fig. 9 was thoroughly discussed in Lesson 24.

Another wave trap circuit is shown in Fig. 12. Here coil L_1 is in series with the antenna lead to the primary L_3 of the first R.F. transformer. The resonant circuit L_2C_1 is placed in inductive relationship with L_1. This is commonly known as an "absorption" wave trap because it absorbs energy from the antenna circuit at the frequency to which it is tuned. L_2C_1 is always tuned to the frequency of the image signal and thus reduces the image frequency current through the primary L_3. If only one strong local station is causing interference, then L_2C_1 could be permanently tuned to that station and no further adjustment is required. However, if the receiver is used in a crowded locality and images are encountered at various points throughout the tuning range, C_1 should be ganged

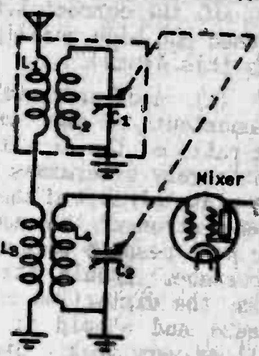


Fig. 12 Absorption wave trap. Sometimes used to prevent image frequencies.

on the tuning condenser assembly so as to maintain the resonant frequency of the wave trap exactly at the image frequency as the tuning dial is rotated. L_2C_1 should be adjusted to twice the intermediate frequency above the resonant frequency of L_4C_2, then properly aligned so as to track with L_4C_2, maintaining this same frequency difference over the entire dial. Some manufacturers incorporate such a variable image suppressor in the design of the set.

6. **THE OSCILLATOR.** The purpose of the oscillator in a superheterodyne is to generate an undamped high-frequency voltage to be beat against the incoming signal in the first detector or "mixer" stage. Several requirements are placed on an oscillator if it is to be satisfactory for this purpose. They may be enumerated as follows:

1. Constant frequency output.
2. Must generate a voltage at least 10 times greater than the strongest modulated R.F. signal fed to the first detector.
3. Low harmonic content.
4. Must be well shielded.
5. Designed so as to couple into the first detector in such a manner that its frequency is not affected by the incoming R.F. signal.

Let us thoroughly analyze each of the above requirements in their respective order.

(1) When the oscillator is set to a certain value so as to beat against the modulated signal and produce the correct I.F. it should remain constantly at that value and not drift above or below during the reception period. If the frequency of the oscillator drifts even 2 or 3 kc. either side of its correct value, then the intermediate frequency produced will not be exactly that to which the I.F. amplifier is tuned and the resultant receiver performance

is unsatisfactory, as evidenced by poor tone quality and lowered sensitivity. "Frequency drift" of the oscillator must be prevented because the receiver's performance depends entirely upon the production of the correct I.F. signal. Stable oscillator circuits must be used and high quality parts employed throughout in order to satisfy this demand.

(2) Another requirement of the oscillator's output is that it be constant in amplitude over the tuning range of the receiver. The ratio of the oscillator's voltage to the modulated signal voltage largely determines the strength of the I.F. signal produced in the plate circuit of the first detector. The oscillator voltage is always stronger than the modulated signal by approximately 10 times for best results when using grid-bias detection in the first detector stage. Should the oscillator voltage output be greater than this, the distortion content in the generated I.F. signal will increase and should it fall below this approximate value, the I.F. will be very weak. Since it is so important to maintain the proper oscillator voltage, it follows that the oscillator should produce the same voltage output at the low-frequency end of the tuning range as at the high-frequency end, as well as at all intermediate frequencies. A variation in oscillator output voltage greater than in a 3:1 ratio over the entire tuning range is considered unsatisfactory and will not be tolerated by good design engineers.

(3) The harmonic content in the output of the oscillator should be low to prevent the possibility of image frequency interference. This point was covered under previous discussion in this lesson.

(4) If the oscillator circuit is not well shielded, it is probable that the high-frequency signal will be radiated over a sufficient distance to cause interference in nearby receivers.

(5) Feeding the oscillator signal into the mixer circuit has long been a serious problem confronting design engineers. With the oscillator operating at a frequency different from the modulated R.F. signal, the two signals have a strong tendency to interact with each other in the mixer stage. The oscillator voltage tends to feed into the circuits tuned to the modulated signal frequency and, as expected, the modulated signal tends to feed into the oscillator circuit. Interactions of this nature produce a tendency toward frequency drift and generally cause the incorrect I.F. to be generated. Innumerable methods have been employed for mixing these two signals to produce the I.F., but not until the recent development of a special mixer tube has the problem been conquered satisfactorily without the objectionable circuit interaction. Since these older mixing methods are continually encountered in service work, several of them will be discussed in the following paragraphs.

7. **TYPICAL OSCILLATOR CIRCUITS.** Any vacuum tube oscillator circuit which will satisfactorily fulfill the preceding requirements may be used as the local oscillator in a superheterodyne receiver. Several typical circuits are illustrated and explained in the following discussion.

Fig. 13 shows an oscillator circuit very similar to the conventional Hartley oscillator as discussed in Lesson 23. The main difference is that the plate of the tube is operated at R.F. ground potential so as to permit the rotor plates of the variable tuning condenser to be grounded. The oscillating circuit consists of L_1C_1

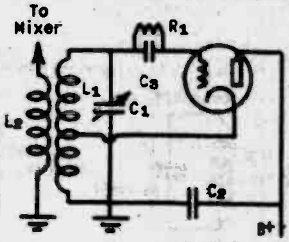


Fig.13 Revised Hartley oscillator circuit for a superheterodyne receiver.

and the feedback energy from the plate to the oscillating circuit is supplied through C_2. Grid bias is secured by the voltage drop produced across the grid-leak resistance R_1 when grid current flows through it.

A conventional feedback type oscillator is shown in Fig. 14. Here the oscillating circuit consists of L_2 and C_1 with the plate feedback coil L_3 serving to return sufficient R.F. energy to the grid circuit to maintain oscillations. Again, the grid bias is secured by the voltage drop across the grid-leak resistance and the R.F. output of the oscillator is inductively coupled into the mixer tube's circuit by mutual induction between L_2 and L_1. In actual construction, the three coils, L_1, L_2 and L_3 are wound on the same coil form.

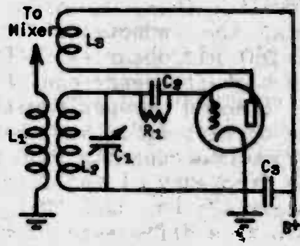


Fig.14 Typical feedback oscillator circuit as used in superheterodynes.

The two oscillator circuits shown in Figs. 13 and 14 must be designed so as to produce an output voltage that is above the frequency of the incoming signal by an amount equal to the I.F. Decreasing either the maximum inductance or capacity permits a higher frequency range to be covered, but unless given consideration, the rate of frequency change in the oscillator circuit will not coincide or "track" with the rate of change in the other tuned circuits. Ordinarily, fewer plates are used for the oscillator condenser and they are also shaped differently so as to "track" with the incoming signal. "Tracking" in a superheterodyne means the maintenance of an equal frequency difference between the oscillator and incoming signal over the entire tuning range of the receiver. Perfect tracking between the oscillator and incoming signal is very necessary if the correct intermediate frequency is to be produced at each setting of the tuning dial. Since this is such an important point in the design of a superheterodyne, it is well to investigate the two tracking methods ordinarily used.

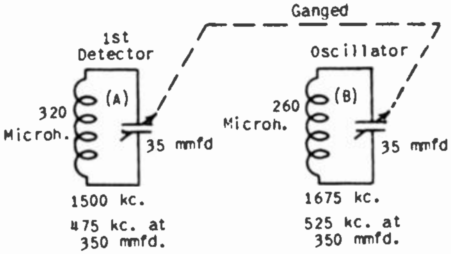


Fig.15 Two resonant circuits tuned to different frequencies using the same size tuning condensers but different size tuning coils. These circuits will not track properly.

In Fig. 15, two tuned circuits are shown, the one at A representing the grid circuit of the first detector and the other the oscillator tuned circuit. The first detector grid circuit must be tuned to the frequency of the desired modulated signal and the oscillator must be maintained above this by 175 kc. (assuming the I.F. to be 175 kc.). Let us assume that the same size condenser is to be used for tuning each of these resonant circuits, the minimum capacity of which is 35 mmfd. and the maximum capacity, 350 mmfd. Since the highest frequency to be received is 1500 kc., a 320-microhenry coil will be necessary with the 35-mmfd. condenser to produce resonance at this frequency in the first detector grid circuit. Then, in order to tune the oscillator to 175 kc. above this, the inductance across the oscillator tuning condenser must be 260 microhenries. (These are approximate values.) Thus, at the high-frequency end of the dial, the oscillator will be aligned or "tracked" properly with the incoming signal and will produce the correct I.F. Now when the tuning condensers are both adjusted for maximum capacity (350 mmfd.) and the inductance values unchanged, the frequency of the first detector grid circuit will be approximately 475 kc. and that of the oscillator will be about 525 kc. This is a difference of only 50 kc.; so the tracking is by no means accurate. An I.F. of 50 kc. will be produced at the lower end of the tuning range instead of the correct value of 175. This is illustrated by the graph shown in Fig. 16. Curve C on the graph illustrates the variation of frequency with the capacity change in the first detector grid circuit. Curve B illustrates the change in frequency that would occur in the oscillator tuned circuit if the condenser plates were of exactly the same size and shape. It will be noted that these two curves, B and C, are separated by 175 kc. only at the high-frequency end of the tuning range and gradually converge as the tuning capacity is increased.

This is unsatisfactory because the correct intermediate frequency is not produced over the complete tuning range of the receiver. To correct this condition, the oscillator rotor plates are generally made different in shape as shown in Fig. 17. By adjusting the taper of the oscillator rotor plates, it is possible

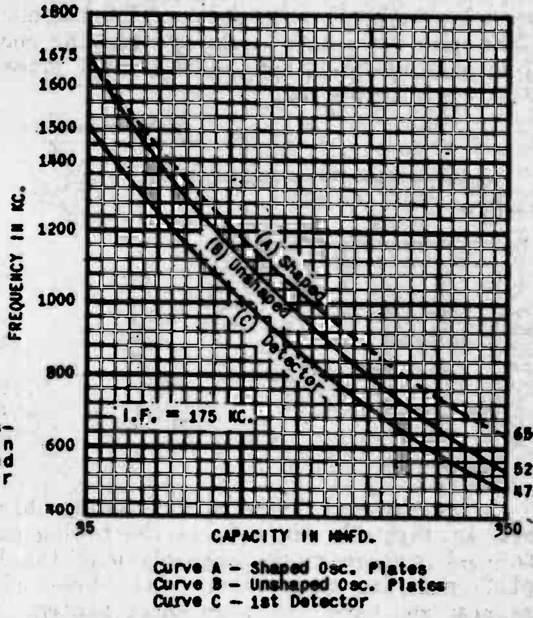


Fig.16 Graph to illustrate the difference in the tracking of unshaped and shaped oscillator plates.

to maintain a frequency difference of exactly 175 kc. as the tuning dial is rotated from minimum to maximum capacity. The output frequency from the oscillator would then track as shown by curve A on the graph in Fig. 16. This method of tracking the oscillator with the frequency of the incoming signal has been used in commercial receivers to a great extent. With properly designed oscillator

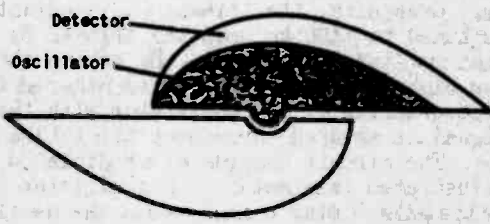


Fig.17 Illustrating how the rotor plates of the oscillator tuning condenser are made smaller and have a different taper than the preselector plates.

rotor plates, it is only necessary to align the oscillator frequency at the high end of the tuning range, then accurate tracking will be maintained throughout the lower frequency end of the dial.

An alternative method of tracking the oscillator employs the use of a separate tracking condenser in the oscillator circuit.

When a tracking condenser is used, the oscillator tuning condenser is made exactly the same size as the other variable condensers on the ganged assembly and has exactly the same shaped rotor plates. To compensate for the tendency of the oscillator frequency to merge with the frequency of the first detector grid circuit, a high-capacity condenser is placed in series with the oscillator tuned circuit. In some cases this high-capacity tracking condenser is made variable and in others it is fixed, with a small trimmer connected across it for alignment purposes.

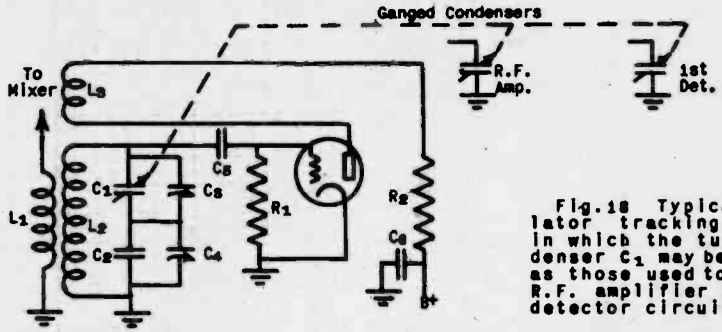


Fig. 18 Typical oscillator tracking circuit in which the tuning condenser C_1 may be the same as those used to tune the R.F. amplifier and first detector circuits.

A typical oscillator circuit using this method of tracking is shown in Fig. 18. Here C_1 is the tuning condenser for the oscillator and is ganged on the assembly with the first detector and R.F. amplifier tuning condensers. All three of them are exactly the same size and have the same shape plates. The tracking or "padding"[1] condenser in this circuit consists of the series fixed condenser C_2. Depending upon the size of C_2, the inductance L_2 may be made the same as the inductance used in the other tuned circuits, or it may be of a smaller value. In Fig. 18, the main tuning condenser C_1 has the small trimmer C_3 connected in parallel with it so as to permit alignment of the oscillator frequency at the high-frequency end of the tuning range. For a low-frequency adjustment, the trimmer condenser C_4 is connected across the padding condenser C_2. Generally, the trimmer C_3 is adjusted when the receiver dial is tuned to 1400 kc. and the trimmer C_4 adjusted when the receiver dial is tuned to 600 kc. By making these two adjustments, one at the high-frequency end and the other at the low-frequency end, perfect tracking of the oscillator with the frequency of the incoming signal is assured throughout the entire tuning range.

The circuit diagram of a Radiola 80 receiver, shown in Fig. 19, illustrates this method of oscillator tracking. The condenser C_9 is the main tuning condenser for the oscillator and C_8 is the series padding condenser. Both of these condensers are connected across the oscillator inductance L_8. The small trimmer C_6 is the low-frequency (600 kc.) adjustment on the oscillator and the small trimmer

[1] A "padding" condenser is another word frequently used for a "tracking" condenser. Both mean the same.

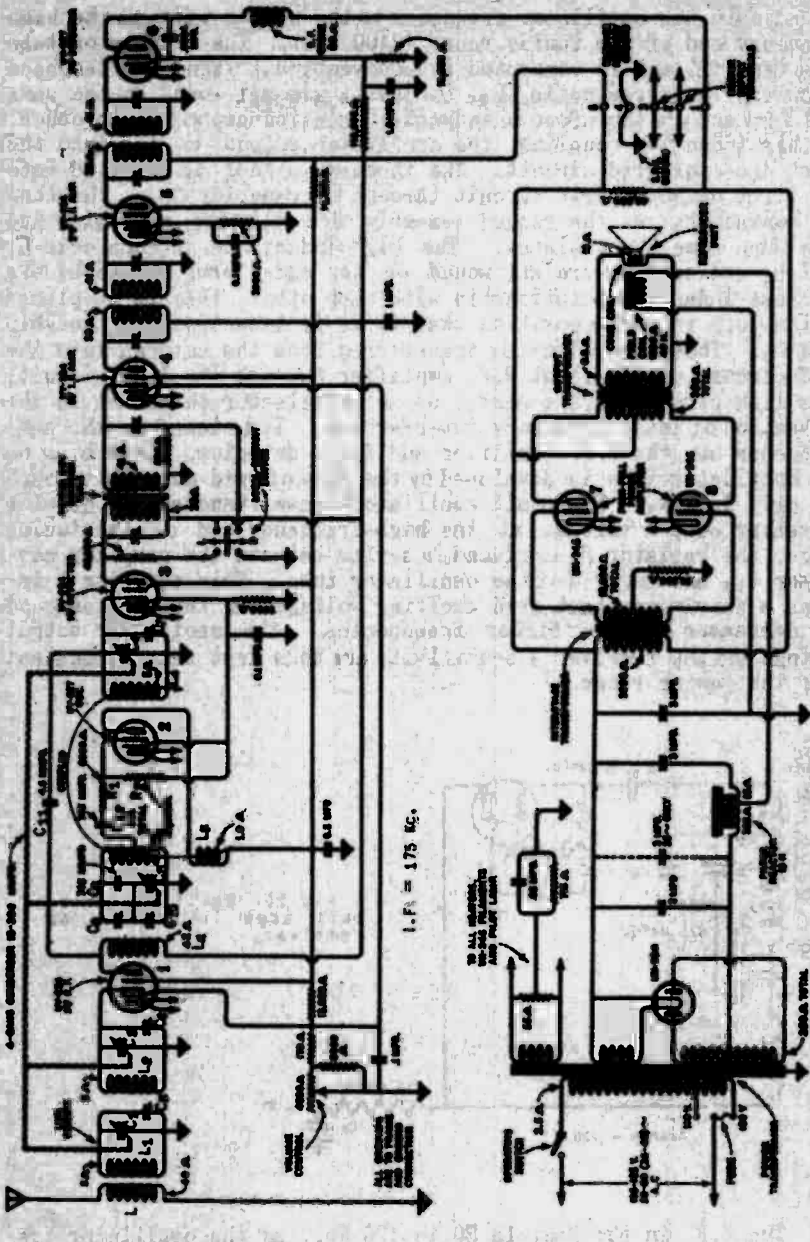


Fig.19 Schematic wiring diagram of Radiola 80 receiver.

C_{10} adjusts the oscillator frequency to the proper value at the high frequency end of the tuning range (1400 kc.). The oscillator tube is a type 227 and is connected in a conventional inductive feedback circuit. The three coils, L_3, L_4 and L_5 are all wound on the same coil form and are therefore in inductive relationship with each other. By this inductive coupling, the oscillator output is fed into the first detector grid circuit. The incoming signal is coupled into the first detector grid circuit through the capacity C_{11}. The tuning condensers on the ganged assembly are all the same size and have the same shape plates. The high-inductance antenna coil L, coil L_1 and coil L_2 are all wound on the same form. L and L_1 are in close inductive relationship with each other, then L_2 is placed on the form in such a position that it is in inductive relationship with L_1. Thus, the signal is transferred from the antenna into the grid circuit of the first R.F. amplifier through the link circuit. This link circuit merely serves as a preselector to assist in the prevention of image frequency interference. It is tuned to the same frequency as the R.F. amplifier and first detector. Grid bias on the oscillator tube is developed by the flow of grid current through the grid leak R_2. Since all oscillators have a tendency to develop a greater output voltage at the high-frequency end of the tuning range, the resistor R_1 is placed in series between the coupling condenser C_{12} and the grid of the oscillator tube. This resistor maintains a fairly constant grid exciting voltage as the reactance of C_{12} decreases at the higher frequencies. The oscillator output voltage and the receiver's sensitivity are thus kept nearly constant over the tuning range.

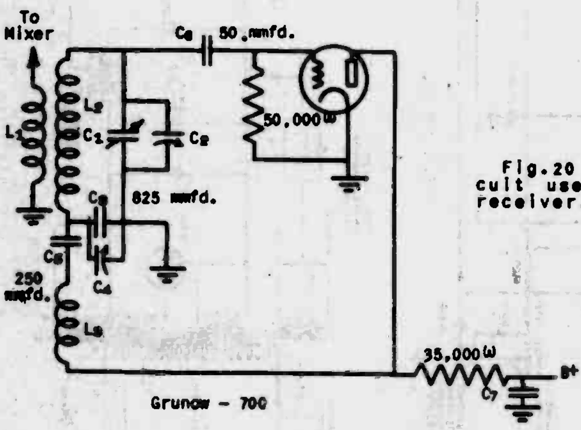


Fig.20 Oscillator circuit used in Grunow 700 receiver.

The I.F. in the Radiola 80 is 175 kc., so the oscillator frequency must be maintained 175 kc. above the frequency of the incoming signal. There will be additional discussion on this circuit in later paragraphs of this lesson.

Another commercial oscillator circuit is shown in Fig. 20.

This is the oscillator stage in a Grunow Model 700 receiver. In this circuit, the oscillator tuning condenser is C_1 with the small trimmer C_2 shunted across it for alignment purposes. The padding condenser is the 825 mmfd. condenser C_3 and a slight adjustment on this capacity is provided by trimmer C_4. The feedback in this circuit occurs from the plate of the oscillator tube through L_3 and C_5 into the resonant grid circuit. The output of the oscillator is inductively coupled to L_1 which in turn is connected to the cathode of the mixer tube.

8. **THE FIRST DETECTOR OR MIXER STAGE.** The mixer stage in a superheterodyne is always operated as a detector; hence, it is often called the "first detector". Square law or linear detection may be employed, both having advantages which will be discussed. The grid-bias method of detection is always used in modern receivers so there is no necessity for introducing grid-leak detector circuits.

A grid-bias, square law detector is one which operates entirely over the curved portion of the grid voltage-plate current characteristic curve and is intended primarily for the reception of weak signals. When used as the first detector in a superheterodyne, a square law detector gives satisfactory results if the oscillator voltage is maintained approximately 10 times the average strength of the incoming signal. The beat frequency (I.F.) output from a square law detector depends upon the product of the strength of the oscillator voltage and the strength of the incoming signal voltage. Thus, it is desirable to feed an oscillator voltage as strong as possible into the first detector circuit in order to secure a greater I.F. output. The limiting factor in this respect is the point at which the grid of the tube is driven positive which, of course, results in the flow of grid current and distortion of the I.F. signal. A square law detector is generally operated at a low plate voltage and low grid bias, so the oscillator output voltage cannot attain a very high value without producing a grid current flow. Because of these conditions, it is not possible to secure an appreciable I.F. voltage output from a square law detector, even though it may be operated under ideal conditions. High *voltage gain*, however, is secured through a square law first detector when extremely weak signals are being received. Therefore, it is more adaptable to short-wave receivers, rather than those designed for broadcast reception. An advantage possessed by a square law detector is that the harmonic content of the I.F. produced in the plate circuit is extremely low.

A linear (power) detector is more satisfactory for mixer tube operation in a superheterodyne receiver designed for broadcast reception. A linear detector, of course, is operated under conditions of higher plate voltage and higher grid bias and thus permits the application of stronger input signals without driving the grid positive. The maximum I.F. output will be secured from a linear detector when the oscillator voltage and incoming signal voltage are approximately equal in value. Under these conditions, however, the harmonic content of the I.F. signal produced in the plate circuit is extremely strong and serious interference in the form of audio beat notes or whistles may occur. Even though these harmonics are present in the plate circuit of the mixer tube, the I.F. or beat frequency will be produced as usual and fed into the I.F. amplifier, the harmonics being excluded by the tuned plate load. These harmonics, however, are objectionable, in that they are apt to feed back to the input circuit of the first detector or into the R.F. amplifier and produce beat notes with low-frequency incoming signals. Thus, if the intermediate frequency is 260 kilocycles and a strong third harmonic is produced in the first detector plate circuit, it is possible for this harmonic signal of 780 kc. to feed back to the input circuit and beat against an incoming signal from a broadcast station operating on 780 kc. When two R.F. signals close to the same frequency are beat against each other, an audio note or whistle is produced. This audio note will cross-modulate onto the carrier to which the receiver is tuned and result in a continuous, low-pitched whistle from the speaker.

To reduce the harmonic content in the output of a linear detector, it is necessary that the oscillator signal be at least 10 times stronger than the incoming signal. When the oscillator voltage is this high, the harmonic frequencies of the I.F. signal are too weak to feed back to the input of the first detector or R.F. stage and produce beat notes.

The performance of a linear detector is different than that of a square law detector in that the maximum I.F. signal voltage is produced by a linear detector when the oscillator and incoming signal voltages are approximately equal in strength. As the oscillator voltage is made greater than the incoming signal, the strength of the I.F. signal produced in the plate circuit decreases; therefore, when the oscillator voltage is increased to prevent the production of I.F. harmonics, at the same time a sacrifice is made in the receiver's sensitivity.

Modern receivers nearly always employ a super-control screen-grid or pentode tube in the mixer or first detector stage. When using this type of tube, operation comparable to square law detection is obtained when receiving weak signals; then upon tuning in a strong local signal, the grid-bias voltage is increased (by the volume control) which causes the tube to perform as a linear detector. In this manner, a strong local station is prevented from driving the grid positive and at the same time increased sensitivity is obtained when receiving weak signals.

The method that is used to couple the output of the oscillator into the first detector circuit is one of great importance. These two signals must be mixed with a minimum of reaction on the oscillator frequency. Several methods of coupling the oscillator are shown in the following figures.

In Fig. 21, the output of the oscillator is shown coupled into the cathode circuit of the first detector. This is one of the most commonly used methods. The incoming modulated R.F. signal is fed into the tuned grid circuit L_1C_1; hence, the modulated R.F. voltages developed across this resonant circuit vary the instantaneous potential difference between the grid and cathode of the tube and thus affects the plate current. The oscillator output voltage is inductively coupled from L_3 into the cathode coil L_2 and thus varies the instantaneous potential between cathode and ground, which likewise affects the plate current. In this manner, the

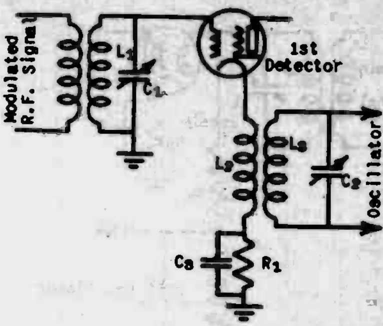


Fig. 21 Oscillator voltage fed into the first detector through inductive coupling with the cathode coil.

plate current of the first detector tube is controlled by both signals. They are mixed together and, since the tube is operated as a detector, the I.F. signal will be produced in the tuned plate circuit. Grid bias is secured on the first detector tube by the passage of plate current through R_1.

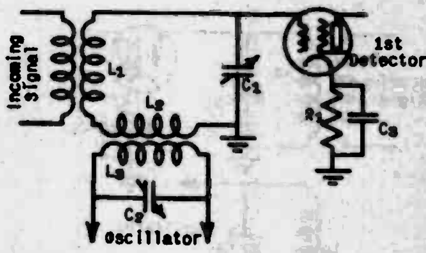


Fig. 22 Oscillator voltage mixed directly in the tuned grid circuit of the first detector.

In Fig. 22, another method of introducing the oscillator voltage into the first detector circuit is shown. This method is not as satisfactory as that shown in Fig. 21 because it is easily possible for the incoming signal to change the oscillator frequency. The oscillator output is inductively coupled into L_2, which is a portion of the tuned grid circuit. The incoming signal is introduced into L_1, so the voltages developed across this resonant grid circuit are determined by both the incoming R.F. signal and the oscillator signal. Coils L_1 and L_2 are tuned by C_1 to the frequency of the incoming signal. As C_1 is rotated to adjust the frequency of the grid circuit, a reflection of impedance is very likely to occur from L_2 into L_3, thus changing the frequency of the oscillator and producing unsatisfactory results.

A widely used method of coupling the oscillator into the mixer circuit is shown in Fig. 23. Here a resistance and capacity are connected from the grid of the mixer tube to the ungrounded end of the oscillator resonant circuit. The R.F. output of the oscillator is fed through this series combination to the grid of the first detector and affects the plate current the same as the modulated signal voltage developed across L_2C_1. The small coupling condenser C_2 and the high resistance R_1 assist in maintaining a constant voltage on the first detector grid from the local oscillator as the

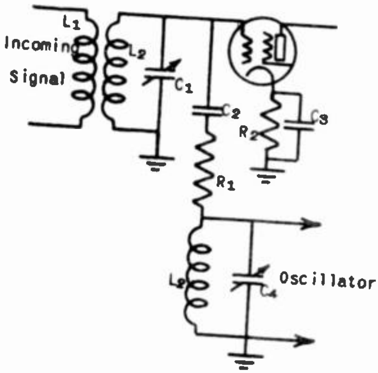


Fig.23 Oscillator voltage fed to the first detector grid through a series resistance-capacity arrangement.

frequency of the oscillator is changed. It should be recalled that the variation of oscillator voltage output should not exceed a ratio of 3:1 over the tuning range.

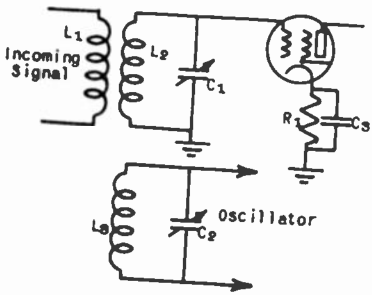


Fig.24 Oscillator voltage inductively coupled into the tuned grid circuit of the first detector.

Another coupling circuit used in some of the earlier superheterodynes is shown in Fig. 24. The oscillator coil L_3 is placed in inductive relationship with the grid coil L_2. L_2 is also in inductive relationship with L_1, from which it receives the incoming modulated R.F. signal. All three of these coils are generally wound on the same form and the complete assembly shielded to prevent the radiation of energy. The model 80 Radiola receiver, shown in Fig. 19, uses this method of coupling.

The oscillator voltage may also be introduced into the mixer tube circuit, as shown in Fig. 25 when a four or five-element tube is used. The output of the oscillator is delivered into the screen-grid circuit. The screen-grid potential is varied in accordance with the oscillator output and since the incoming signal is applied directly to the control grid of the tube, both voltages will affect the plate current and the modulated I.F. voltage is produced in the plate circuit. In this type of circuit, the voltage output from the oscillator must be greater than in those circuits previously shown. Before, the oscillator voltage has been introduced into the control grid or cathode circuit where the full amplification of the tube is obtained. The transconductance from screen-grid to plate is much less than the Sm from control grid to plate, so the

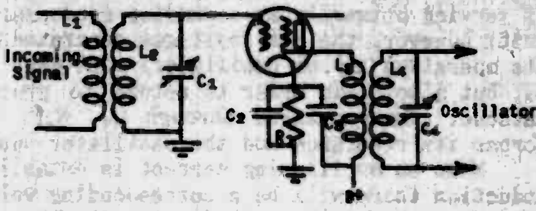


Fig. 25 The incoming signal is applied to the control grid and the oscillator voltage is applied to the screen grid; the beat frequency is produced in the plate circuit.

oscillator voltage must be greater when applied to the screen grid if the conventional 10:1 ratio is to be maintained. If a pentode tube is used as the first detector, the oscillator output may be introduced into either the screen-grid or suppressor-grid circuit, but in either case, it must be a high voltage.

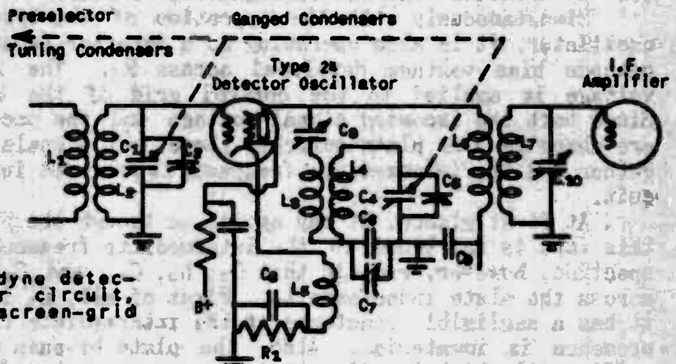


Fig. 26 Autodyne detector-oscillator circuit, using type 24 screen-grid tube.

Another oscillator-first detector arrangement that is quite popular in auto and midget receivers is shown in Fig. 26. This type of circuit is generally known as an "autodyne" detector-oscillator combination. Here a type 24 screen-grid tube serves as the first detector, as the mixer, and as the oscillator tube. This is an exact circuit diagram of the autodyne detector-oscillator stage in a Philco model 51 receiver. The intermediate frequency is 175 kc. A pentode tube may also be used in this same type of circuit.

In Fig. 26, the oscillator tuned circuit consists of the inductance L_4 and the tuning condenser C_4. C_4 is on the ganged assembly with the variable condensers which tune the grid circuit of the first detector and the preselector. It has the same size and same shape plates. C_6 is the series padding condenser used for tracking the oscillator; C_5 is the high-frequency alignment trimmer and C_7 is the low-frequency trimmer. The plate of the type 24 detector-oscillator tube is coupled to the oscillator tuned circuit both inductively and capacitively. The inductive coupling exists between L_3 and L_4. The condenser C_3 is so high in value that its reactance to the oscillator frequency is negligible. The capacity coupling between the plate of the detector-oscillator tube and the oscillator tuned circuit exists by way of condenser C_6. C_6 is serving primarily as a padding condenser in the oscillator circuit; however, the R.F. voltages generated by the tube (considering its operation as an oscillator) must pass not only through C_3 and L_3, but also C_6 in order to return to ground and then back to the cathode. Upon passing through C_6, R.F. voltages are developed across its reactance and the oscillator tuned circuit is excited.

When an oscillating current is established in L_4C_4, by mutual induction there will be a corresponding voltage induced in L_3. L_3 is connected in the cathode circuit; hence, the plate current is varied by this induced voltage. The plate current variations are then fed back into the oscillating circuit through the inductive and capacitive coupling provided by L_3 and C_6. Considering proper values chosen throughout the design of the circuit, there will be sufficient feedback from the plate circuit into the cathode circuit to maintain undamped oscillations in L_4C_4.[1]

Simultaneously with the operation of the type 24 tube as an oscillator, it is also operating as a detector because of the high cathode bias voltage developed across R_1. The incoming signal voltage is applied to the control grid of the tube from L_2C_1. Since both the incoming signal voltage and the oscillator voltage are changing the plate current, these two signals are mixed together and the intermediate frequency is produced in the plate circuit.

At first glance, it may appear as though the plate circuit of this tube is not tuned to the intermediate frequency. Closer inspection, however, reveals that C_3, L_3, C_6, and C_9 are connected across the plate inductance L_6. First of all, L_3 is so small that it has a negligible reactance at the intermediate frequency so its presence is immaterial. Also, the plate by-pass condenser C_9 is sufficiently high in value that its reactance may be disregarded. There remains, then, the condensers C_3 and C_6 connected across the plate circuit inductance L_6. Since C_6 is fixed in value, C_3 is adjusted until the resonant circuit C_3, C_6, L_6 is tuned exactly to the intermediate frequency of 175 kc. When this adjustment is made, the plate circuit of the detector-oscillator tube is properly tuned and the I.F. current passing through L_6 will be transferred by mutual induction into the grid circuit of the first I.F. amplifier.

From this discussion, it is apparent that a single tube is performing a multitude of operations and that the total number of parts used for converting the incoming signal to the intermediate frequency is at a minimum. This provides for cheaper production and a more compact arrangement of the receiver. For these reasons,

[1] Voltages applied between cathode and ground in any vacuum tube affect the plate current the same as voltages applied between the grid and ground; hence, the cathode is always considered to be a portion of the input circuit and voltages applied thereto produce plate current changes.

an autodyne frequency changer of this design is quite popular in auto and midget receivers. Due to the close association between the oscillator, incoming signal and I.F. currents, it is probable that there will be circuit interactions which tend to change the oscillator frequency. This is especially true when a screen-grid tube is used, but is somewhat overcome in a pentode due to its reduced interelectrode capacities.

Detector-oscillator tubes used in autodyne circuits have a tendency to stop oscillating when the cathode emission becomes low. It is very essential that the tube have a very high transconductance to maintain operation. Decreased cathode emission causes the transconductance of any tube to drop; therefore, should the occasion arise to locate trouble in this type of frequency converter circuit, a defective tube should be the first suspect. Even upon inserting a new tube, it is sometimes found that the oscillator will still not operate. This is simply because the new tube's characteristics are such that it will not function properly in the delicate circuit. It may be that several new tubes will have to be tried until one is found that does not possess the slight defect which prevents oscillation. Stubborn cases can sometimes be remedied by reducing the size of the cathode biasing resistance R_1. Reducing this resistance to about two-thirds its former value will allow the transconductance and amplification factor of the tube to increase. Care should be taken, however, not to reduce its value too much, because the operating point may be shifted to the straight portion of the E_g-I_p characteristic and detection will not take place.

Because of the delicate performance, characteristic of a screen grid detector-oscillator tube, a newer tube has been introduced, known as a pentagrid converter. This type of tube has two separate sections in one envelope, a triode and a pentode. The triode section is used to generate the oscillator voltage and the pentode section serves as a mixer and first detector. Thus the advantage of using the single tube and a minimum of parts is acquired without the difficulty of extremely sensitive operation. Among pentagrid converter tubes designed for this purpose are the 2A7, 1C6, 6A7, 1A6, 6A8, etc. Their operation will be discussed in Lesson 30 of this unit.

Even pentagrid converter tubes are found to possess certain disadvantages when used for the reception of ultra-high frequency signals in all-wave receivers. In most of the modern, all-wave superheterodynes, a special type of mixer tube (such as the 6L7) is used as the first detector. A separate oscillator must be used with this special mixer tube since it only performs the function of mixing the oscillator and incoming signals to produce the I.F. voltage in the plate circuit.

9. I.F. AMPLIFIERS. The sensitivity, selectivity and fidelity characteristics of a superheterodyne receiver depend largely on the design of the I.F. amplifier. Conversion of the incoming signal to the intermediate frequency has been done solely for the purpose of making these advantageous characteristics possible.

The I.F. amplifier is permanently tuned to one frequency. In all broadcast receivers, the I.F. is below 500 kc. When the manufacturer selects the intermediate frequency, his choice is governed by several factors. If a low intermediate frequency is used, that is, below 250 kc., it will be possible to obtain a high amplification per stage, since stray coupling (capacity and magnetic) throughout the circuit is at a minimum. This permits the use of a high plate load impedance in each plate circuit with the resultant high voltage gain. On the other hand, a low intermediate frequency is undesirable from the standpoint of image frequency interference. A station likely to cause image frequency interference is then closer to the desired signal, so the off-channel selectivity of the preselector or R.F. amplifier must be much improved. Good fidelity or tone quality is also more difficult to secure when the intermediate frequency is low. This is because the carefully tuned I.F. circuits will not easily permit the passage of a band of frequencies 10 or 20 kc. wide when it is adjusted to a fundamental resonant frequency below 200 kc.

A high intermediate frequency, that is, between 400 and 500 kc., is advantageous in preventing image frequency interference and also in securing the 10 to 20 kc. band-pass through the I.F. amplifier necessary for high-fidelity reproduction. Raising the intermediate frequency to this value, however, does not permit as much voltage amplification per stage because of the increased tendency toward instability due to stray inductive and capacitive coupling. The use of highly efficient I.F. transformers greatly compensates for this latter disadvantage.

Considering all requirements, an intermediate frequency between 450 kc. and 480 kc. is quite satisfactory and is used in most modern receivers. With intermediate frequencies in this range, stations that could cause an image frequency signal are placed between 900 and 1,000 kc. away from the desired signal, making it unnecessary for the preselector or R.F. amplifier to possess extremely good off-channel selectivity. In fact, many modern superheterodynes eliminate the use of an R.F. stage by merely using a high intermediate frequency. The fidelity of reproduction can also be made much better with a high-frequency I.F. amplifier. For example, if it is permanently tuned to 460 kc., then with practically no sacrifice of voltage amplification, the resonant frequency of the various tuned circuits can be adjusted to permit a band of frequencies 10 or 20 kc. wide to pass through. This is necessary for good tone quality because the sideband frequencies which accompany all modulated signals must not be attenuated. If a 10,000-cycle audio note is modulated on an I.F. of 460 kc., then the upper sideband has a frequency of 470 kc. and the lower sideband 460 kc. To properly reproduce this 10,000-cycle audio note, it is necessary for the carrier and both sidebands to reach the second detector, so the characteristics of the I.F. amplifier must be such that the passage of a band of frequencies 20 kc. wide is allowed; that is, from 450 to 470 kc.

A typical one-stage I.F. amplifier using a pentode tube is shown in Fig. 27. The first detector plate circuit is tuned by the resonant circuit L_1C_1 to the intermediate frequency desired. Through transformer coupling, the I.F. signal is fed into the grid circuit of the pentode I.F. amplifier. L_2C_2 is tuned to exactly

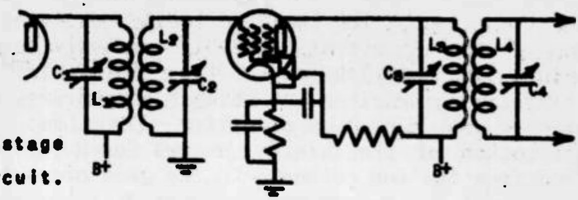


Fig.27 Typical one-stage I.F. amplifier circuit.

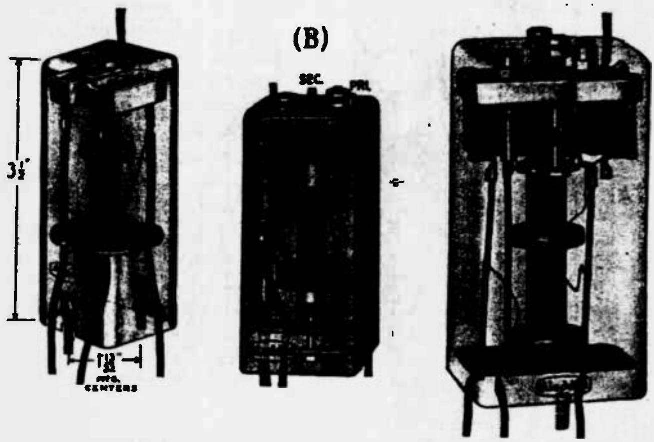
the same frequency as L_1C_1. Bear in mind that these resonant circuits are not changed when the incoming signal is tuned; their original adjustment is a servicing operation. The parallel tuned circuit L_3C_3 is the plate load impedance for the pentode I.F. amplifier. When it is tuned to resonance, a very high impedance load is presented to the plate of the tube. Since all screen-grid and pentode tubes have a high plate resistance, the high impedance load makes it possible to obtain a high voltage gain from the stage. Amplification of from 100 to 250 times is possible through a single-stage I.F. amplifier. This is about four or five times as much amplification as could be obtained if the same type tube were used as an amplifier of radio-frequency voltages from 1,000 to 1,500 kc.

The amplified I.F. voltage produced across L_3C_3 is transformer coupled to L_4C_4 (both circuits permanently tuned). This may be the grid circuit of a second I.F. amplifier or the second detector.

The design of the I.F. coupling transformers is of paramount importance. Three I.F. transformers, each slightly different, are shown in Fig. 28. The I.F. transformer at A has the primary and secondary windings permanently fixed and each is tuned by a small

(B)

(A)



(C)

Fig.28 (A) I.F. transformer with fixed coupling between the primary and secondary, each tuned by a mica compression-type condenser.
(B) I.F. transformer which uses the fixed condenser, variable inductance method of tuning.
(C) I.F. transformer with fixed coupling between the primary and secondary, each being tuned by small, air-dielectric variable condensers.

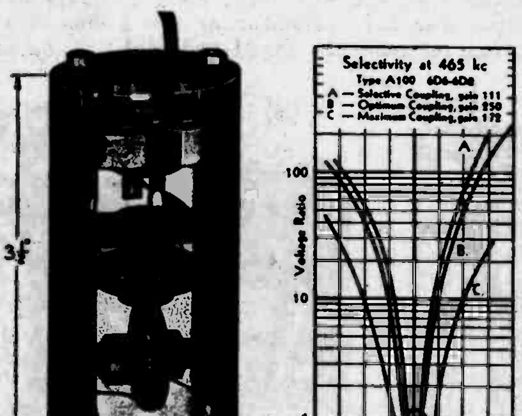
mica, compression-type condenser. The two windings are on a wooden dowel in the center of the transformer and permanently separated about one inch. The two mica tuning condensers are located on the top of the transformer assembly, directly beneath the top of the shield can. Small holes in the shield permit the insertion of an insulated screwdriver or hexagon-shaped wrench for adjusting the primary and secondary circuits. The three leads protruding from the bottom of the shield can are for B+, plate, and ground. The lead from the top connects to the grid of the I.F. amplifier.

The I.F. transformer shown at B is provided with a means of varying the inductance of the two coils so as to tune the circuits to resonance. The two small fixed condensers on the left side of the shield can are connected across the primary and secondary windings respectively. A finely divided iron core is fitted into each of them. The positions of the cores may be adjusted by slot-headed screws protruding from the top of the shield can. Changing the position of the iron cores causes enough inductance change to tune the circuits to resonance. A variable inductance gives a smoother change through resonance than a variable capacity.

The I.F. transformer shown at C in Fig. 29 has the primary and secondary windings permanently fixed and each is tuned with a small air-dielectric condenser. Air dielectric condensers are more satisfactory than the mica type, due to the lower dielectric losses exhibited by air. Also humidity and temperature changes do not affect air-dielectric tuning condensers to a noticeable degree.

An I.F. transformer wherein the coupling between the primary and secondary windings is variable is shown at A in Fig. 29. The

(A)



(B)

Fig.29 (A) Modern I.F. transformer wherein the coupling between primary and secondary is variable.
(B) Graph to show the selectivity at 465 kc. when the I.F. transformer at A is used between two 6D6 I.F. amplifying stages.

two coils are closer together than in the three transformers shown in Fig. 28, but are placed at right angles to each other and the lower coil is arranged on a track whereby its distance relative to the upper coil can be changed. Each winding is tuned by small mica condenser. The characteristics of this transformer are illustrated by the graph at B in Fig. 29. When the greatest selectivity is desired, the two coils are moved far apart; this reduces the voltage gain at the same time. Curve A on the graph shows the selectivity when the two windings are adjusted for selective coupling and under this condition, a gain of approximately 111 times can be secured with a type 6D6 tube as the I.F. amplifier. Curve B on the graph is obtained when the two windings are moved slightly closer together, giving the optimum coupling value. The selectivity is thus decreased slightly, but the gain rises to a value in the vicinity of 250. This represents the most desirable coupling unless the transformer is to be adjusted for high-fidelity reception. Moving the two coils extremely close together gives maximum coupling, the characteristics of which are illustrated by curve C. Then, the gain is decreased slightly, but the band width has been broadened to permit equal amplification of a band of frequencies approximately 20 kc. wide. In high-fidelity receivers, the I.F. transformers are adjusted to this condition.

When an I.F. amplifier is adjusted for high-fidelity reception, it is quite possible that an adjacent channel station 10 or 20 kc. away from the desired station will also pass through the I.F. amplifier to cause interference. This is especially true when the broadly-tuned receiver is used for distant reception. The result is very annoying, since reproduction from the speaker consists mainly of garbled and unintelligible speech together with beat notes or whistles. The expression often used to describe this type of interference produced by a broadly tuned I.F. amplifier is "monkey-chatter". For distant reception, the I.F. amplifier should be made selective so as to prevent this adjacent channel interference. Most modern receivers that are designed for high-fidelity reception have a control knob on the front panel to change the characteristics of the I.F. amplifier from "selective" to "fidelity" for distant and local reception, respectively.

The first I.F. transformer, which couples from the first detector into the grid circuit of the first I.F. amplifier, is always adjusted by the manufacturer for maximum selectivity characteristics. This is to prevent those adjacent channel stations which are heterodyned (beat) by the oscillator to a frequency 10 kc. away from the I.F. from passing into the I.F. amplifier circuit. A single, selective transformer in this first position will not suppress the sidebands of the desired station if the remaining tuned circuits in the I.F. amplifier are properly adjusted for band-pass characteristics. To improve the selectivity of this first I.F. transformer, some manufacturers place a copper shield ring between the fixed primary and secondary windings. If the primary and secondary coupling is variable, the copper ring is not necessary. The copper ring has the effect of decreasing the mutual inductance between the two coils, because of the obstruction it offers to the magnetic lines of force. It will be noticed that on the diagram of the RCA Radiola in Fig. 19, this copper shield is indicated between the primary and secondary windings of the first I.F. transformer.

10. THE SECOND DETECTOR AND A.F. AMPLIFIER. There is no need for a detailed discussion on this portion of a superheterodyne receiver because it is similar in all respects to the detector and A.F. amplifier employed in T.R.F. receivers. Prior to the renewed use of diode detection, the second detector was generally of the grid-bias type. The purpose of the second detector is to remove the audio modulation on the I.F. signal. Following the second detector, a conventional A.F. amplifier is employed which in turn drives the loudspeaker.

11. ADVANTAGES AND DISADVANTAGES OF THE SUPERHETERODYNE RECEIVER. Amplification is secured in a superheterodyne receiver from a source which cannot be duplicated in a T.R.F. receiver. When the oscillator is beat against the incoming signal to reduce the modulated carrier to the intermediate frequency, the strength of the I.F. signal depends not only upon the strength of the incoming broadcast signal, but also upon the oscillator voltage. By using a strong oscillator voltage, a definite voltage gain is secured through this frequency conversion process.

It is possible to obtain more uniform amplification over the tuning range with a superheterodyne receiver than with a T.R.F. receiver because the major portion of the amplification takes place at a fixed frequency in the superheterodyne; namely, the intermediate frequency. In the T.R.F. receiver, amplification is obtained at the frequency of the incoming signal which is continuously variable from 550 to 1600 kc. in a broadcast receiver.

Since most of the amplification occurs at a fixed frequency in a superheterodyne and since this fixed frequency is below 500 kc., it is possible to obtain an amplification extremely high without sacrificing fidelity.

Also, since the majority of the amplification is secured at a low fixed frequency, it is possible to design the I.F. amplifier so that selectivity and amplification are available with minimum sideband attenuation and reduction of tone quality. As mentioned, quite a number of the modern receivers are equipped with a selectivity-fidelity control to adjust the I.F. amplifier response to optimum conditions.

During the frequency conversion in a superheterodyne, greater selectivity is automatically secured. This is because both the desired and undesired signals are reduced to a lower frequency when heterodyned with the local oscillator. Since they are still 10 kc. apart at the lower (beat) frequency, the interfering station is a lesser percentage of the desired station, thus making it possible for the tuned resonant circuits to exclude the undesired signal more easily. Suppose that a station operating on 990 kc. is interfering with a desired signal of 1,000 kc. At their own frequencies, the interfering station is 99% of the desired station. Assuming the intermediate frequency of the set to be 260 kc., when the local oscillator is set to 1260, the 1,000-kc. station will be reduced to the correct value of 260 kc. and the interfering station will be reduced to 270 kc. By calculation, the interfering frequency is now found to be only 96% of the desired frequency. Thus, the selectivity of the superheterodyne is automatically improved. In this example, it should be noted that the lower the intermediate frequency, the greater will be the improved selectivity due to the frequency conversion process.

The superheterodyne is far superior to a T.R.F. receiver for all-wave reception because of the practical impossibilities of designing a sufficient number of cascade T.R.F. amplifying stages to produce high sensitivity and selectivity without becoming extremely unstable.

Rather than erringly jeopardize the T.R.F. receiver, however, it should be stated that it is possible to obtain the equivalent selectivity, sensitivity, and fidelity in a T.R.F. receiver as in a superheterodyne. But, such a T.R.F. receiver would require a greater number of tubes and more elaborate circuit design than a superheterodyne and would, therefore, be much more expensive to give the same performance. The T.R.F. receiver would also be more unstable because it contains many more continuously variable tuned circuits. A superheterodyne receiver, of course, has as many or more tuned circuits compared to a T.R.F. receiver, but all those contained in the I.F. amplifier are permanently tuned and only the oscillator, first detector, and R.F. grid circuit need be tuned by the variable ganged-condenser assembly.

An advantage possessed by the T.R.F. receiver over the superheterodyne is that it is not bothered with image frequency interference. Only adjacent channel selectivity is taken into consideration in the design of a T.R.F. amplifier, whereas in a superheterodyne receiver, precaution must be taken against image frequency reception. Also the presence of a local oscillator in the superheterodyne causes miscellaneous harmonic frequencies to be produced which are apt to beat against other broadcasting stations, thus producing annoying whistles or beat notes. The absence of the local oscillator in the T.R.F. receiver eliminates the possibility of this type of interference.

The advantages of a superheterodyne receiver more than compensate for its disadvantages, this being definitely proved by their increased popularity since about 1930.

In Lesson 30 of this unit, we shall continue the study of superheterodyne receivers in conjunction with the design and use of multi-element tubes.

COPPER WIRE TABLE

GAUGE NO. B. & S.	DIAM. IN MILS*	AREA IN CIRCULAR MILS	FEET PER OHM (25° C.)	OHMS PER 1,000 FEET (25° C.)	TURNS PER LINEAR INCH**						TURNS PER SQUARE INCH			SAFE CURRENT CARRYING CAP. AT 1,500 CM PER AMPERE	CURRENT REQUIRED TO FUSE WIRE
					BARE	S.S.C.	D.S.C.	S.C.C.	D.C.C.	ENAM.	ENAMEL S.C.C.	D.C.C.	S.C.C.		
1	289.3	83,690	7,918	.1264	—	—	—	—	—	—	—	—	—	55.7	—
2	257.6	66,370	6,276	.1593	—	—	—	—	—	—	—	—	—	44.1	—
3	229.4	52,640	4,977	.2009	—	—	—	—	—	—	—	—	—	35.0	—
4	204.3	41,740	3,947	.2533	—	—	—	—	—	—	—	—	—	27.7	—
5	181.9	33,100	3,130	.3195	—	—	—	—	—	—	—	—	—	22.0	—
6	162.0	26,250	2,482	.4028	—	—	—	5.6	5.44	—	—	—	—	17.5	—
7	144.3	20,820	1,969	.5080	—	—	—	6.23	6.00	—	—	—	—	13.8	—
8	128.5	16,510	1,561	.6405	—	—	—	6.94	6.8	7.6	—	—	—	11.0	—
9	114.4	13,090	1,238	.8077	—	—	—	7.68	7.64	8.6	—	—	—	8.7	—
10	101.9	10,380	981.8	1.018	—	—	—	8.55	8.51	9.6	84.0	80.0	87.5	6.9	330.0
11	90.74	8,234	778.7	1.284	—	—	—	9.60	9.58	10.7	105.	97.5	118.	5.5	284.0
12	80.81	6,530	617.5	1.619	—	—	—	10.80	10.62	12.0	131.	121.	136.	4.4	235.0
13	71.96	5,178	489.7	2.042	—	—	—	12.06	11.88	13.5	162.	150.	170.	3.5	200.0
14	64.08	4,107	388.3	2.575	15.6	—	—	13.45	13.10	15.0	198.	185.	211.	2.7	166.0
15	57.07	3,257	308.0	3.247	17.5	—	—	14.98	14.68	16.8	250.	223.	262.	2.2	139.0
16	50.82	2,583	244.2	4.094	19.6	—	—	17.20	16.40	18.9	306.	271.	321.	1.7	117.0
17	45.26	2,048	193.7	5.163	22.0	—	—	18.80	18.10	21.2	372.	329.	397.	1.3	99.0
18	40.30	1,624	153.6	6.510	25.0	—	—	21.00	20.00	23.6	454.	399.	493.	1.1	82.0
19	35.89	1,288	121.8	8.210	27.8	—	—	23.60	21.83	26.4	553.	479.	592.	.86	66.7
20	31.96	1,022	96.6	10.35	31.0	27.0	25.0	26.40	23.91	29.4	725.	625.	775.	.68	58.3
21	28.46	810.1	76.61	13.05	35.0	30.0	27.0	29.70	26.20	33.1	895.	754.	940.	.54	49.3
22	25.35	642.4	60.75	16.46	39.0	34.0	30.5	32.00	28.58	37.0	1,070.	910.	1,150.	.43	41.2
23	22.57	509.5	48.18	20.76	44.0	38.0	34.0	34.30	31.12	41.3	1,300.	1,080.	1,400.	.34	35.5
24	20.10	404.0	38.21	26.17	50.0	43.0	38.0	37.70	33.60	46.3	1,570.	1,260.	1,700.	.27	28.9
25	17.90	320.4	30.30	33.00	56.0	47.0	41.0	41.50	36.20	51.7	1,910.	1,510.	2,060.	.21	24.6
26	15.94	254.1	24.09	41.62	63.0	52.0	45.0	45.30	39.90	58.0	2,300.	1,750.	2,500.	.17	20.6
27	14.20	201.5	19.06	52.48	70.0	58.0	50.0	49.40	42.60	64.9	2,780.	2,020.	3,030	.13	17.7
28	12.64	159.8	15.11	66.17	79.0	64.0	53.0	54.00	45.50	72.7	3,350.	2,310.	3,670.	.11	14.7
29	11.26	126.7	11.98	83.44	88.0	71.0	58.0	58.80	48.00	81.6	3,900.	2,700.	4,300.	.084	12.5
30	10.03	100.5	9.50	105.2	100.0	80.0	66.0	64.40	51.10	90.5	4,660.	3,020.	5,040.	.067	10.25
31	8.92	79.70	7.54	132.7	112.0	87.0	71.0	69.00	56.80	101.0	5,280.	—	5,920.	.053	8.75
32	7.95	63.21	5.98	167.3	125.0	99.0	76.0	75.00	60.20	113.0	6,250.	—	7,060.	.042	7.28
33	7.08	50.13	4.74	211.0	141.0	105.0	83.0	81.00	64.30	127.0	7,360.	—	8,120.	.033	6.19
34	6.31	39.75	3.76	266.0	159.0	110.0	88.0	87.60	68.60	143.0	8,310.	—	9,600.	.026	5.12
35	5.62	31.52	2.98	335.0	179.0	130.0	104.0	94.20	73.00	158.0	8,700.	—	10,900.	.021	4.97
36	5.00	25.00	2.36	423.0	200.0	140.0	110.0	101.0	78.50	175.0	10,700.	—	12,200.	.017	3.62
37	4.45	19.83	1.87	533.4	222.0	150.0	115.0	108.0	84.00	198.0	—	—	—	.013	3.08
38	3.96	15.72	1.49	672.6	250.0	160.0	120.0	115.0	89.10	224.0	—	—	—	.010	2.56
39	3.53	12.47	1.18	848.1	285.0	180.0	130.0	122.5	95.00	248.0	—	—	—	.008	2.20
40	3.14	9.88	.94	1,069.0	321.0	200.0	140.0	130.0	102.50	282.0	—	—	—	.006	1.86
41	2.80	7.84	.75	1,323.0	—	—	—	153.0	112.00	—	—	—	—	.005	—
42	2.50	6.22	.60	1,667.0	—	—	—	168.0	124.00	—	—	—	—	.004	—
43	2.22	4.93	.47	2,105.0	—	—	—	192.0	140.00	—	—	—	—	.003	—
44	1.98	3.91	.39	2,655.0	—	—	—	210.0	153.00	—	—	—	—	.0025	—

* A mil is 1/1000 (one thousandth) of an inch.
** These figures are only approximate, as they depend upon the thickness of the insulation. This, in turn, depends upon the manufacturer of the wire.

S.S.C. = Single Silk Covered.
D.S.C. = Double Silk Covered.
S.C.C. = Single Cotton Covered.
D.C.C. = Double Cotton Covered.

Notes

(These extra pages are provided for your use in taking special notes)

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POWER & LIGHT BUILDING, KANSAS CITY, MISSOURI

UNIT NO. 1

AUDIO POWER AMPLIFIERS

LESSON NO. 28

IN 1866....

An employee left a good job in the United States Patent Office. He thought EVERYTHING HAD BEEN INVENTED!

Wait! Don't laugh at him....
He simply had no foresight!

The difference between YOU, TODAY, and that man above, is:

He had no faith in the future. YOU HAVE.......which is why you're training with Midland.

They laughed at this man who quit on the threshold of development.

No one is going to laugh at you.......
You have FORESIGHT and FAITH IN THE FUTURE!

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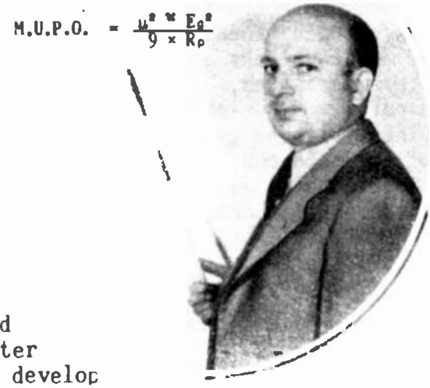
KANSAS CITY, MO.

Lesson Twenty-Eight

AUDIO POWER AMPLIFIERS



"Audio power amplifiers are specific types of audio-frequency amplifiers that we studied in Lesson 19. The demand for better tone quality and greater volume has made it necessary to develop these special A.F. amplifying circuits and also to design special A.F. power tubes.

"In this lesson, you will find these circuits and tubes described thoroughly. I am sure you will have many opportunities to use the knowledge gained from this lesson."

1. **NEED FOR A POWER TUBE.** In all the vacuum tube circuits so far studied, the primary objective has been to secure as much distortionless voltage amplification as possible. Voltage amplification means the magnitude of the output voltages across the plate circuit of a vacuum tube relative to the input voltages applied to the grid circuit. Formulas have been given for calculating the amount of voltage amplification, and various operating conditions have been specified which are necessary to secure an undistorted voltage across the plate circuit.

As we shall find in the following lesson, not only audio voltages, but also audio currents are necessary to operate the loudspeaker of a receiving set. In other words, a loudspeaker requires the application of audio power to produce the sound waves. The audio output of a voltage amplifier tube is not capable of supplying power to a loudspeaker, so it is necessary to employ a special type of tube (or tubes) in a properly designed circuit. The tube or tubes used for this purpose are called "power tubes" and the stage itself is called a "power amplifier". The voltage gain secured through a power amplifier stage is of little consequence, the main object being the production of A.F. power, which means not only voltage variations, but also a high amplitude of current changes through the plate circuit.

All radio receivers employ a power amplifier stage and use power tubes to operate the loudspeaker; therefore, a detailed study of these subjects is extremely important.

2. POWER TUBE CONSTRUCTION. Since a power amplifier tube is used for an entirely different purpose than a voltage amplifier, it follows that the construction of the tube itself must differ to a great extent. In a voltage amplifier tube, an attempt is made to secure as high an amplification factor as possible and, at the same time, maintain the plate resistance of the tube at a figure as low as constructional features will permit. The resulting transconductance (found by taking the ratio of Mu to R_p) gives a figure of merit whereby amplifying tubes may be compared. To obtain these characteristics, the plate resistance of a voltage amplifier is generally so high that the plate current which flows at ordinary plate voltages is low. The plate resistance is high as a result of the tube construction necessary to maintain a high amplification factor. Another notable feature of typical voltage amplifier tubes is that only a low grid bias is needed to operate the tube on the straight portion of its grid voltage-plate current characteristic.

The operating conditions and tube characteristics are entirely different in a power amplifier tube. A power amplifier tube will always be operated with a high plate voltage and high grid bias. A much greater plate current will also flow in the plate circuit. The amplification factor of a power amplifier tube is relatively low; the plate resistance low; and the transconductance quite high. These characteristics are all a result of the tube's construction. Power tubes are constructed with a large plate surface area, designed specifically to radiate the heat generated by the high plate current which normally flows. The plate of a power tube is located relatively close to the filament or cathode; hence, the plate resistance is reduced to a low value. The grid winding is generally spaced relatively far from the cathode and wound with open turns so as to reduce its effectiveness in controlling the plate current. Thus, the amplification factor of most power tubes is low. The transconductance resulting from the lower Mu and R_p is quite high in a power tube compared to a voltage amplifier.

To facilitate quick reference to the characteristics of typical tubes, those of a type 56 (voltage amplifier) and a type 45 (power amplifier) are listed on the following page.

In a later discussion, it will be found that the power output produced by a vacuum tube is inversely proportional to its plate resistance. Thus, it is desirable to maintain the plate resistance at a low figure so as to obtain greater power efficiency from the tube's operation. Since the amplification factor of a power tube is also low, voltage amplification of the A.F. signal must be secured before it is applied to the power tube's grid. The A.F. voltage amplifier following the detector is for the purpose of building up the signal until it is of sufficient strength to properly swing the grid[1] of the power tube. The power output secured from

[1] The "grid swing" means the extent of the grid voltage variations. For example, if a tube had a zero grid bias and an AC signal voltage were applied which drove the grid from 25 volts negative to 25 volts positive, the "grid swing" would be 50 volts. Likewise, when bias is applied, the "swing" still refers to the AC signal voltage as measured from the peak of the positive to the peak of the negative alternation.

Type 45 POWER AMPLIFIER

As Single-Tube Class A Amplifier

FILAMENT VOLTAGE (A. C.)			2.5	Volts
PLATE VOLTAGE	180	250	275 max.	Volts
GRID VOLTAGE	−31.5	−50	−56	Volts
PLATE CURRENT	31	34	36	Milliamperes
PLATE RESISTANCE	1650	1610	1700	Ohms
AMPLIFICATION FACTOR	3.5	3.5	3.5	
MUTUAL CONDUCTANCE	2125	2175	2050	Micromhos
LOAD RESISTANCE	2700	3900	4600	Ohms
SELF-BIAS RESISTOR	1020	1470	1550	Ohms
UNDISTORTED POWER OUTPUT	0.825	1.6	2.0	Watts

Type 56 DETECTOR, AMPLIFIER

CHARACTERISTICS

HEATER VOLTAGE (A. C. or D. C.)	2.5	Volts
HEATER CURRENT	1.0	Ampere
PLATE VOLTAGE	250 max.	Volts
GRID VOLTAGE	−13.5	Volts
PLATE CURRENT	5	Milliamperes
PLATE RESISTANCE	9500	Ohms
AMPLIFICATION FACTOR	13.8	
MUTUAL CONDUCTANCE	1450	Micromhos

any power tube is proportional to the square of the grid exciting voltage, so it is desirable to apply as much input signal voltage as the grid bias will permit without driving the grid positive. In a type 45 power tube, the grid bias is 50 volts negative (for 250 volts on the plate); thus a signal voltage of high amplitude may be applied to its grid circuit without overloading. To allow enough plate current to flow with this high grid bias, it is necessary that the grid construction be such that it is relatively ineffective in controlling the plate current. Thus, the amplification factor of the power tube is reduced.

It is impossible to operate a voltage amplifier tube, such as the type 56, as a power amplifier, because the plate resistance is relatively high, the plate current low and the grid bias voltage low. Such a high plate resistance and low plate current make it impossible to establish high amplitudes of current changes through the plate circuit; hence, the power output is not sufficient to properly operate a loudspeaker. Also, a high amplitude grid exciting voltage cannot be applied to its grid circuit without undue overloading.

For a vacuum tube to produce power output, it must be especially designed for the purpose. In its construction, some desirable features such as the amplification factor are reduced, but this must be tolerated in view of the other important conditions that have to be satisfied to efficiently operate the loudspeaker on a receiving set.

3. CLASSES OF AMPLIFIERS. The operation of a vacuum tube as an amplifier is diversified in that it may amplify A.F. voltages or R.F. voltages under widely different conditions. Vacuum tube amplifiers may be adapted to radio circuits in a number of different ways, depending upon the results to be achieved. To identify these different modes of operation, definite standards have been established by the Institute of Radio Engineers wherein amplifier circuits are divided broadly into three different classes. These are: Class A, Class B and Class C. The class of operation is based primarily upon the fraction of the input cycle during which plate current is permitted to flow under operating conditions.

A Class A amplifier is an amplifier in which the grid bias and exciting grid voltages are adjusted to allow plate current to flow at all times. The ideal Class A amplifier is one in which the alternating component of the plate current is an exact reproduction of the waveform of the alternating grid voltage and the plate current flows during the entire 360 electrical degrees of the grid voltage cycle. A Class A amplifier is characterized by low efficiency and relatively low power output. Fig. 1 illustrates the conditions under which a Class A amplifier is operated.

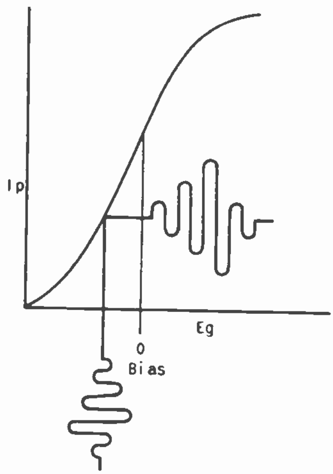


Fig.1 Class A amplifier. The plate current flows through 360° of the grid exciting cycle.

A Class B amplifier is an amplifier in which the grid bias is approximately equal to the cutoff value; that is, plate current is nearly zero under static conditions. When an exciting grid voltage is applied, the plate current flows during about one-half of each cycle. The ideal Class B amplifier is one in which the alternating component of the plate current is an exact reproduction of the alternating grid voltage for the half cycle when the grid is positive with respect to the bias voltage. Plate current flows during 180° of the grid exciting cycle. The characteristics of a Class B amplifier are medium efficiency and medium power output. A diagram illustrating the conditions under which a typical Class B amplifier operates is shown in Fig. 2.

A Class C amplifier is an amplifier in which the grid bias is appreciably beyond the cutoff value, so that the plate current is zero when no exciting grid voltage is applied and so that the plate

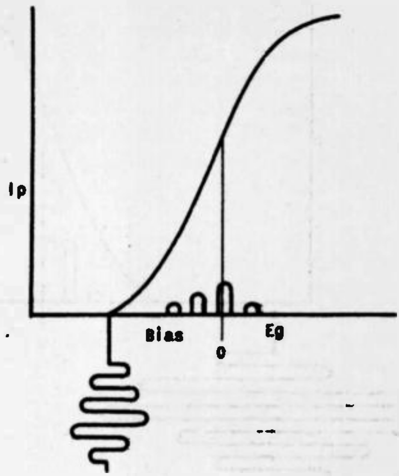


Fig.2 Class B amplifier. The plate current flows through 180° of the grid exciting cycle.

current flows for appreciably less than one-half of each cycle of the grid exciting voltage. Class C amplification is used when high plate circuit efficiency is a paramount requirement and where a departure from linearity between input and output is permissible. The characteristics of a Class C amplifier are high plate circuit efficiency and high power output. A diagram illustrating the conditions under which a Class C amplifier is operated is shown in Fig. 3. Class C amplifiers are never used as audio amplifiers.

Oftimes it is convenient to have other terms available so as to identify amplifier services when tubes are operating under conditions intermediate to Class A and Class B, or intermediate between Class B and Class C. Such conditions are classified as Class AB and Class BC, respectively. Class AB amplifiers are those in which the grid bias and exciting grid voltages are such that the plate current flow is appreciably more than 180 electrical degrees, but less than 360 electrical degrees of the grid exciting cycle. This is sometimes called Class A prime operation. The characteristics of the Class AB amplifier are efficiency and power output intermediate to Class A and Class B amplifiers. The no-signal plate current and attendant plate dissipation may be made substantially less than is possible with Class A amplifiers. A Class BC amplifier is an amplifier in which the grid bias and grid exciting voltage are such that the plate current flows during less than 180 electrical degrees, but for a longer portion of the grid exciting cycle than in Class C. The characteristics of a Class BC amplifier are efficiency and power output intermediate to that of Class B and Class C amplifiers. Class BC amplifiers are not in general use.

These classifications of various amplifier services have been given primarily because it is necessary to definitely affirm the fact that all the power amplifier circuits (and calculations pertaining to these circuits) in this lesson are specifically for Class A operation. All types of amplifiers we have discussed in previous

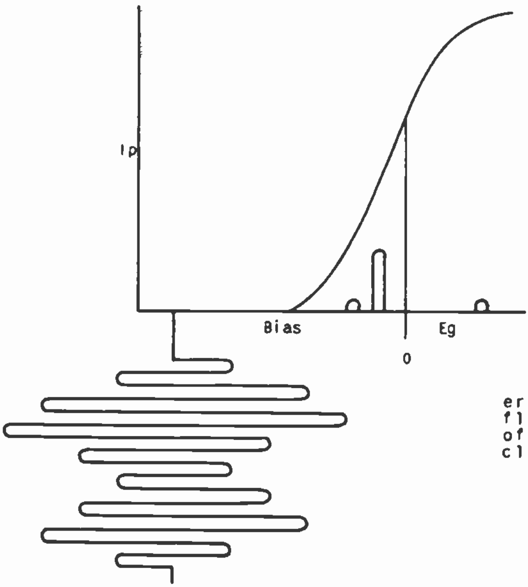


Fig.3 Class C amplifier. The plate current flows only on the peaks of the grid exciting cycle.

lessons are Class A amplifiers. R.F. and I.F. amplifiers are operated under Class A conditions and, likewise, all audio amplifiers studied in previous lessons were operated Class A. Of all the circuits studied, the operation of a grid-bias detector is the only one which closely approaches Class B conditions. We shall later learn that an oscillator circuit, such as that described in Lesson 29, automatically adjusts itself for Class C operation.

Since all single-ended power amplifiers are operated Class A, we shall now study in detail the design of these circuits and the method of calculating the audio power output.

4. SINGLE-ENDED CLASS A POWER AMPLIFIERS. When a triode power amplifier is properly worked under Class A conditions, the harmonic distortion does not exceed 5% of the total power output. For tetrodes and pentodes in Class A circuits, the usual distortion percentage is from 7% to 10%. In all power amplifiers, the percentage of total harmonic distortion in the A.F. power output should be kept below these values. They have been experimentally determined as values beyond which the distortion is sufficiently noticeable to result in disagreeable reproduction from the loudspeaker. Fig. 4 shows a three-stage circuit consisting of a detector, an A.F. voltage amplifier and a power amplifier. A type 57 tube is used as the grid-bias detector and the audio voltage output produced across the .25 meg plate coupling resistance is capacity

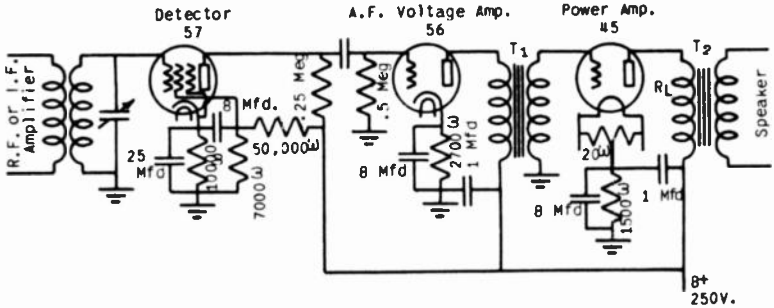


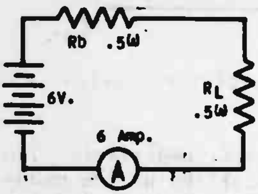
Fig.4 Pentode detector followed by voltage amplifier, which in turn drives single-ended power amplifier.

coupled into the grid circuit of the first A.F. amplifier. The type 56 tube is operated under conditions as specified by the manufacturer and its amplified A.F. output is transformer coupled into the grid circuit of the 45 power amplifier tube. The purpose of this 56 voltage amplifier is to increase the amplitude of the voltage variations that are produced in the output of the detector so they will be of sufficient magnitude to properly excite the grid of the power amplifier tube. Since the grid bias on the 45 is approximately -50 volts, the audio voltages developed across the secondary of the input transformer T_1 should not exceed this value. The audio voltage variations applied to the grid create corresponding current changes through the plate circuit. These current changes pass through the primary (R_L) and are inductively coupled into the secondary where the audio currents pass through the windings of the loudspeaker and produce a vibration of its diaphragm.

The actual load on the 45 power amplifier tube consists of not only the primary winding R_L, but also the load presented by the loudspeaker. The power taken from the plate circuit by the loudspeaker is pulled directly through the output transformer T_2 by electromagnetic induction; hence, the speaker serves to load the plate circuit of the power amplifier, the same as the primary winding R_L. The total load impedance presented by the transformer and speaker must be of the proper value if the A.F. power output delivered by the power tube is to be at its maximum undistorted value. From the table of characteristics for a type 45 tube, the recommended plate load impedance is seen to be 3900 ohms; hence, the transformer and loudspeaker must be designed to produce a load impedance of this value. Under proper load conditions and assuming maximum grid exciting voltage, the total audio power output which can be obtained from a type 45 tube is 1.6 watts. This amount of audio power is sufficient for average volume from a home receiver.

The maximum power output that can be obtained under adverse conditions from a type 45 tube is somewhat greater than 1.6 watts; however, the percentage of harmonic distortion will exceed 5%. Manufacturers always rate power tubes according to their ability to deliver maximum *undistorted* power output. When a greater amount of audio power is required than one tube can deliver, a different type of power stage is necessary or a larger power tube must be used. It is possible to connect two type 45 tubes in a push-pull or parallel arrangement and thus secure a greater A.F. power without employing a higher B supply voltage. If a larger power tube, such as a 10 or 50, is used, a greater plate input power is necessary and generally a higher grid exciting voltage is required.

5. **CALCULATING A.F. POWER OUTPUT.** Maximum power output will always be delivered from a vacuum tube or any other voltage generating device when the load impedance is exactly equal to its internal resistance. This can be proved by the following example:



Total $R = R_b + R_L = .5\Omega + .5\Omega = 1\Omega$

Total $I = E \div R = 6 \div 1 = 6$ Amp.

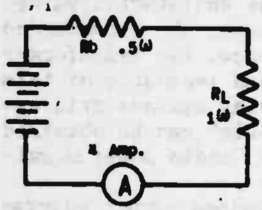
Voltage Across $R_L = I \times R = 6 \times .5 = 3$ Volts.

Power Delivered to $R_L = E \times I = 3 \times 6 = 18$ Watts.

Fig.5 Simple resistance circuit to illustrate that maximum power output is secured when the load resistance equals the internal resistance of a generator. Chart on right shows calculations.

Suppose that a six-volt battery having an internal resistance of .5 ohm is used to supply power into a load resistance. First, let the load resistance equal the internal resistance of the battery; that is, .5 ohm. A diagram of the circuit is shown in Fig. 5. Here, R_b represents the internal resistance of the battery and R_L represents the load impedance. The total resistance in the circuit equals the sum of R_b and R_L or 1 ohm. The current through the circuit is 6 amperes, so the voltage drop across R_L is 3 volts. Using E × I, the power delivered to R_L is found to be 18 watts.

Now let us assume that the load resistance R_L is made greater than the internal resistance of the battery. If it is increased to 1 ohm, then the conditions are as shown in Fig. 6. Increasing the value of R_L to one ohm increases the total resistance in the circuit to 1.5 ohms. The total current then is decreased to 4 amperes. The voltage across R_L is 4 volts and the total power de-



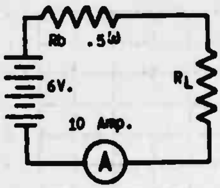
Total $R = R_b + R_L = .5\Omega + 1\Omega = 1.5\Omega$.

Total $I = E \div R = 6 \div 1.5 = 4$ Amp.

Voltage Across $R_L = I \times R = 4 \times 1 = 4$ Volts.

Power Delivered to $R_L = E \times I = 4 \times 4 = 16$ Watts.

Fig.6 Load resistance made twice the internal resistance. Calculations on right show that the power output is less.



Total $R = Rb + R_L$
$= .5 + .1$
$= .6\Omega.$

Total $I = E \div R$
$= 6 \div .6$
$= 10$ Amp.

Voltage Across $R_L = I \times R$
$= 10 \times .1$
$= 1$ Volt.

Power Delivered
to $R_L = E \times I$
$= 1 \times 10$
$= 10$ Watts.

Fig.7 Load resistance made less than battery's internal resistance. Calculations on right show that power output is less.

livered to R_L ($E \times I$) is 16 watts. This is seen to be 2 watts less than in Fig. 5, where R_L was only .5 ohm. Fig. 7 shows an opposite condition; that is, the load resistance is made less than the internal resistance of the battery. Here the load resistance is decreased to .1 ohm, the .5 ohm internal resistance of the battery remaining the same. The total resistance in the circuit, then, is equal to .5 + .1 or .6 ohm. The total current flowing through the circuit is found by dividing the applied voltage by the total resistance and is equal to 10 amperes. The voltage drop then produced across the load resistance R_L = 10 × .1 or 1 volt. The power delivered into the load resistance R_L is equal to the voltage across it times the current passing through it, or 10 watts.

Thus, the power delivered into R_L from a voltage source having an internal resistance of .5 ohm is 18 watts, when R_L = .5 ohm; 16 watts, when R_L = 1 ohm; and only 10 watts, when R_L = .1 ohm. This proves that when the internal resistance of a voltage source remains constant, the power delivered to an external load will be maximum when the external load resistance equals the internal resistance.

This example uses a battery circuit, but the same principle may be applied to any voltage generator or vacuum tube circuit. Since the application of a signal voltage to the grid causes a vacuum tube to generate voltage changes across its plate circuit, it is truly a voltage generator and the maximum power output will be delivered from it when the load resistance is equal to the plate resistance of the tube. The graph in Fig. 8 illustrates the variation in output power with load changes on a type 45 tube. A type 45 tube has a plate resistance of 1600 ohms and from the graph, it is seen that when the load resistance is made equal to this value, the maximum power output is secured. For load values less than 1,600 ohms, the power output decreases very rapidly and for load values greater than 1,600 ohms, the power output again decreases, but at a slower rate. The load impedance in the plate circuit can be made greater than 1,600 ohms without a great sacrifice in power output. When it is increased to about 3,000 to 4,000 ohms, the power output is reduced only a few tenths of a watt.

It will be recalled from previous study that undistorted voltage amplification will not be secured unless the load impedance is equal to at least twice the plate resistance of a tube. The same is true for power tubes; that is, the power output will be distorted

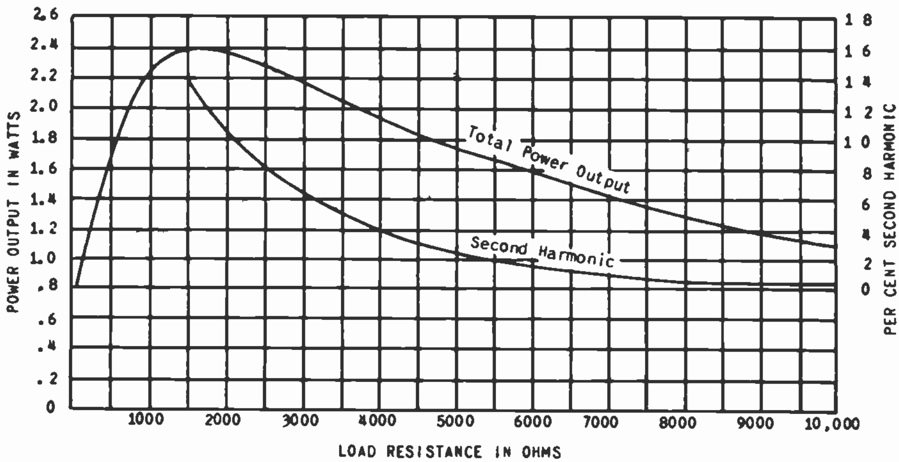


Fig.8 Graph showing total power output and percentage of second harmonic content with various load values on the type 45 power amplifier. Note that M.P.O. is secured when $R_L = R_p$.

unless the load impedance is equal to at least twice the plate resistance of the power tube. Even though a slight amount of power is sacrificed, this is necessary to prevent a high percentage of distortion. *Maximum undistorted power output is obtained when the load is about twice the plate resistance.*

The curve in Fig. 9 illustrates the power output and second harmonic distortion for a type 45 triode. As will be noted, the

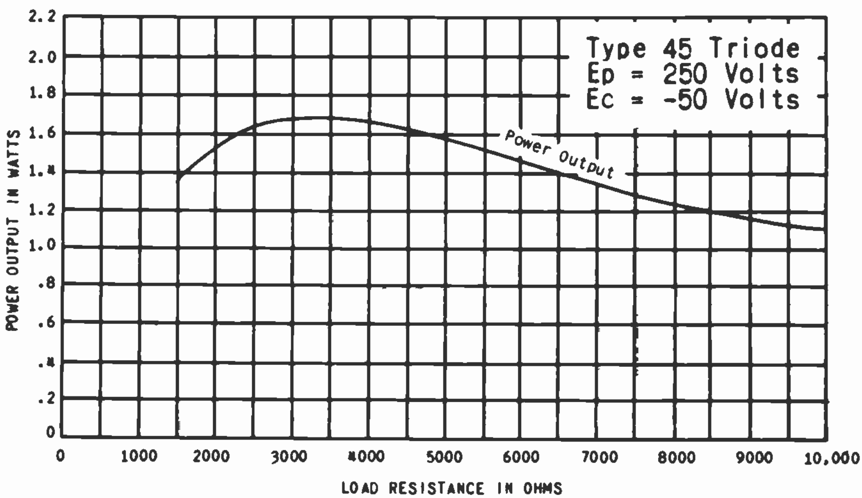
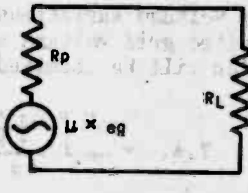


Fig.9 Graph showing power output of the type 45 tube at the fundamental frequency (no harmonics). Note that it is maximum when R_L is about twice as large as R_p.

undistorted power output is maximum with a load of approximately 3500 ohms, so from the standpoint of distortion, it is advisable to use a load resistance between 3,000 and 4,000 ohms with this type of tube. This reduces the power output somewhat for a given grid signal voltage, but the distortion is reduced considerably. The power output curve in Fig. 9 illustrates the power delivered to the speaker only at the fundamental frequency; that is, without its harmonic content. The reason for the difference between the curves in Figs. 8 and 9 is that the curve in Fig. 8 represents the total power output; that is, the fundamental frequency plus all its harmonic frequencies, whereas Fig. 9 does not. The maximum power output is secured when the load impedance is equal to the plate resistance of the tube (Fig. 8), but the *maximum undistorted power output* is obtained with a load of twice the plate resistance (Fig. 9).

The actual power output of a vacuum tube may be calculated by the use of simple formulas. To show the derivation of these formulas, it is necessary to again consider the vacuum tube as a voltage generating device and assume the plate circuit to be loaded with a pure resistance. The equivalent electrical circuit for the plate circuit of any vacuum tube amplifier is shown in Fig. 10.[1] Here the generator $\mu \times e_g$ represents the voltage output produced across the plate circuit of the tube. This voltage output depends on the product of the grid exciting voltage and the amplification factor of the tube. For convenience, we shall first consider that the grid exciting voltage is given in R.M.S. values.

Fig. 10 Equivalent electrical circuit for the plate circuit of any vacuum tube amplifier.



The changing current which flows through the plate circuit (Fig. 10) must pass through both R_p, the plate resistance of the power tube, and R_L, the load resistance in the plate circuit. Since $\mu \times e_g$ represents the total voltage output and $R_p + R_L$ is the total opposition, applying Ohm's Law, we have:

$$\Delta I_p = \frac{\mu \times e_g}{R_p + R_L} \qquad (1)$$

The varying plate current passes through both R_p and R_L. When it passes through R_p, the plate resistance of the tube, power is dissipated in the tube itself ($I^2 \times R$) and it is not available for driving the loudspeaker. As the varying plate current passes through R_L, the remainder of the total power is dissipated in R_L. It is this power that actually drives the loudspeaker; that is,

[1] First discussed in Lesson 19; Section 2.

it is the power output from the tube. Let us proceed to calculate this power in watts.

The voltage developed across R_L is equal to the changing current passing through it times R_L in ohms ($E = I \times R$). This is represented by the following formula:

$$\Delta E_L = \frac{\mu \times e_g \times R_L}{R_p + R_L} \quad (2)$$

Where:
- ΔE_L is the varying voltage across R_L
- μ is the amplification factor of the tube
- e_g is the R.M.S. value of the grid exciting voltage
- R_L is the load resistance in ohms
- R_p is the plate resistance in ohms

In Lesson 12, it was stated that the formula for voltage amplification would be explained in this lesson. The formula is:

$$\text{Voltage Amplification} = \frac{\text{Amplification Factor} \times \text{Plate Load Resistance}}{\text{Plate Load Resistance} + \text{Plate Resistance}}$$

This gives the number of times an applied grid signal voltage is actually amplified through a vacuum tube circuit. Its derivation can be determined from formula (2). Formula (2) gives the varying voltages produced across the load resistance in the plate circuit. Now, the voltage amplification is actually the ratio of the voltage variations produced across the plate circuit to the applied grid voltage variations. Therefore, if we divide formula (2) by e_g (applied grid voltage variations), the formula for voltage amplification will be obtained. The mathematical procedure is as follows:

$$V.A. = \frac{\frac{\mu \times e_g \times R_L}{R_p + R_L}}{e_g} = \frac{\mu \times \cancel{e_g} \times R_L}{R_p + R_L} \times \frac{1}{\cancel{e_g}} = \frac{\mu \times R_L}{R_p + R_L}$$

Where:
- μ is the amplification factor
- e_g is the R.M.S. grid exciting voltage
- R_L is the plate load resistance
- R_p is the plate resistance.

Returning to our calculation of A.F. power, we know the current variations through R_L (from formula [1]) and the voltage variations produced across it, so we can now calculate the power, using the fundamental formula, $W = E \times I$. This is expressed as follows:

$$W \text{ (A.F. power output)} =$$

$$\frac{\mu \times e_g}{R_p + R_L} \times \frac{\mu \times e_g \times R_L}{R_p + R_L} =$$

$$\frac{\mu^2 \times e_g^2 \times R_L}{(R_p + R_L)^2} \quad (3)$$

Formula (3) can be used to find the power output of any tube under any known conditions of operation. This formula should be remembered because it enables one to calculate the audio power output produced by any triode power tube when operated into any size load. It applies only to Class A power amplifiers.

Since the *maximum power output* will be secured from a vacuum tube when the load resistance is equal to the plate resistance of the tube, to obtain a formula with which to calculate the maximum power output, we can substitute R_p for R_L in formula (3). Formula (3) then becomes:

$$M.P.O. = \frac{\mu^2 \times e_g^2 \times R_p}{(R_p + R_p)^2}$$

$$= \frac{\mu^2 \times e_g^2 \times R_p}{4 \times R_p^2}$$

$$= \frac{\mu^2 \times e_g^2}{4 \times R_p} \qquad (4)$$

Using this formula, it is possible to calculate the maximum power output (M.P.O.) that can be obtained from any Class A power amplifier when the μ of the tube, the R.M.S. value of the grid exciting voltage and the plate resistance are known; also, the load impedance of the plate circuit must be equal to the plate resistance of the tube.

In nearly all problems, the peak value of the grid exciting voltage will be given or can be determined more easily than the R.M.S. value. Formula (4) can be changed to accommodate the peak value of the grid exciting voltage. From Lesson 13, we know:

$$E_g = e_g \times 1.414$$

Where: E_g is the *peak* value of grid exciting voltage
e_g is the *R.M.S.* value of grid exciting voltage

Since $1.414 = \sqrt{2}$, in this particular case we will find it more convenient to use $\sqrt{2}$ as the multiplying factor. Therefore, $E_g = e_g \times \sqrt{2}$. Solving for e_g, we have:

$$e_g = \frac{E_g}{\sqrt{2}}$$

Now that we have the R.M.S. e_g expressed in its peak value, we can substitute the equivalent of e_g directly in formula (4) and thus derive a new formula wherein the grid exciting voltage is in its peak value. The mathematical solution is as follows:

$$M.P.O. = \frac{\mu^2 \times e_g^2}{4 \times R_p} \qquad (4)$$

Substituting $\frac{E_g}{\sqrt{2}}$ for e_g:

$$= \frac{\mu^2 \times \left(\frac{Eg}{\sqrt{2}}\right)^2}{4 \times R_p}$$

Squaring $\frac{Eg}{\sqrt{2}}$:

$$= \frac{\frac{\mu^2 \times Eg^2}{2}}{4 \times R_p}$$

Performing the division:

$$= \frac{\mu^2 \times Eg^2}{2} \times \frac{1}{4 \times R_p} = \frac{\mu^2 \times Eg^2}{8 \times R_p} \qquad (5)$$

Formulas (4) and (5) were both derived assuming the load impedance (R_L) equal to the plate resistance (R_P), the condition necessary for maximum power output. We know that it is more desirable to obtain the maximum undistorted output from a power tube when it is to be used to drive a loudspeaker. For maximum undistorted power output (M.U.P.O.), the load impedance must be at least twice the plate resistance of the tube. Assuming $R_L = 2 \times R_p$, let us substitute $2 \times R_p$ for R_L in formula (3). Then, calculating the maximum undistorted power output, we have:

$$P.O. = \frac{\mu^2 \times eg^2 \times R_L}{(R_p + R_L)^2} \qquad (3)$$

Since $R_L = 2 \times R_p$:

$$M.U.P.O. = \frac{\mu^2 \times eg^2 \times (2 \times R_p)}{(R_p + 2 \times R_p)^2}$$

$$= \frac{\mu^2 \times eg^2 \times (2 \times R_p)}{(3 \times R_p)^2}$$

$$= \frac{\mu^2 \times eg^2 \times (2 \times R_p)}{9 \times R_p^2}$$

$$= \frac{\mu^2 \times eg^2}{4.5 \times R_p} \qquad (6)$$

Where:
M.U.P.O. is the maximum undistorted power output
μ is the amplification factor
eg is the R.M.S. grid exciting voltage
R_p is the plate resistance of the tube and is also ½ of R_L

As before, it is convenient to derive a formula wherein the peak value of grid exciting voltage is used instead of the R.M.S. value. Since $eg = \frac{Eg}{\sqrt{2}}$, we may substitute directly in formula (6) as follows:

$$M.U.P.O. = \frac{\mu^2 \times e_g^2}{4.5 \times R_p} \qquad (6)$$

$$e_g = \frac{E_g}{\sqrt{2}}$$

$$M.U.P.O. = \frac{\mu^2 \times \left(\frac{E_g}{\sqrt{2}}\right)^2}{4.5 \times R_p}$$

$$= \frac{\frac{\mu^2 \times E_g^2}{2}}{4.5 \times R_p}$$

$$= \frac{\mu^2 \times E_g^2}{2} \times \frac{1}{4.5 \times R_p}$$

$$= \frac{\mu^2 \times E_g^2}{9 \times R_p} \qquad (7)$$

Where: E_g is the peak value of the grid exciting voltage

Formula (7) has many practical uses when working with A.F. circuits. As an example of its application, let us solve a problem using a type 71A triode power tube. We are assuming, of course, that the tube is being operated under Class A conditions.

Example 1: What is the maximum undistorted power output that may be secured from a type 71A power tube when operated at a plate voltage of 180 volts, -40.5 grid bias, and loaded with 3,500 ohms in the plate circuit?

Solution: Since the grid bias is given as -40.5 volts, the grid signal voltage may attain this peak value before driving the grid positive. Then, 40.5 volts is the peak value of the grid exciting voltage to be used in calculating the maximum undistorted power output. From the manufacturer's table of characteristics, it is found that the amplification factor of the type 71A tube is 3 and that when operated under the conditions specified in the problem, the plate resistance of the tube is 1,750 ohms. Substituting the known values in formula (7), we have:

$$M.U.P.O. = \frac{3^2 \times (40.5)^2}{9 \times 1750}$$

$$= \frac{9 \times 1640.25}{9 \times 1750}$$

Cancelling the 9's:

$$= \frac{1640.25}{1750} = .937 \text{ watt}$$ [1]

[1] The manufacturer's rating is slightly less than this due to the higher recommended load impedance.

Example 2: What is the maximum undistorted power output that may be secured from a type 2A3 power amplifier when operated with a plate voltage of 250 volts and a grid bias of -45?

Solution: Referring to the manufacturer's characteristics, we find the plate resistance of this tube to be 800 ohms and its amplification factor 4.2. Assuming that the load resistance is twice the plate resistance of the tube, that is, 1600 ohms, the maximum undistorted power output may be calculated as follows:

Substituting in formula (7):

$$\text{M.U.P.O.} = \frac{(4.2)^2 \times 45^2}{9 \times 800}$$

$$= \frac{17.64 \times 2025}{7200}$$

$$= \frac{35,721}{7,200} = 4.9 \text{ watts}$$

This power output is considerably greater than that specified by the manufacturer. The reason is because we have used a load resistance of 1600 ohms rather than the 2500 ohms as recommended. Increasing the load resistance (assuming the tube's plate resistance to remain constant), decreases the power output and also decreases the harmonic content. This is shown graphically for a 45 tube in Fig. 8 and, of course, the same applies to all other triode power amplifiers. When the plate circuit of a type 2A3 is loaded with 2,500 ohms, the undistorted power output that will be obtained is 3.5 watts.

There are two reasons why a greater power output may be secured from a 2A3 tube than from a type 45. Both tubes are triode power amplifiers, but they differ considerably in internal construction. The 2A3 was brought out approximately four years after the type 45 and by comparing their transconductance values, the 2A3 is seen to be a considerable improvement. The first reason for the 2A3's greater power output is that its plate resistance is reduced to a much lower value. By all the power formulas that have been derived, it is proved that the power output is inversely proportional to the tube's plate resistance. A lower plate resistance then means a greater power output. Second, it is also shown in all the formulas that the A.F. power output is directly proportional to the square of the amplification factor. The higher amplification factor possessed by the 2A3 is responsible for obtaining the greater power output in addition to its lowered plate resistance.

6. **POWER TUBES CONNECTED IN PARALLEL.** When it is impossible to obtain sufficient audio power output from a single tube and the voltage supply is inadequate to operate a larger power tube, two or more small tubes may be connected in parallel to obtain the greater power output desired. Two power tubes connected in parallel are shown in Fig. 11. The input transformer T_1 is used to couple the

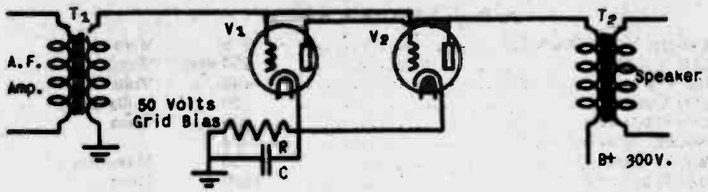


Fig.11 Circuit diagram showing two power tubes connected in parallel.

output of the A.F. voltage amplifier to the grid circuits of the two parallel power tubes. The audio voltages developed across the secondary of T_1 are applied to the grid of V_1 and to the grid of V_2 simultaneously because these two grids are connected together. In the plate circuit, the output transformer T_2 serves to couple the output power from the two tubes into the loudspeaker. Since the plates of both tubes are connected together, the voltage as fed through the primary of T_2 will be applied to both plates. Each tube draws its rated plate current and the total current of both tubes passes through the biasing resistance R and the primary of the output transformer. The primary winding must be capable of carrying the high DC current and the magnetization characteristics of the transformer core must be such that it will not saturate. To satisfy this latter requirement, it is necessary to provide the iron core with air gaps, then use more iron to obtain the proper primary inductance. Such a transformer is ordinarily quite expensive.

When calculating the size of the biasing resistor for parallel power tubes, bear in mind that the total current drawn by both tubes passes through it. The value used, then, is just one-half the size that would ordinarily be used for a single tube. The bypass condenser C must be large to prevent low-frequency degeneration of the grid-signal voltage. It should have a capacity of from 16 to 25 mfd., and a voltage breakdown rating not less than 75 volts (when the grid bias is 50 volts). A condenser of this kind is slightly more expensive than an ordinary cathode bias by-pass condenser.

Let us assume that V_1 and V_2 are type 2A3 tubes. The operating characteristics of a type 2A3 power amplifier triode and the family of plate voltage-plate current characteristic curves are shown in Fig. 12. The plate voltage is 250 volts and the recommended grid bias is -45 volts, so the power supply should be capable of delivering at least 300 volts. The plate current drawn by each tube is 60 ma.; therefore, the total current passing through the primary of the output transformer and also the biasing resistor is 120 ma. Calculating the size of the biasing resistor, we have:

$$R = \frac{E}{I} = \frac{45}{.120} = 375 \text{ ohms}$$

To determine the size necessary for the by-pass condenser, we shall

As Single-Tube Class A Amplifier

FILAMENT VOLTAGE (A. C.)	2.5	Volts
PLATE VOLTAGE	250 max.	Volts
GRID VOLTAGE	−45	Volts
PLATE CURRENT	60	Milliamperes
PLATE RESISTANCE	800	Ohms
AMPLIFICATION FACTOR	4.2	
MUTUAL CONDUCTANCE	5250	Micromhos
LOAD RESISTANCE	2500	Ohms
SELF-BIAS RESISTOR	750	Ohms
UNDISTORTED POWER OUTPUT	3.5	Watts

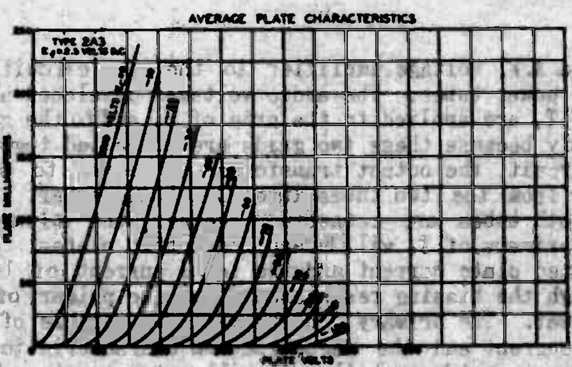


Fig. 12 Family of Ep-Ip characteristic curves for a type 2A3 power amplifier.

assume that its capacitive reactance should not be greater than 37.5 ohms at a frequency of 100 cycles.[1] The capacity will, therefore, be:

$$C = \frac{1}{6.28 \times F \times X_C}$$

$$= \frac{1}{6.28 \times 100 \times 37.5}$$

$$= \frac{1}{23,550} = .000042 \text{ farad, or } 42 \text{ mfd.}$$

When selecting the load impedance for parallel power tubes, we must take into consideration the fact that the two tubes are connected in parallel. Each has a plate resistance of 800 ohms, so the combined plate resistance of the two parallel tubes is 400 ohms, and the load impedance should be at least twice this value; that is, 800 ohms. The output transformer T_2 should be designed so that when connected to a loudspeaker and delivering its full power output, the primary places an 800-ohm load on the two parallel power tubes.

[1] Refer to Lesson 20, Section 1.

The grid exciting voltage developed across the secondary of T_1 causes the plate current of both tubes to increase and decrease simultaneously. Assuming the same turns ratio for the input transformer, the grid exciting voltage necessary to drive two or more power tubes connected in parallel is the same as that required for a single tube. The amplitude of the plate current changes through the primary of the output transformer will be twice as great as would occur if one tube were working alone. The higher amplitude of plate current changes creates greater magnetic field variations which in turn deliver more power to the loudspeaker than one tube alone could deliver. In connection with the high amplitude of current changes through the primary of the output transformer, it must be remembered that the transformer core should be designed so as not to magnetically saturate on the peaks of the current increases. Should this occur, the instantaneous voltage developed across the secondary will not be in accordance with the primary current and a high percentage of harmonic distortion will result.

Parallel power tubes were popular in radio receiver design around 1929 and 1930. Since then, the push-pull method of power amplification has been adopted and parallel power tubes are now obsolete for receiver use.

7. **PUSH-PULL POWER AMPLIFIERS.** Several advantages are to be gained by connecting power tubes in push-pull, two of the more important being the production of a greater power output and the reduction of harmonic distortion. In the output of single-ended amplifiers, there will always be a certain amount of harmonic distortion due to the curvature of the grid voltage-plate current characteristic. The use of a high load resistance causes the dynamic E_g-I_p characteristic to become more linear; however, it is accompanied with a decrease in power output. With a push-pull circuit as shown in Fig. 13, the harmonic distortion can be reduced to an extremely low value and a high power output secured at the same time.

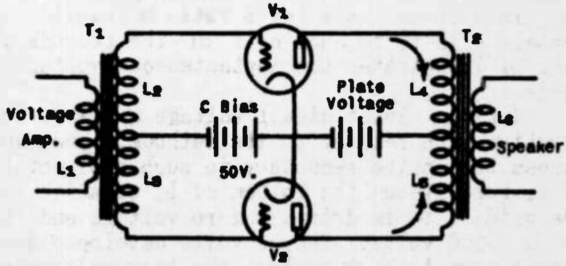


Fig. 13 Typical push-pull power amplifier stage.

The input transformer T_1 has a center tap on the secondary winding which is connected to the negative side of the C battery. The positive side of the C battery in turn is connected to the cathode of both tubes. The primary of the output transformer T_2 is also equipped with a center tap, to which the plate supply voltage is connected. Let us first consider the static conditions in a push-pull circuit; that is, when no input signal voltage is applied. Since the C battery is connected in a position that is common to both tubes, both grids will be placed at a negative potential with respect to their cathodes by an amount equal to the C battery voltage. The bias on the grid of V_1 is fed through the upper half of the secondary L_2 and the bias on the grid of V_2 is fed through the lower half, L_3. In Fig. 13, both grids are placed at a 50-volt negative potential with respect to their cathodes.

In the plate circuit, the plate current for V_1 passes through the upper half of the primary L_4 and the plate current for V_2 passes through the lower half of L_6. The direction of the plate current in each half of the winding is opposite as indicated by the arrows. The primary is exactly center tapped, so L_4 and L_6 have the same number of turns. Assuming V_1 and V_2 to be identical tubes, the current passing through L_4 is equal to the current through L_6. The magnetic field set up around L_4 will thus be equal and opposite to the magnetic field established around L_6. With the field around L_4 tending to magnetize the iron core of the transformer in one direction and the field around L_6 tending to magnetize it in the opposite direction, these two equal and opposite forces cancel, resulting in no core magnetization by the DC plate current through the primary. This is a distinct advantage of the push-pull circuit in comparison to a parallel circuit. The core of the output transformer in a push-pull circuit is not magnetized at all by the DC plate current, whereas with the power tubes connected in parallel, the core magnetization is extremely high, being produced by the total plate current drawn by both tubes.

Now, let us assume that an input signal voltage is developed across the secondary of the input transformer T_1. Since the secondary is center tapped, the total voltage developed is divided between the two tubes. Assuming a given AC voltage applied to (or developed across) the primary, each grid will receive only one-half as much excitation as a single-ended power tube would with the same transformer turns ratio. This means that twice as much primary voltage would have to be applied to secure the same grid excitation or the turns ratio from primary to secondary doubled. In all push-pull input transformers, the turns ratio is doubled; that is, made approximately 1 to 3½ to each half of the secondary, or 1 to 7 overall. Fig. 14 illustrates the instantaneous voltages applied to the two grids.

With no input signal voltage applied, each grid is 50 volts negative with respect to its cathode. When 100 volts is developed across the entire secondary in such a direction as to make the top of L_2 positive and the bottom of L_3 negative (shown at A, Fig. 14), the grid of V_1 is driven to zero voltage and the grid of V_2 is driven to -100 volts. The 50 volts developed across L_2 is in such a direction as to buck against the bias voltage supplied by the C battery and thus cause the instantaneous grid potential of V_1 to be driven to zero. On the other side, the 50 volts developed across L_3 is in such a direction as to add to the bias voltage produced by the C battery, thus increasing the negative voltage on the grid of V_2 to -100 volts. The plate current in V_1 is then caused to increase and at the same time the plate current in V_2 decreases.

At B in Fig. 14, the conditions are shown when the voltage developed across the secondary of T_1 is in the opposite direction.

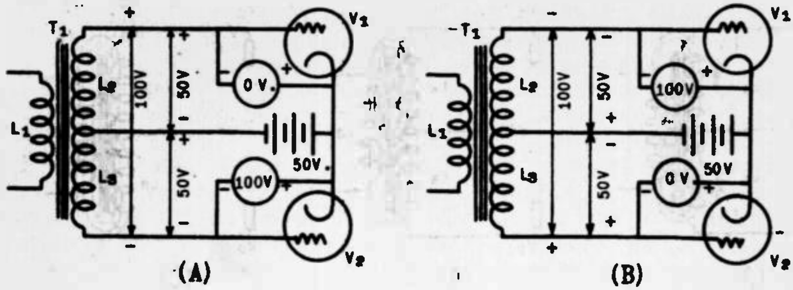


Fig.14 (A) When the induced secondary voltage is in the direction as shown, the grid of V_2 is made more negative and the grid of V_1 less negative.
(B) Induced secondary voltage in the opposite direction. V_1 made more negative and V_2 made less negative.
Note that in each case, the two grids are being excited 180° out of phase.

Assuming that a peak of 100 volts is again induced across the entire secondary, there will be 50 volts across L_2 and 50 volts across L_3. The direction of the voltage induced in each half of the winding is shown on the diagram. The voltage induced in L_2 is now in such a direction as to add to the 50 volts of the C battery, so the grid potential of V_1 is driven to -100 volts and the plate current decreases. At the same time, the voltage induced in L_3 bucks against the 50-volt C battery and makes the instantaneous grid potential of V_2 zero. The plate current of V_2 increases.

In these examples, it will be noted that the plate current of one tube increases while the plate current of the other tube decreases at the same time. The reason, of course, lies in the fact that the grids are being excited exactly 180° out of phase; that is, when the grid of one tube is made more negative, the grid of the other tube is made less negative. The plate current changes through the two halves of the primary in the output transformer will likewise be exactly 180° out of phase.

The three diagrams at A, B and C in Fig. 15 will be used to explain the action that takes place in the plate circuit. First, with no signal voltage applied to the input of the push-pull amplifier, the plate current drawn by V_1 is equal to the plate current of V_2. Therefore, the magnetic field set up around L_4 is equal to the field around L_5. Since these two currents are in opposite directions, the magnetic fields are also opposite, so they buck against each other and cancel. No voltage is produced in the secondary L_6 at this time.

Now let us assume that a signal voltage is applied to the input of the push-pull amplifier and is in such a direction as to make the grid of V_1 less negative and the grid of V_2 more negative. The plate current through L_4 then increases and the plate current through L_5 decreases. The magnetic field set up around L_4 expands and the field around L_5 collapses as illustrated at B, Fig. 15. These two fields were formerly equal and opposite, but are now widely different in strength, so the total flux change in the core (and through the secondary) is quite high. Inductively, the two magnetic fields have added together, because one has increased above its former value,

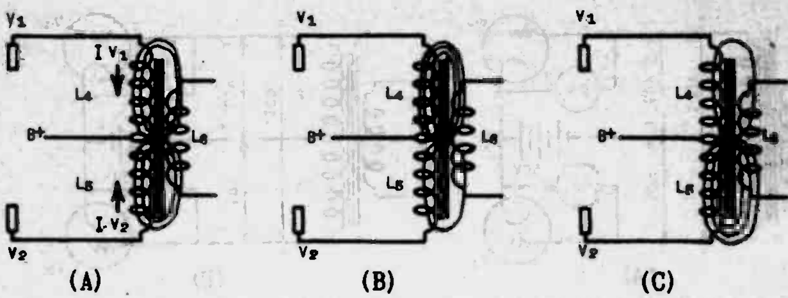


Fig. 15 (A) No grid exciting voltage. Field around L_4 equal and opposite to field around L_5.
(B) V_1 made less negative. V_2 made more negative. Field around L_4 expands due to increased I_p. Field around L_5 collapses at the same time.
(C) Conditions opposite that shown at B. Field around L_5 expands, and field around L_4 collapses as Ip through V_2 increases and Ip through V_1 decreases.

whereas the other has decreased below its former value. The total flux change thus created cuts through the secondary winding L_6 and induces a voltage therein. The total voltage induced in L_6 by the two changing fields is greater than that which could be induced by either winding alone. *This is because an induced voltage always depends upon the total flux change through the secondary turns.* Here we have one field increasing and the other decreasing, so there is a greater magnetic field change through the turns of L_6 than either field alone could produce and the power thus transferred to the secondary circuit is greater.

On the next alternation of the applied grid voltage, the grid of V_2 is made less negative and the grid of V_1 more negative. The plate current through L_5 increases and the plate current through L_4 decreases. The magnetic field around L_5 then expands and the field around L_4 collapses as illustrated at C, Fig. 15. The same action occurs as before; that is, the collapsing field inductively adds to the expanding field, thereby establishing a greater flux change through the secondary than either field alone could produce and a higher output voltage is induced in L_6.

From the foregoing explanation, the reason for the peculiar name applied to this type of circuit may be understood. These two tubes are working on opposite sides of a balanced circuit. Their grids are excited exactly 180° out of phase and their plate currents vary likewise. The opposite phase current changes through the primary of the output transformer have the effect of adding together to produce the secondary output voltage and output power. One field collapsing (pulling) and the other field expanding (pushing) results in a total magnetic field change through the secondary of high magnitude and a resultant power output from the circuit equal to approximately three times the power output that either tube can produce when working alone in a single-ended circuit under similar voltage and load conditions.[1]

[1] The erroneous statement is often made that the output of two tubes in push-pull is theoretically only twice that of a single tube. As will be shown later, a greater output is possible, due to the lowered internal resistance of the push-pull tubes.

8. EVEN HARMONIC CANCELLATION IN PUSH-PULL AMPLIFIERS. Another outstanding advantage of a push-pull amplifier is that all even harmonics produced by the power tubes are cancelled in the plate load circuit. The cancellation of these even harmonics results in an output power relatively free from amplitude distortion. Generally, the greater part of the amplitude distortion produced by any audio amplifier is due to the high percentage of second harmonics. The elimination of this second harmonic content (and other even harmonics) in push-pull circuits enables the production of audio driving power for the loudspeaker that is relatively free from distortion.

It should be understood that a push-pull power stage will not eliminate or cancel the even harmonic distortion if it is contained in the grid signal voltage. The cancellation is effective only on those harmonics generated by the power tubes themselves, so to obtain a distortionless output, it is also necessary for the input signal voltage to be free from harmonic content.

Let us assume that improper operating conditions exist in a push-pull amplifier stage, then proceed to show how the generated harmonics are cancelled. We learned in Lesson 19 that an excessive grid bias always results in amplitude distortion. Of course, there are other causes for this distortion, but for explanation, we shall assume that only this defect exists in the amplifier circuit. When in an overbiased condition, the plate current increase in one push-pull tube will not be equal in amplitude to the simultaneous decrease in plate current which occurs in the other tube. This is shown graphically by A and B, Fig. 16. Assuming that the grid of V_1 is

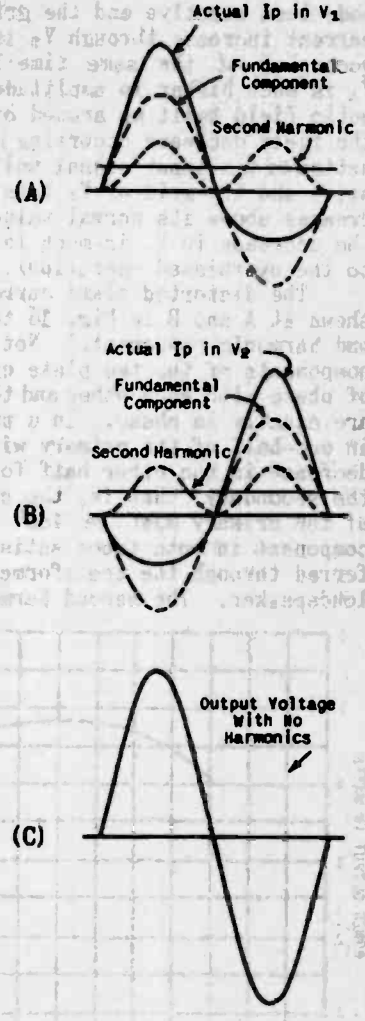


Fig.16 (A) Distorted Ip flowing through V_1 resolved into its fundamental and second harmonic components.
(B) Distorted Ip flowing through V_2 resolved into its fundamental and second harmonic components.
(C) Output voltage across secondary. No harmonics are contained due to their cancellation in the primary circuit.

made less negative and the grid of V_2 made more negative, the plate current increase through V_1 is shown at A and the current decrease occurring at the same time in V_2 is shown at B. The increase in V_1 is much higher in amplitude than the decrease in V_2 so the magnetic field built up around one-half of the primary winding exceeds the field decrease occurring in the other half. On the next alternation of the input signal voltage, the grid of V_1 is made more negative and the grid of V_2 less negative. The plate current now increases above its normal value through V_2 and decreases in V_1, but the decrease in V_1 is much less than the increase through V_2 (due to the overbiased operation).

The distorted plate current variations through V_1 and V_2 are shown at A and B in Fig. 16 to consist of a fundamental and a second harmonic component.[1] Notice particularly that the fundamental components of the two plate current variations are exactly 180° out of phase with each other and that the two second harmonic components are exactly in phase. In a push-pull circuit, a current increase in one-half of the primary winding must be accompanied by a current decrease in the other half for an output voltage to be induced in the secondary; that is, the current changes through the two halves of the primary must be 180° out of phase. Since the fundamental component in both tubes satisfies this condition, it will be transferred through the transformer to the secondary and applied to the loudspeaker. The second harmonic component, however, will be can-

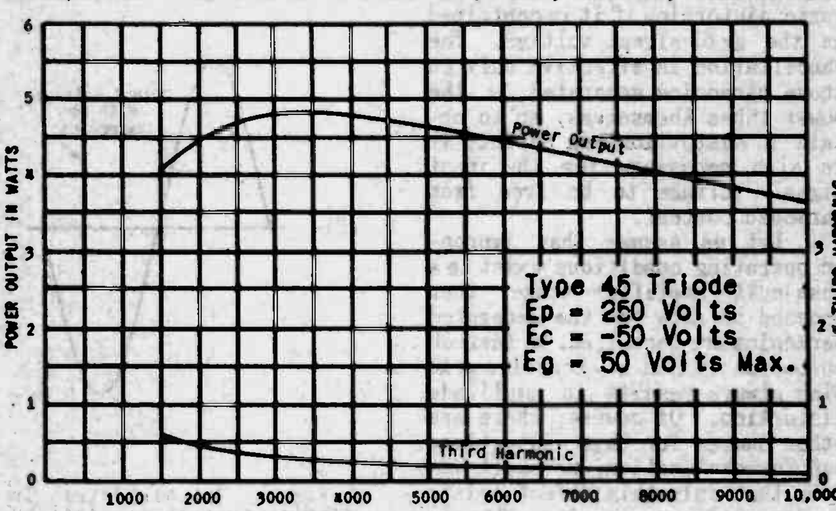


Fig. 17 Variation of power output and third harmonic with load resistance for two typical triodes in push-pull.

[1] Refer to Lesson 26, Section 5.

celled because it is exactly in phase in both tubes. From A and B (Fig. 16) it can be seen that as the second harmonic in V_1 increases, the second harmonic in V_2 increases at the same time. The magnetic fields established around the two halves of the primary winding by these components will be rising and falling together; they will always be exactly equal and opposite and will thus cancel each other.

By the same reasoning, all other even harmonics are cancelled in the plate load impedance. The fourth, sixth, eighth, etc., harmonics are generally of such small magnitude, however, that their effect on the tone quality is negligible. The odd harmonics, such as the third, fifth, seventh, ninth, etc., are not cancelled by a push-pull circuit. By graphical analysis, it can be shown that these harmonics are out of phase in the transformer primary and will appear in the output along with the fundamental component. The graph shown in Fig. 17 illustrates the percentage of third harmonic content in the output power from a push-pull amplifier under varying conditions of load impedance. The load impedance specified on this graph is that measured from plate to plate of the push-pull tubes. It is seen that the third harmonic content is not of appreciable value as long as the load impedance is high and that it only rises to a small percentage when the plate-to-plate load resistance is decreased to a low value.

9. POWER OUTPUT OF PUSH-PULL AMPLIFIERS. In a properly loaded push-pull amplifier, the total power output which may be secured from the two tubes is equal to nearly three times the power that can be obtained from either tube working alone in a single-ended circuit. To show why this is true, we must determine the effective plate resistance of the push-pull tubes and the actual load resistance into which these tubes are working. The two tubes are magnetically coupled together through the two halves of the output transformer primary and for the present[1] the internal plate resistance of the push-pull combination may be considered the same as a single tube having an internal plate resistance equal to one-half the plate resistance of one tube. The two push-pull tubes are working into the primary of the output transformer at the same time (one increasing and the other decreasing), so they may be regarded the same as two parallel signal sources. The internal impedance of the signal source (both push-pull tubes) is then one-half the internal resistance of either tube. Thus, if two type 45 power amplifier tubes are being used, each having a plate resistance of 1600 ohms, the internal resistance of the combination will appear as 800 ohms to the primary of the output transformer.

Next, let us find the load impedance into which the two tubes are working. It is improper to assume that each of the push-pull tubes is delivering its power into its respective portion of the primary winding through which its plate current flows. It is improper because of the close magnetic coupling which exists between the two halves of the primary winding. Current and magnetic field changes in one-half of the primary cause voltages to be induced in

[1] More complete treatise on this subject in Unit 3, Lesson 6, Section 8.

the other half, and vice versa. The mutual coupling that exists between the two halves of the primary is in some ways similar to the primary and secondary relations in a two-winding transformer. The load impedance actually presented to the push-pull tubes is closely equal to one-fourth the total primary impedance and may be considered as such for all practical calculations. This value of load impedance arises from the fact that at any one instant, the two push-pull tubes are, in reality, working into one-half of the total primary inductance. Bear in mind that the pair of push-pull tubes are considered as equivalent to a single unit when working into the primary, and that the total output produced in the secondary depends upon the *current difference* established in the primary rather than on the total current flowing in each plate circuit. The total primary inductance is thus not effective in loading the push-pull tubes. The actual load inductance should be considered as just one-half the total primary inductance. Both halves of the primary have the same number of turns, but since the inductance of a winding varies as the square of the turns, the inductance of one-half the winding is not equal to one-half the total inductance, but rather to $(\frac{1}{2})^2$ or $\frac{1}{4}$ the total inductance. The impedance of a coil varies directly with the inductance, so if the plate-to-plate inductance load on the push-pull tubes is $\frac{1}{4}$ the total inductance, the load is also $\frac{1}{4}$ the total impedance.

When a manufacturer specifies the load impedance to be used for push-pull tubes, he always means the total primary impedance and generally calls it the "plate-to-plate" load. It should be remembered that the actual load impedance into which the push-pull circuit is working at any one instant is equal to $\frac{1}{4}$ of this plate-to-plate load value.

Having learned how to determine the plate resistance and the load impedance in a push-pull circuit, we may proceed to calculate the power output that can be obtained. The average power output of a push-pull amplifier, operating Class A, may be calculated with the following formula:

$$P = \frac{\mu^2 \times E_g^2 \times R_L}{2 \times (R_p + R_L)^2} \qquad (8)$$

Where:
- μ is the amplification factor of one tube
- E_g is the peak value of the signal voltage applied to one grid
- R_L is one-fourth the plate-to-plate load impedance
- R_p is one-half the plate resistance of one tube

Let us use this formula to calculate the power output from two type 45 tubes using a 3200-ohm plate-to-plate load and 50 volts peak grid excitation. To simplify calculations, we shall assume the plate resistance of the type 45 tube to be 1600 ohms. Substituting these given values in formula (8), we have:

$$P = \frac{(3.5)^2 \times 50^2 \times 800}{2 \times (800 + 800)^2}$$

$$= \frac{12.25 \times 2500 \times 800}{2 \times (1600)^2}$$

$$= \frac{24,500,000}{5,120,000} = 4.78 \text{ watts}$$

The maximum undistorted power output will always be secured from a push-pull amplifier when R_L (½ the plate-to-plate load) is equal to R_p (½ the R_p of one tube). To simplify formula (8) under these conditions, by substituting R_p for R_L in formula (8), we have:

$$\text{M.U.P.O.} = \frac{\mu^2 \times E_g^2 \times R_p}{2 \times (R_p + R_p)^2}$$

$$= \frac{\mu^2 \times E_g^2 \times R_p}{2 \times (2 \times R_p)^2}$$

Squaring $2 \times R_p$ and multiplying by 2:

$$= \frac{\mu^2 \times E_g^2 \times R_p}{8 \times R_p^2}$$

Cancelling the R_p in the numerator with one in the denominator:

$$= \frac{\mu^2 \times E_g^2}{8 \times R_p} \qquad (9)$$

Using formula (9), the maximum undistorted power output of a Class A push-pull amplifier may be calculated when:

- μ is the amplification factor of one tube
- E_g is the peak grid signal to one tube
- R_p is equal to ½ the plate-to-plate load and also equal to ½ the plate resistance of one tube.

Using formula (9) to solve the preceding problem:

$$\text{M.U.P.O.} = \frac{3.5^2 \times 50^2}{8 \times R_p}$$

$$= \frac{12.25 \times 2500}{8 \times 800}$$

$$= \frac{30,625}{6,400}$$

$$= 4.78 \text{ watts (same answer as using [8])}$$

The power output from the push-pull combination is thus found to be 4.78 watts and, by referring to the graph in Fig. 17, it is seen that the third harmonic distortion with this value of plate-to-plate load resistance is slightly greater than .5 of 1%, a value extremely low and not objectionable. The second harmonic distortion of course, is negligible, because of the cancellation that occurs in the output circuit. This, nearly 5 watts of undistorted audio power, is obtained by connecting two type 45 tubes in a push-pull circuit. With an equal input grid signal of 50 volts and a plate load impedance of 3200 ohms, the power output secured from a single 45 tube is approximately 2.1 watts. This was calculated by use of formula (7) on page 15 of this lesson.

10. **ADDITIONAL ADVANTAGES OF PUSH-PULL AMPLIFIERS.** As well as obtaining reduced harmonic distortion and increased power output, the push-pull circuit has several other advantages. A vacuum tube rectifier circuit is used as the power supply for most push-pull amplifiers and in units of this kind, the output voltage is generally not a pure DC, but rather has a slight 120-cycle ripple. This causes a corresponding 120-cycle current ripple through each half of the primary of the output transformer. The current in both halves of the primary, however, will be increasing and decreasing simultaneously (in phase); thus, the magnetic fields established by these current changes will always be equal and opposite, resulting in complete cancellation. The advantage of this is that practically no hum will be produced from the speaker, as would be the case if parallel power tubes or a single-ended power stage were used. For complete cancellation of the hum voltage, the two tubes must be identical and the entire circuit well-balanced.

Grid-bias voltage for a push-pull amplifier is usually obtained by a resistance in the cathode (or filament) lead to ground. In an ordinary amplifier, the plate current changes passing through the biasing resistance cause a varying bias voltage to be developed, which degenerates the grid-exciting voltage. This, however, is not true in a push-pull amplifier because the total plate current drawn from and returned to the power supply remains constant when a grid signal voltage is applied. In a well-balanced push-pull circuit, the plate current increase of one tube is equalled by the plate current decrease of the other; hence, the total current passing through the biasing resistance will always remain at a constant value. Degeneration of the grid exciting voltage will, therefore, not occur, so it is unnecessary to place a high-capacity by-pass condenser across the resistance to maintain a steady grid-bias voltage. If a 120-cycle ripple exists in the plate current that passes through the biasing resistance, the 120-cycle voltage developed across it will be applied to both grids simultaneously and the current changes created through the two halves of the primary of the output transformer will be in phase with each other and thus cancel. For these reasons, a by-pass condenser need not be used across the biasing resistor in a push-pull amplifier. Fig. 18 at A shows the position of the biasing resistance in a typical push-pull power stage, using directly heated power tubes, and B in Fig. 18 illustrates the proper connection when cathode or indirectly heated power tubes are used.

The elimination of this by-pass condenser greatly reduces the cost of manufacturing the receiver and also simplifies construction; hence, an advantage is gained in comparison to parallel and single-ended power stages.

Another advantage possessed by a push-pull amplifier has been pointed out in a previous paragraph, but should be recalled in this summary. This is the fact that the DC plate current for both tubes flows in opposite directions through the two halves of the output

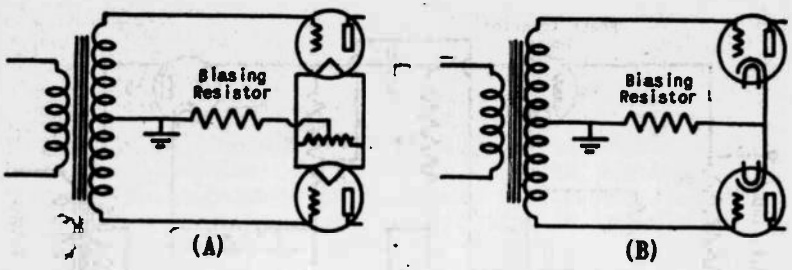


Fig.18 (A) Biasing resistor for directly heated tubes in push-pull power amplifier.
(B) Biasing resistor for cathode type tubes.

transformer primary, and as a result, the core is not subjected to continuous DC magnetization. The absence of magnetization greatly increases the permeability of the iron core and enables a higher primary inductance to be obtained with the same number of turns. Magnetic alloys are generally used for the core material and the construction of the transformer is greatly simplified with corresponding decrease in cost.

It should be understood that if the two tubes used in a push-pull circuit are not balanced as to their characteristics, the above advantages will not be secured. Quite often, separate and adjustable biasing resistors are used for each of the push-pull tubes so as to avoid the possibility of an unbalanced condition and its resulting distortion. With separate biasing resistors, the two plate currents may be equalized.

11. **PHASE INVERTER CIRCUITS.** It is necessary that the grids of two tubes connected for push-pull operation be excited 180° out of phase. By use of a transformer input as explained in Fig. 14, this condition is satisfied. The grids of push-pull tubes may also be properly excited by the use of a "phase inverter" circuit, the advantage of which is that no coupling transformer is used. A circuit of this kind is shown in Fig. 19. V_1 and V_2 operate together to excite the grids of the push-pull tubes, V_3 and V_4, 180° out of phase. Applying the excitation to a push-pull stage with a phase inverter circuit eliminates the use of the input coupling transformer with its associated frequency discrimination and probable generation of harmonic frequencies.

The operation of the circuit shown in Fig. 18 is as follows: The A.F. input voltage is applied across the resistance R_1. The voltage developed across this resistance is applied directly to the grid of V_1 and causes corresponding current changes through the plate load resistance R_3. The A.F. voltages developed across R_3 are transferred through C_1 and appear across the grid-leak resistance R_5. The A.F. voltages developed across R_5 are in turn applied to the grid of push-pull tube V_3. To obtain grid excitation for the second tube V_2 in the phase inverting circuit, a portion of the voltage developed across R_5 is used. R_5 may consist of a single, tapped resistance or two series resistors. It is important to determine the phase of the voltages developed across R_5 relative

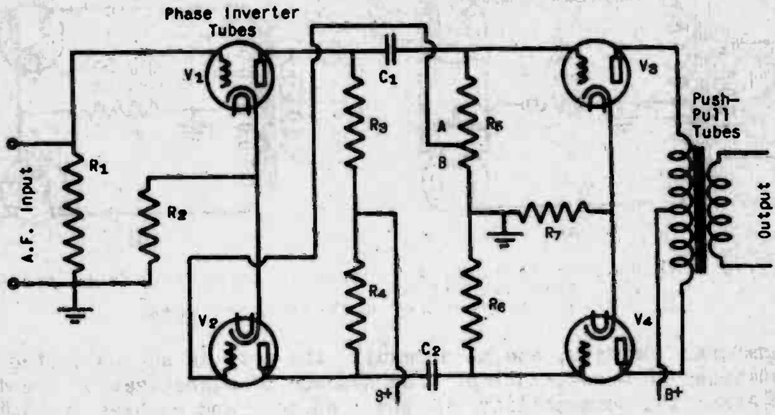


Fig.19 Phase inverter circuit for input to push-pull tubes.

to the grid exciting voltage applied to V_1. Neglecting the slight effect of coupling condenser C_1, the A.F. voltages across R_5 are in phase with those developed across the plate resistor R_3. The A.F. voltages across R_3 are, in turn, 180° out of phase with the input voltage as applied across R_1.[1] Likewise, the voltages produced across R_5 are 180° out of phase with the grid voltage of V_1, so it is possible to secure grid excitation for V_2 by using a portion of the A.F. voltage across R_5. The grid of V_2 is then excited 180° out of phase with V_1 and the amplified output is coupled through condenser C_2 to the grid of V_4, the opposite tube in the push-pull circuit. Since V_3 is receiving its grid excitation from V_1 and V_4 is receiving its excitation from V_2, the grids of V_3 and V_4 are being excited 180° out of phase.

The next problem is to properly proportion the two sections of R_5 so as to secure equal excitation on the grids of the push-pull tubes. To do this, it is necessary to know the amplification factor of tubes V_1 and V_2. In nearly all phase-inverter circuits, these tubes are identical; so for explanation, we will assume that the Mu of each is 20. Accepting the conditions of ideal amplification, the A.F. voltages developed across R_3 will then be 20 times greater than the amplitude of the input voltages applied to R_1. Neglecting Xc of the coupling condenser, the voltages developed across R_5 (both A and B) will be 20 times greater than the input voltage on the grid of V_1. To obtain a grid excitation on V_2 that is equal to that applied to V_1, the voltage developed across section B of R_5 must be

[1] This fact follows from the study of resistance-coupled A.F. amplifiers in Lesson 19. On the positive alternation of the signal voltage, the grid is made less negative and the plate current increases. The increased plate current through R_3 results in an increased voltage drop, thus reducing the plate voltage at that instant. On the negative alternation, the negative grid potential of V_1 is decreased, decreasing the plate current and causing less voltage drop across R_3 with a rise in plate voltage. Thus, the voltages produced across the plate circuit are exactly 180° out of phase with the voltages applied to the grid circuit in a resistance-coupled amplifier.

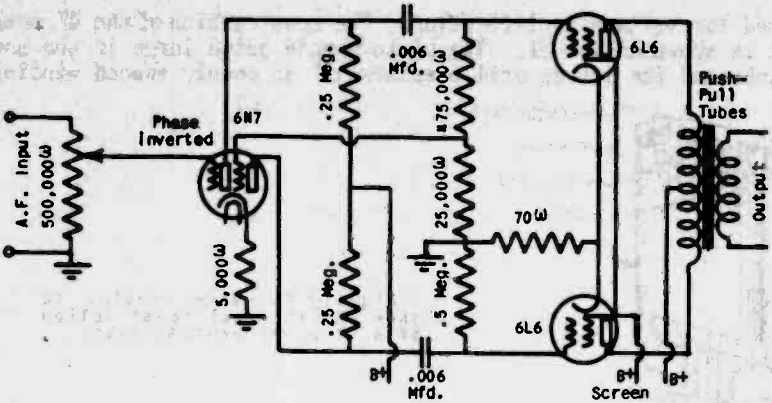


Fig.20 Single tube used for phase inversion.

one-twentieth of the total voltage developed across A and B. Thus, if the total resistance of R_3 is 500,000 ohms, it should be divided to have 475,000 ohms in section A and 25,000 ohms in Section B. When these values are used, the grid exciting voltage on V_2 will be equal in amplitude to that applied to V_1. Then, since the mu of V_2 is also 20 and the plate coupling resistance R_4 is the same value as R_3, the grid of V_4 will be excited with a voltage exactly equal in amplitude and 180° out of phase to that applied to the grid of V_3.

In Fig. 19, two tubes are being used for inverting the phase of the input signal to the push-pull circuit. The two triode sections of a duo-triode tube such as the 2A6, 6A6, 53, 6N7 etc., may also be used for the same purpose. A diagram of a phase inverter circuit using the all-metal 6N7 is shown in Fig. 20. Comparison to Fig. 19 reveals that the same type of circuit is used.

12. PENTODE POWER TUBES. A triode power amplifier tube always requires a fairly high grid exciting voltage to obtain appreciable power output. By inspecting the characteristics of a type 45 tube, it is seen that a maximum undistorted power output of 1.6 watts is secured with a peak grid exciting voltage of approximately 46 volts. Of course, two of these tubes may be connected in parallel or in push-pull to obtain a greater power output, but the increased current demand from the power supply makes the over-all design of the receiver more expensive. On the other hand, a single pentode power tube may be used to economically develop the greater power when it is desired.

The physical construction of a pentode power tube is similar to that of the pentode R.F. amplifier in that it contains the same number of elements; that is, the electron emitter, control grid, screen grid, suppressor grid and plate. The relative size of the elements and their spacing within the tube, however, is considerably different, because the power tube is designed specifically to produce a high A.F. power output, whereas the R.F. pentode is designed for voltage amplification. The construction of the 47 power tube is shown in Fig. 21. The plate is made quite large in the power tube and the screen grid consists of an openly spaced winding.

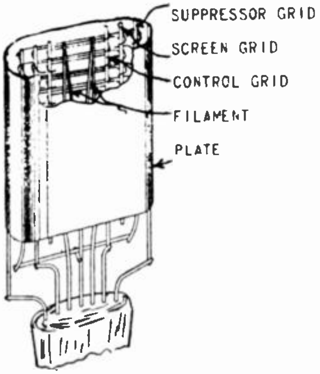
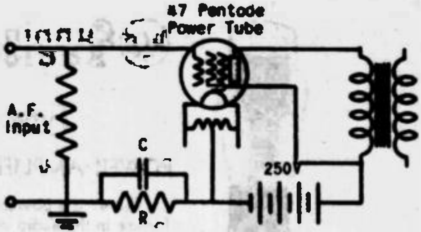


Fig.21 Cut-away drawing to show the internal construction of a 47 power pentode tube.

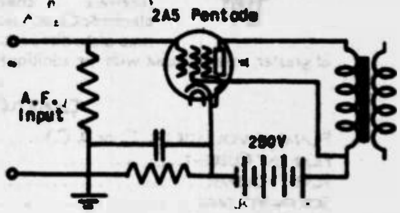
No outer screen is used because it is not necessary to shield the plate from external inductive and capacitive fields when working in A.F. circuits. The suppressor grid is still located between the screen grid and the plate, but is not closely wound. It is maintained at the same potential as the cathode and thus serves to repel the secondary electrons back to the plate when the plate potential falls below that of the screen grid. This, of course, is the same purpose for which it is used in the R.F. pentode. In the type 47 tube (typical pentode power amplifier), the filament is directly heated and the suppressor grid is internally connected to the midpoint of the filament wire. The suppressor does not have an external connection in the type 47. In later pentode power tubes, such as the 2A5 and 42, the electron emitter is indirectly heated and the suppressor grid is provided with a prong on the base of the tube. Drawings A and B in Fig. 22 show the circuit connections for the indirectly and directly heated tubes, respectively. The suppressor grid enables the screen grid to be operated at the same potential as the plate, which increases the transconductance and amplification factor of the tube.

A table of characteristics for the type 47 pentode power tube is listed in the accompanying chart. As can be seen, with 250 volts applied to the plate and screen, the negative grid bias need only be -16.5 volts to limit the plate current to 31 ma. The amplification factor of the tube is 150 and the plate resistance is 60,000 ohms. The plate load impedance, as recommended by the manufacturer, is 7,000 ohms, considerably less than the plate resistance of the tube. When a plate load higher than 7,000 ohms is used, a greater power output will be secured, but the amplitude or harmonic distortion also increases. This is due to the fact that with a high load impedance, the plate voltage varies over an extremely wide range, a direct result of the high transconductance possessed by the tube.

Fig. 22



(A) Tube symbol and connections to directly heated pentode power tube.



(B) Tube symbol and connections to indirectly heated pentode power tube.

Thus, on plate current increases, the minimum plate voltage falls to a value far less than the screen voltage and the suppressor grid is unable to prevent the secondary electrons from passing to the screen grid. A reverse current then flows through the tube, with resultant harmonic distortion. When the load resistance is reduced to 7,000 ohms, the plate voltage does not swing over such a wide range and the plate potential is maintained sufficiently high (even at its minimum value) to prevent a reverse current flow. A load resistance of 7,000 ohms gives a maximum power output of 2.7 watts with 6% total harmonic distortion. This is about the maximum percentage of distortion that can be tolerated, so a load greater than 7,000 ohms should not be used.

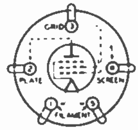
In comparison to a 45 triode power tube, it is seen that nearly twice the power output is secured from a pentode with only one-third as much grid exciting voltage. A 45 requires a grid-exciting voltage in the neighborhood of 45 volts to obtain 1.6 watts power output, but the type 47 requires only about 15 volts to produce 2.7 watts. These desirable features of the pentode tube are a direct result of its higher amplification factor and transconductance. The advantage of the 45, however, is that its harmonic distortion is of negligible percentage.

When operating pentode power tubes, it is necessary for the plate load impedance to be maintained at a constant value of 7,000 ohms as nearly as possible. Since a transformer primary is generally used to load the plate circuit, it is obvious that the load impedance will tend to change with the frequency of the audio signal being amplified. The load impedance increases somewhat at the higher audio frequencies and the result is extreme harmonic distortion. When a dynamic speaker is used to load the secondary of the output transformer, the primary impedance remains fairly constant (due to the low impedance of the dynamic speaker's voice coil), so whenever possible, this type of speaker should be used in conjunction with a pentode power tube. If, however, a loudspeaker is used that has highly-inductive windings, the plate load on the power

RCA Cunningham Radiotron Radio Tubes

Type 47

POWER-AMPLIFIER PENTODE



BOTTOM VIEW

The 47 is a power-amplifier pentode for use in the audio output stage of a-c receivers. In comparison with three-electrode Class A power amplifiers of the same plate dissipation, the 47 is capable of greater power output with the additional feature of higher amplification.

CHARACTERISTICS

Filament Voltage (A. C. or D. C.)	2.5	Volts
Filament Current	1.75	Amperes
Plate Voltage	250 max.	Volts
Screen Voltage	250 max.	Volts
Grid Voltage	−16.5	Volts
Plate Current	31	Milliamperes
Screen Current	6	Milliamperes
Plate Resistance	60000	Ohms
Amplification Factor	150	
Mutual Conductance	2500	Micromhos
Load Resistance	7000	Ohms
Self-Bias Resistor	450	Ohms
Power Output (6% total harmonic distortion)	2.7	Watts

tube tends to change over a wide range, particularly increasing at the higher frequencies and resulting in excessive harmonic distortion. To prevent this high-frequency distortion, a condenser of .02 to .03 mfd. in series with about 15,000 ohms is often shunted across the primary of the output transformer. This combination is called a "load equalizer" and prevents a rise in load impedance due to the decreased reactance of the condenser at the higher frequencies. Sometimes this load equalizer is converted into a tone control by using a larger condenser and making the resistance variable. Many manufacturers always use the equalizer, even with a dynamic speaker. A typical "equalized" pentode plate circuit is shown in Fig. 23.

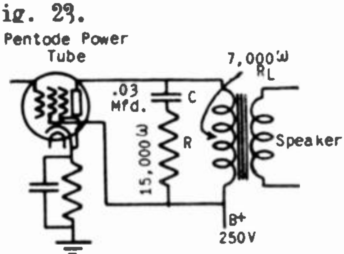


Fig.23 Pentode plate circuit with "equalizer" (R and C) to maintain constant plate load impedance.

A graph showing the variation in power output, second harmonic distortion, and third harmonic distortion, with changes in load resistance, is shown in Fig. 24. It should be noticed that at exactly 7,000 ohms load impedance, the second harmonic distortion is minimum and the 6% total distortion consists mainly of third harmonics. Obviously, 7,000 ohms is the optimum load for this type of tube.

The proper load impedance for any pentode power tube is nearly equal to the ratio of the plate voltage to the DC plate current at the operating point. In the type 47 tube, this ratio is:

$$R_L = \frac{E_p}{I_p} = \frac{250}{.031} = 8,064 \text{ ohms}$$

This is rather close to the recommended value of 7,000 ohms; at least sufficiently close for all practical purposes. When this value of load impedance is used, the efficiency with which the DC power input is converted into A.F. power output is approximately 33⅓%. This means that the maximum undistorted power output obtainable from a pentode power tube is approximately one-third of the DC power supplied to the plate circuit.

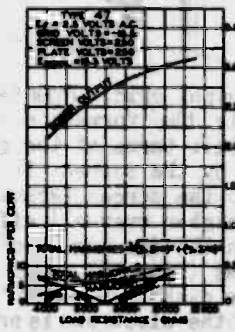


Fig. 24 Average output characteristics of a type 47 pentode power amplifier.

Pentode power tubes are often connected in push-pull to obtain a higher A.F. power output. The plate-to-plate load impedance in push-pull circuits should be approximately 14,000 ohms; that is, twice the recommended load for a single tube.

13. BEAM POWER TUBES. A beam power tube, such as a 6L6 makes use of a different method of suppressing secondary emission. This tube employs four elements; a cathode, grid, screen grid, and plate. These elements are so spaced that secondary emission from the plate is suppressed without an actual suppressor grid. The suppressor grid in a conventional pentode power tube is the chief source of the third harmonic distortion produced; hence, by removing the suppressor grid, the third harmonic distortion is greatly reduced. Instead of using the actual suppressor grid in a beam power tube, the electrodes are so spaced and arranged that the electrons traveling to the plate are slowed down when the plate voltage is low; almost to zero velocity in a certain region between the screen and plate. In this region, the electrons from a stationary cloud—actually a space charge. The effect of this space charge is to repel secondary electrons emitted from the plate and thus cause them to return to the plate. In this way, the secondary emission is suppressed and, at the same time, the suppressor grid is not used.

Fig. 25 shows the structure of the beam power tube. It should be especially noted that the electrons are confined to definite beams. The screen and control grids used are of constant spacing and assembled so that the screen grid is hidden from the cathode by

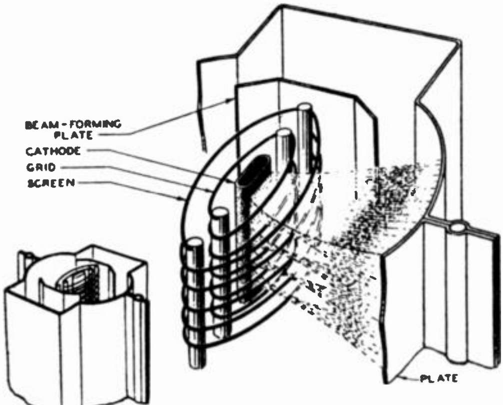


Fig.25 Internal structure of a Beam Power Tube.

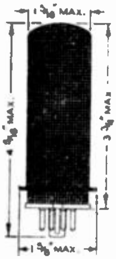
Courtesy: RCA Mfg. Co.

the control grid. This feature has many desirable virtues. It makes possible the formation of uniform electron beam "sheets" between successive turns of the grid wires; it reduces the current intercepted by the screen; it reduces the number of electrons which return to the screen because of their high velocity and it makes possible higher over-all efficiency as well as a higher power output.

In the drawing which illustrates how the electrons are confined to beams (Fig. 25), the space charge region is indicated by the heavily dashed portion of the beam. The accurate guidance and control of the electrons is produced by the two "beam confining" plates which are at the same potential as the cathode. Notice that the edges of these beam-forming plates coincide with the darkened portion of the beam and thus extend the zero potential region beyond the beam-plate boundaries to prevent stray secondary electrons emitted at the plate of the tube from returning to the screen.

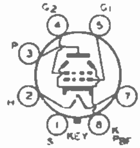
A table of characteristics and the E_p-I_p curves of the 6L6 beam power tube are shown in Fig. 26. On the graph, note the flatness of the characteristic curves, the sharpness of the knee and the extension of the straight portion beyond the left of the 250-volt line. The latter is an important point because it indicates increased power handling ability and improved efficiency. The efficiency of a 6L6 is remarkably high. When two of these tubes are connected in push-pull (Class A) and operated with a plate voltage of 400 volts and a screen voltage of 300 volts, they can produce 32 watts of audio power and an over-all efficiency of 45% including the losses due to screen, plate, self-bias resistor and heater. Under these same conditions, the peak signal input for the tube is 28.5 volts.

14. **INVERSE FEEDBACK.** Inverse feedback circuits are used in A.F. amplifiers to reduce the distortion in the output stage where the load impedance on the tube is a loudspeaker. The impedance of a loudspeaker is not constant at all audio frequencies; therefore, the load impedance on the output tube will change with frequency. If the output tube is a pentode or a beam power tube (each has a high plate resistance), this variation in plate load can, if not



RCA-6L6

BEAM POWER AMPLIFIER



The 6L6 is a power-amplifier tube of the All-Metal type for use in the output stage of radio receivers, especially those designed to have ample reserve of power-delivering ability. The 6L6 provides high power output sensitivity and high efficiency.

CHARACTERISTICS

HEATER VOLTAGE (A. C. or D. C.)	6.3	Volts
HEATER CURRENT	0.9	Ampere
AVERAGE CHARACTERISTICS		
Plate Voltage	250	Volts
Screen Voltage	250	Volts
Grid Voltage	−14	Volts
Plate Current	72	Milliamperes
Screen Current	5	Milliamperes
Plate Resistance	22500	Ohms
Amplification Factor	135	
Transconductance	6000	Micromhos
BASE	Small Wafer Octal 7-Pin	

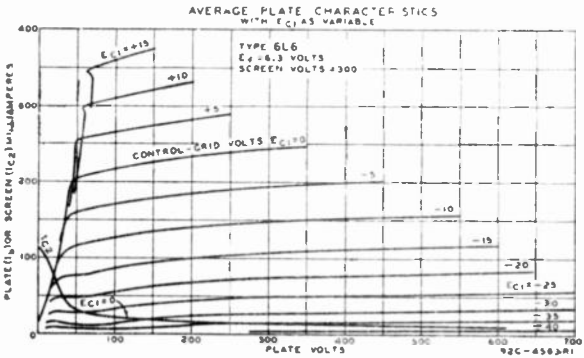


Fig.26 Average plate characteristics of a 6L6 Beam Power Tube.

corrected, produce considerable frequency distortion. Such frequency distortion can be corrected by means of inverse feedback.

As explained by RCA: "The application of inverse feedback to a power output stage using a single 6L6 is illustrated in Fig. 27. Here, R_1, R_2, and C are connected across the output of the 6L6 as

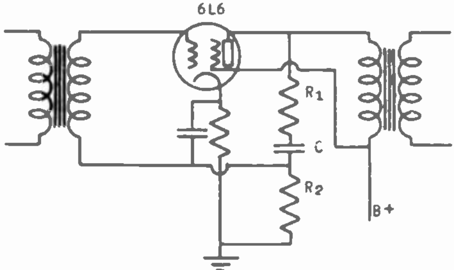


Fig.27 Inverse feedback circuit applied to single 6L6 power stage.

a voltage divider. The secondary of the input transformer is returned to a point on this voltage divider. Condenser C blocks the DC plate voltage from the grid. A portion of the tube's A.F. output voltage, approximately equal to the output voltage multiplied by the fraction $\frac{R_2}{R_1 + R_2}$, is applied to the grid. There results a decrease in distortion as can be explained by the curves in Fig. 28.

"First, consider the operation of the amplifier without inverse feedback. Suppose that when a signal voltage E_q is applied to the grid, the A.F. plate current I_p has an irregularity in its positive half cycle. This irregularity represents a departure from the waveform of the input signal and is, therefore, distortion. For this plate current waveform, the A.F. plate voltage has a waveform shown by E_p. The plate voltage waveform is inverted compared to that of the plate current waveform, because a plate current increase produces an increase in the drop across the plate load impedance. The voltage at the plate is the difference between the drop across the load and the supply voltage. Thus, when the plate cur-

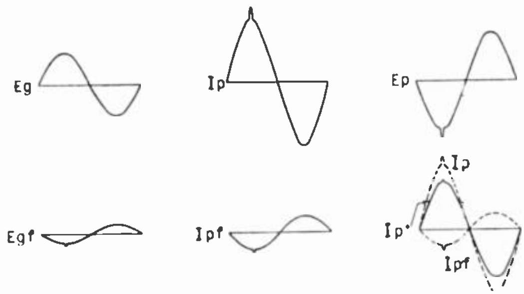


Fig.28 Curves to illustrate inverse feedback.

rent goes up, the plate voltage goes down, and when the plate current goes down, the plate voltage goes up.

"Now suppose that inverse feedback is applied to the amplifier. The distortion irregularity in plate current is corrected in the following manner. With an inverse feedback arrangement, the voltage fed back to the grid has the same waveform and phase as the plate voltage, but is smaller in magnitude; hence, with a plate voltage waveform as shown by E_p, the feedback voltage appearing on the grid is shown by E_{gf}. This voltage applied to the grid produces a component of plate current I_{pf}. It is evident that the irregularity in the waveform of this component of plate current would act to cancel the original irregularity and thus reduce distortion.

"After a correction of distortion has been applied by inverse feedback, the relations are as shown in the curve for I_p'. The dotted curve shown by I_{pf} is the component of plate current due to the feedback voltage on the grid. The dotted curve shown by I_p is the component of plate current due to the signal voltage on the grid. The sum of these two components gives the resultant plate current shown by the solid curve of I_p'. Since I_p is the plate current that would flow without inverse feedback, it can be seen that the application of inverse feedback has reduced the irregularity in the output current. In this manner, inverse feedback acts to correct any component in the plate current that does not correspond to the input signal voltage and thus reduces distortion.

"From the curve for I_p', it can be seen that besides reducing distortion, inverse feedback also reduces the amplitude of the output current. It follows that when inverse feedback is applied to an amplifier, there is a decrease in power output as well as a decrease in distortion. However, by means of an increased signal

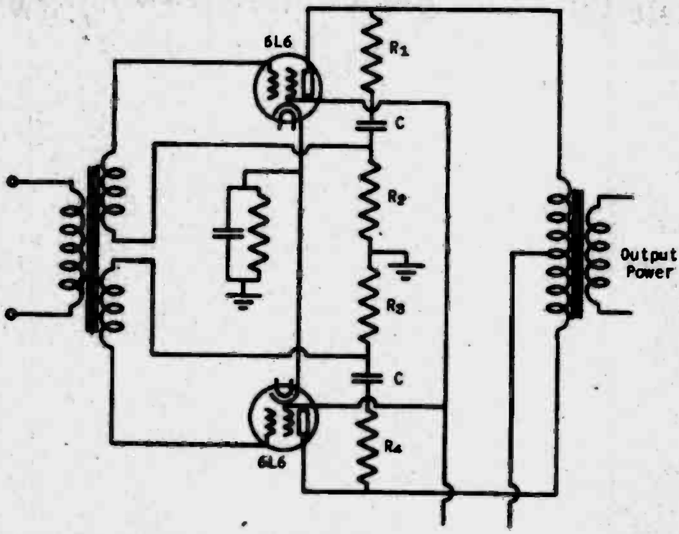


Fig.29 Inverse feedback applied to push-pull 6L6 power amplifier.

voltage, the power output can be brought back to its full value. Hence, the application of inverse feedback to an amplifier means that more driving voltage must be applied to obtain full power output, but this full power output is obtained with less distortion. Inverse feedback can be applied to any Class A power amplifier tube operating in a single-ended or push-pull circuit. In push-pull, it is necessary that the input transformer have a separate secondary winding for each grid. A circuit of this kind is shown in Fig. 29. Inverse feedback is not generally applied to a triode power amplifier such as a 45 or 2A3, because the variation in speaker impedance with frequency does not produce much distortion due to the tube's low plate resistance. It is especially applicable to a pentode or a beam power tube, because these tubes have a high plate resistance and the increased driving voltage necessary is relatively small."

BASIC TELEVISION AND TELEVISION-

RECIEVER SERVICING 1958

BY PAUL B. ZBAR

McGRAW-HILL BOOK COMPANY, INC.

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MIDLAND RADIO AND TELEVISION SCHOOLS INC.

POWER & LIGHT BUILDING, KANSAS CITY, MISSOURI

UNIT NO. 1

LOUD SPEAKERS

LESSON NO. 29

RICHES

.......WITHIN YOURSELF!

Included in the folklore and legends of the Orient, is a story of a Persian farmer. This farmer owned a vineyard of good value, and from it he made a fair living.

But one day there came to the farmer a neighbor, and this neighbor carried in his pocket a diamond. Upon learning the great value of the diamond, the Persian farmer cast his hoe and plow away and, packing up his scant belongings, he went forth into the far corners of the world to hunt for diamonds.

Many years later he returned, weary and without money, to his own land. He knew at last that his real happiness and safe income was right there on his farm. And so, taking up his shovel, he went about clearing out the weeds from around his grape-vine.

But with the first shovel full of earth, he dug up a large diamond, and digging deeper, he found more. There was wealth such as he had never known before, needing only a little deeper digging.....a bit more effort..... to bring to the surface.

Most of us are like that. Deep within us we 'have what it takes'. But it takes digging, and determination, to bring it to the surface.

A little more effort, a little more studying, and some properly guided development of 'what-we-have-inside-us,' and we are on the clean, happy road to Success.

Your lessons and experiments are your tools. KEEP DIGGING!

A Good Job

Happiness

Contentment

Self Respect

Success

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Lesson Twenty-Nine

LOUD SPEAKERS

"In the earlier days of radio a loudspeaker was made by connecting a horn to a regular headphone unit. The volume and tone quality of these "makeshift" horns was very unsatisfactory.

"Today, the modern loudspeaker is a highly-engineered device. In this lesson you will find the latest information on their precision design and intricate construction."

1. PURPOSE OF THE LOUDSPEAKER. A loudspeaker is used to convert the audio power generated in the receiver's final stage into audible sound waves. Headphones are used for the same purpose, but are generally considered unsatisfactory, because they must be held closely to the ear in order to distinguish the weak sound waves produced. It is due to the inconvenience of headphone reception that audio frequency amplification is employed following the detector stage, thereby making it possible to obtain sufficient audio power to actuate a loudspeaker. The loudspeaker should be capable of producing sound waves sufficiently intense to be easily heard and distinguished in a room of ordinary size. In public address and sound picture work, a greater volume of sound is required than from home radio receivers; therefore, more audio amplification is necessary. In all instances, the loudspeaker converts the electrical power supplied to it into sound energy.

It is well to impress the importance of the job performed by the loudspeaker in all radio receiving sets. No matter how "high quality" the transmitting station may be or how perfectly the receiving set is designed, the program is spoiled for the listener if the loudspeaker does not function properly. It must be relatively free from *waveform distortion;* that is, the emitted sound waves should exactly correspond with the waveform of the audio current passing through the speaker winding. It should also produce a minimum of *frequency distortion*, which means that its frequency discrimination should be as low as possible to the various A.F. voltages which may be applied to it. As a third requirement, *volume distortion* must be avoided. This means that the volume of sound produced by the vibrating cone should correspond at every instant to the variations in A.F. power supplied to the speaker. Any loudspeaker may be overloaded; that is, more audio power may be delivered to it than it is capable of properly reproducing. To avoid volume distortion, the amount of audio power supplied to a loudspeaker must be well within the limits of the speaker's capacity.

Other factors incident to the selection of a loudspeaker are that it be *sufficiently rugged* to withstand the normal amount of abuse; it should be *economical* in initial cost and maintenance and should have an *efficiency* as high as possible. The efficiency with which ordinary loudspeakers convert electrical power into sound energy is relatively low.

How sound waves are produced by a vibrating cone or diaphragm was explained in Lesson 26. Therein, it was found that the forward and backward movement of the cone resulted in the establishment of a series of compressions and rarefactions at the front and back of the cone. These air pressure changes travel outward from the vibrating cone at a speed of 1130 feet per second (when the temperature is 68° F.).

2. TYPES OF SPEAKERS. Having learned of the requirements imposed on a satisfactory sound-reproducing device, let us investigate the construction of various commercial loudspeakers. As each type of speaker is discussed, its characteristics and limitations relative to the other types of speakers will be given. To facilitate the study of commercial speakers, we have made the following general classification:

1. Magnetic armature (magnetic)
    a. Bi-polar
    b. Balanced-armature
    c. Inductor or "fringing flux"
2. Condenser
3. Crystal
4. Moving conductor (dynamic)

3. MAGNETIC ARMATURE SPEAKERS. Speakers of this type are those generally known as "magnetic" speakers. As just shown, there are three types which fall under this general classification. In each, the difference lies entirely in the construction of the driving unit or "motor." The driving unit (often called the "motor") of a loudspeaker is that portion of it which serves to convert the electrical current variations into corresponding mechanical vibrations. These mechanical vibrations in turn are applied to the cone or diaphragm and by its movement the air pressure variations (sound waves) are set up.

(A) Bi-Polar Driving Unit. This type of loudspeaker motor is often called the "iron-diaphragm" driving unit. Its construction is shown in Fig. 1. It can be seen that this construction is identical with that of a headphone as explained in Section 4 of Lesson 13. Since the operation of this unit was thoroughly discussed in Lesson 18, the information will not be repeated. It is well, however, to discuss a few of its characteristics so that we may compare it to the other types of driving units.

The iron diaphragm is under a constant strain, even when no signal current is passing through the signal coil. This is due to the attraction exerted by the pole pieces of the permanent magnet and causes the diaphragm to be slightly deflected in the center.

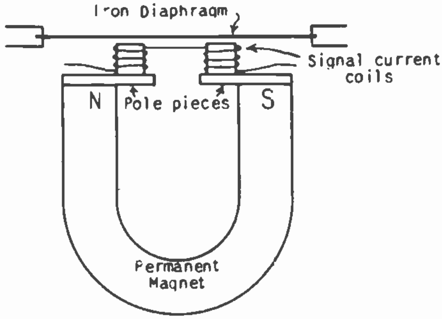


Fig.1 Bi-Polar driving unit.

This, of course, tends to limit the maximum amplitude of the diaphragm's vibration and often results in "clattering" as the diaphragm strikes the pole pieces when a strong signal current passes through the coils. This could be prevented by using a wider air gap between the top of the pole pieces and the diaphragm; however, the sensitivity of the unit would be reduced by this construction. If the unit is to be used specifically for the reception of weak signals, it must be sensitive, so the diaphragm is placed fairly close to the top of the pole pieces. On the other hand, if the unit is to be used in conjunction with a horn or trumpet, the space in question may be made larger, thus permitting loud reproduction, but, of course, at the sacrifice of sensitivity.

As a general rule, bi-polar driving units do not possess good frequency response, due to the stiffness of the iron diaphragm. Also, the diaphragm often resonates at some particular frequency which results in a reproduction of that frequency at exceptionally loud volume. Also, the high inductance of the signal coils does not provide a constant load on the plate circuit of a power tube at all audio frequencies. This, of course, is due to the reactance change of the inductive winding with frequency. At low audio frequencies, the reactance of the signal coils is low, so if serving as the plate load impedance of a power tube, amplitude distortion will be produced and normal power output cannot be obtained. At high audio frequencies, the increased reactance of the signal coils supplies a higher load impedance to the power tube and the amplitude distortion is somewhat reduced. Exceptionally good high frequency response cannot be obtained from this unit, due to the limitations of the mechanical vibrating system and also the by-passing effect of the distributed capacity contained in the signal coils.

Bi-polar driving units for loudspeakers experienced popularity in the earlier days of radio, but later units with their improved characteristics have caused the bi-polar motors to become obsolete in present practice (except in the construction of headphones).

(B) Balanced-Armature Driving Unit. This type of driving unit is illustrated in Fig. 2. It is the most popular of the so-called "magnetic" speakers. The unit is constructed so that the initial pull of the permanent magnet on the armature is "balanced" at the top and bottom; hence the reason for its name.

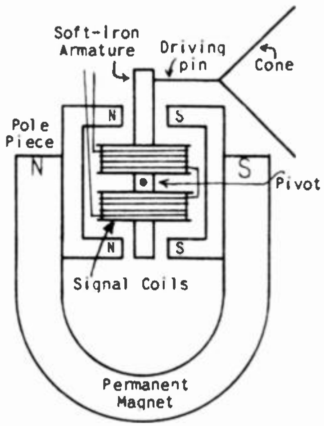


Fig.2 Balanced-armature driving unit.

As shown in Fig. 2, each pole of the polarizing (permanent) magnet has a U-shaped pole-piece attached to it. The magnetic (soft-iron) armature is then located between these two pole pieces and is pivoted at the center. The signal coils are located in the open space between the two U-shaped pole pieces. Since the armature rod is magnetic and pivoted at the center, the attraction and repulsion exerted at the top is equalized by corresponding magnetic forces acting at the bottom. Thus, the armature remains in a balanced condition as long as there is no current passing through the signal coils.

The application of an AC audio voltage to the signal coils will cause a corresponding AC signal current to pass through them. As current passes through the coils, the magnetic flux established around their turns causes the soft-iron armature to become magnetized. The direction of the magnetization will depend upon the direction of the current flow. At A in Fig. 3, assume that the signal current is passing through the windings in such a direction as to magnetize the armature bar with the top S and the bottom N. Being pivoted at the center, the top of the armature bar will then be attracted to the left and the bottom will be attracted to the right. The combined magnetic forces causes a movement of the armature and diaphragm to the left.

At B, Fig. 3, the signal current is passing through the speaker's coils in the opposite direction. The magnetic field set up causes the armature bar to be magnetized in the opposite direction and, since the top of the bar is N and the bottom S, the combined magnetic forces result in a movement of the armature and speaker cone to the right.

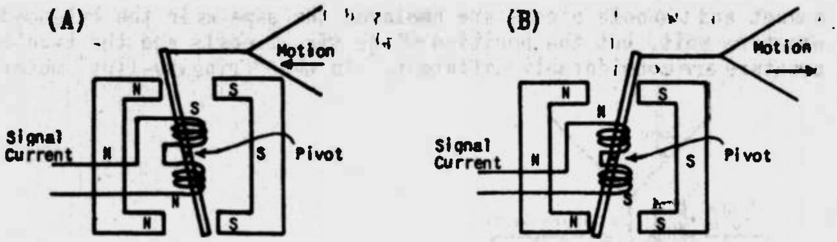


Fig.3 (A) Direction of armature and cone movement with current passing one way.
(B) Current in opposite direction through coil causes movement of armature and cone in opposite direction.

Variation of the A.F. current passing through the coil windings thus establishes a magnetization of the armature, first in one direction, then the other. As the direction of magnetization changes, the armature bar is moved back and forth in direct accordance. Since the diaphragm is securely attached to the armature bar; as the armature vibrates, so does the diaphragm. In some speakers, the driving pin connecting the armature to the cone is soldered directly to the armature whereas in others, a small bolt and nut are used for the attachment.

The balanced-armature driving unit possesses two disadvantages similar to those encountered with the bi-polar type unit. First, the amplitude of armature vibration is limited by the air gap between the two pole pieces. This air gap may be widened to permit loud volume of reproduction, but, at the same time, a sacrifice is made in sensitivity. Second, the two coils surrounding the armature are highly inductive; so the reactance of the speaker load changes with frequency. Low frequency reproduction is impaired, due to the low reactance of the speaker coils. The high frequency end of the audio range cannot be faithfully reproduced because of the high distributed capacity contained in the inductive windings.

In general, however, the frequency response of a balanced-armature unit is considerably better than that of a bi-polar, mainly due to the absence of the stiff iron diaphragm. A light cone may easily be driven by the vibrating armature as shown in Fig. 3 without undue restriction. Also, the mechanical construction of a balanced-armature unit permits the use of a larger permanent magnet, thereby making it possible to obtain good sensitivity consistent with moderately loud volume of reproduction. If operated properly with some regards to its limitations, the balanced armature unit will give very satisfactory service. It has been developed to a fairly high degree of perfection and for moderate volume, this unit is generally used, especially when the cost is an important factor and a wide-range frequency response is not a paramount consideration. It was used in many of the first AC operated receivers and in nearly all of the older DC operated sets. It is still very popular for farm receivers because it does not require a polarizing voltage or an initial magnetizing current.

(C) "Fringing Flux" or Inductor Driving Unit. This type of driving unit is illustrated in Fig. 4. A horseshoe-shaped permanent

magnet and two pole pieces are employed the same as in the balanced-armature unit, but the position of the signal coils and the type of armature are considerably different. In the "fringing-flux" motor,

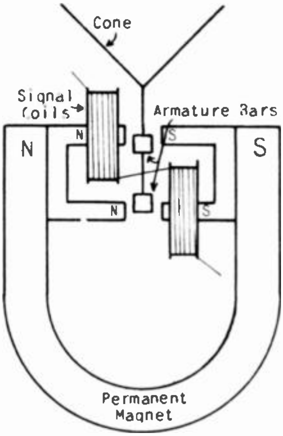


Fig.4 "Fringing - flux" or inductor driving unit.

the movement of the armature is parallel to the pole faces, thus eliminating the possibility of the armature striking the pole faces on high amplitudes of motion. It has the disadvantage, however, of being wasteful of magnetic flux. The operation of the unit is as follows.

In Fig. 5, it is shown that the armature consists of two sep-

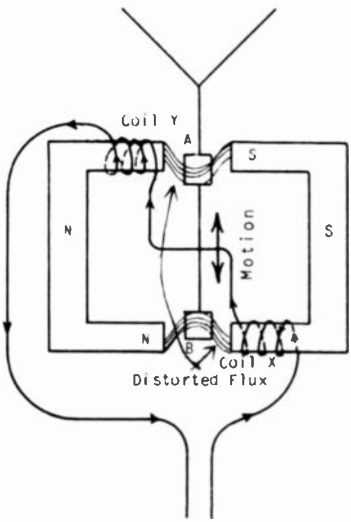


Fig.5 Illustrating bar positions and distorted flux in inductor driving unit.

arate, soft-iron blocks, A and B. These are connected together by a light, insulating rod. The cone is attached to the armature so that when the armature is set in vibration, the cone will also move. The two armature blocks A and B are slightly displaced towards the center between the projecting pole faces. Since the reluctance of the soft-iron blocks is much less than the reluctance of air, the magnetic flux passing from N to S between the two pairs of pole faces becomes distorted as it follows the easier path though the iron blocks. The pattern of the field flux that would normally exist between the pole faces is thus distorted. The lines of force passing through each of the bars causes them to be magnetized and attracted by the faces of the pole pieces. Due to the magnetic pull, bar A tends to move between the two top pole pieces and bar B is pulled toward the two lower pole pieces. Since these two forces are tending to pull the small armature bars in opposite directions, they will normally remain at rest because the connecting rod between the two bars is not elastic.

The series signal coils are placed on opposite legs of the two pole pieces and are wound in opposite directions. As the signal current passes through these coils, the magnetic field set up around each will either add to or subtract from the field of the permanent magnet. When current passes through the two coils in the direction indicated on Fig. 5, the action is as follows. Using the left-hand rule, the polarity of the magnetic field set up around coil X is such that the left side of the coil is a N pole and the right side, a S pole. Then, by using the left-hand rule on coil Y, it is found that the right side is a N pole and the left side, S. The N pole produced on the left of coil X bucks against the S pole of the permanent magnet, thus reducing the magnetomotive force between the two bottom pole pieces. This reduces the pull on armature bar B. At the same time, the N pole produced on the right of coil Y adds to the N pole of the permanent magnet, thus increasing the magnetomotive force between these two faces. This increases the magnetic pull on bar A. Thus, while the pull on bar A is increased, that on bar B is decreased, so the result is a movement of the entire armature and cone assembly in the upward direction.

As the signal current passes through the two coils in the direction opposite to that indicated on Fig. 5, the S pole produced on the right end of coil Y will reduce the magnetomotive force between the two upper poles and the S pole produced on the left end of coil X will increase the magnetomotive force between the two lower poles. The entire armature and cone assembly is then moved downward.

The movement of the armature in this speaker is longitudinally between the pole faces of the permanent magnet; thus, it may move through great distances without overloading. This is in contrast with the conditions existing in the bi-polar and balanced-armature units, because in both of these, an excessive amplitude of vibration causes the armature to strike the pole pieces and produce rattling sounds from the speaker. Very strong permanent magnets are required in a fringing-flux driving unit to secure an appreciable amplitude of armature movement. By making the air gap between the armature bars and the pole faces small, the unit can be made sensitive and, at the same time, maintain its ability to reproduce loud volume.

The fringing-flux driving unit possesses a disadvantage that is also common to the bi-polar and balanced-armature units in that the high inductance coil windings cause high and low frequency distortion. Reproduction throughout the middle of the audio range, however, is exceptionally good, and can be compared in some respects to the performance of moving-conductor speakers.

4. DC THROUGH SPEAKER COILS. The DC current in the plate circuit of a power tube is generally not permitted to flow through the signal coil windings of a speaker. DC current is not effective in producing a vibration of the cone, this depending entirely upon the amplitude of the current changes. Since only the *changes* are desired through the speaker's coils, they are generally passed through a transformer or a condenser. Both of these latter units will block the passage of a DC current.

Volume limitation and demagnetization of the permanent magnet are apt to result when DC passes directly through the speaker's coils. In a bi-polar unit, if the DC passes through the signal coils in one direction, the electromagnetic field set up around each coil aids the pole of the permanent magnet on which it is wound; but if passed through the coils in the opposite direction, the electromagnetic fields will buck against the poles of the permanent magnet and tend to demagnetize them. Obviously, the latter should not be permitted, because continued use of the unit in this condition soon completely demagnetizes the permanent magnet and the sensitivity is seriously impaired. To guard against the possibility of connecting a bi-polar unit in the wrong direction, the external leads from the two coils are always colored differently; one is black and the other is red, brown, or has a brightly colored stripe in it.

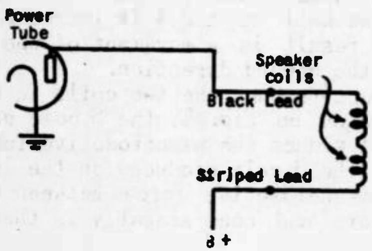


Fig.6 DC plate current must pass through the speaker coils in this circuit.

The black lead is the negative side; that is, if used in the plate circuit of a vacuum tube, it should be connected toward the plate of the tube. The colored or striped lead is the positive side and should be connected toward the positive side of the voltage source. Current should flow through the unit from the negative (black) lead to the positive lead. When this polarity of connection is observed, there is no possibility of demagnetizing and ruining the permanent magnet. Since most present-day headphones have bi-polar driving units, always be sure to connect the external leads in the proper direction when DC current is going to flow through the coils.

In a balanced-armature unit, the passage of a DC current causes the initial position of the armature to be somewhat inclined between the two pole faces, rather than in a perfectly-balanced, vertical position. A signal voltage superimposed on the DC is then likely to cause the armature to strike the pole faces during loud volume. In a fringing-flux driving unit, the pure DC current results in the two armature bars being pulled away from their normal, intermediate positions. This, of course, limits its motion in that direction when a signal voltage is applied.

For these reasons, it is generally desirable to prevent the DC current from passing through the speaker coils as shown in Fig. 6. Two popular methods are used to separate the DC and AC currents. One is to insert a coupling transformer between the plate of the power tube and the speaker coils; the other makes use of a choke and condenser output coupling circuit. The method of connecting the output transformer is shown in Fig.7 and the choke-condenser

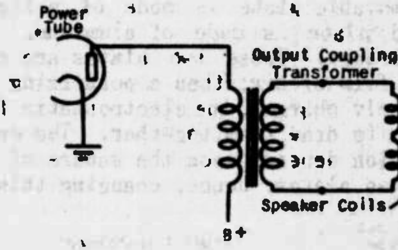


Fig.7 Output transformer as used to couple the A.F. signal into the speaker coils.

arrangement is illustrated in Fig. 8. In Fig. 7, the DC current passes through the primary of the output transformer. When a sig-

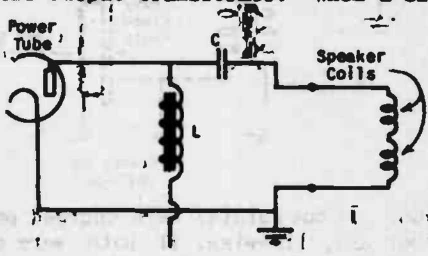


Fig.8 Choke-condenser arrangement to prevent DC from passing through the speaker coils.

nal voltage is applied to the grid of the power tube, the current changes set up in the plate circuit create corresponding magnetic field variations around the primary which in turn are induced in the secondary. The induced secondary voltages then produce an AC current through the speaker coils. This current corresponds in amplitude and frequency to the signal current changes in the plate circuit of the power tube. Using the output choke and condenser arrangement, A.F. signal voltages are produced across the high-inductance choke L in the plate circuit. These voltages charge and discharge the coupling condenser C, thus passing the signal variations on through the condenser and through the speaker coils. It is not practical to use a resistance as the load on a power tube (instead of the inductance), because the high plate current drawn by a power tube would produce an abnormally large voltage drop across the resistive load.

5. CONDENSER SPEAKERS. This type of speaker has never been employed to any great extent in commercial radio receivers; however, a knowledge of its construction and operation is of interest.

The operation of the electrostatic (condenser) loudspeaker is based on the electrostatic attraction and repulsion between two electrically charged plates in accordance with the fundamental law: "Like charges repel and unlike charges attract." The speaker has no driving unit; it consists only of a large, two-plate condenser. Fig. 9 illustrates its construction and the method of connection to the power tube.

The speaker has two large plates; one fixed and one movable. The movable plate is made of a light foil material whereas the fixed plate is made of aluminum. The fixed plate is heavy and stationary. These two plates are separated from each other by a thin film of air; then a polarizing voltage is applied. Being oppositely charged, the electrostatic forces set up between the plates tends to draw them together. The extent of this electrostatic attraction depends upon the square of the voltage difference between the two plates; hence, changing this voltage will vary the attrac-

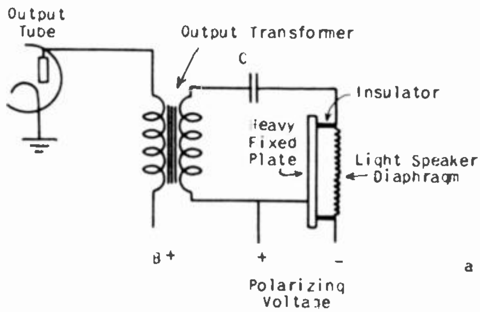


Fig. 9 Connections to a condenser loudspeaker.

tion. If both plates were charged positively, they would repel each other and, likewise, if both were charged negatively, they would repel, but, being oppositely charged, an attraction exists. Since one plate of the condenser is light and movable (the diaphragm) and the other fixed, as voltage changes are applied across them, the movable plate vibrates mechanically in direct accordance. These mechanical vibrations of the light diaphragm in turn set up the air pressure variations (sound waves) which travel outward from the speaker.

The polarizing voltage necessary for operation of the condenser type speaker may be secured from the power supply within the set. Ordinarily, this is between 300 and 500 volts. Since there is practically no current drawn, it does not place an additional load on the rectifier circuit. The two plates of the condenser speaker are separated by insulators as shown in Fig. 9, then as an additional precaution against a possible short circuit, the front face of the heavy fixed plate is generally coated with a thin, rubber compound.

In Fig. 9, the alternating signal voltages developed across the secondary of the output transformer are applied through condenser C to the plates of the condenser speaker. Condenser C must be used so as to prevent a short circuit of the polarizing voltage through the secondary of the output transformer. The AC signal voltage variations are superimposed upon the polarizing voltage, thus causing the attraction between the plates to be increased and decreased in direct accordance with the A.F. signal. The diaphragm's vibration then produces the sound waves.

When using a condenser speaker, the output stage must be designed differently than when using magnetic-armature or moving-conductor speakers. Both of these latter type speakers constitute a fairly low impedance load in the plate circuit of the power tube and both of them require current variations for their operation. In contrast with these characteristics, the condenser loudspeaker has an impedance of around 50,000 ohms at 1,000 cycles and requires voltage variations for its operation. Thus, to operate a condenser speaker, the final audio amplifier should be a high-impedance voltage amplifier rather than a low-impedance power tube. The connection from the plate of the last tube to the condenser speaker may be made through a step-up transformer or through a high-impedance choke and condenser coupling circuit. If a push-pull final stage is employed, a single, tapped choke may be used as the load on the two tubes and the signal voltages transferred to the condenser speaker through a fixed coupling condenser as in Fig. 8.

Condenser type loudspeakers have never experienced great popularity in this country; however, they were used extensively in Europe. One of the main disadvantages is the fact that a high polarizing voltage must be supplied. Condenser loudspeakers are also large in physical size because the strength of the sound waves produced depends on the plate area. This limits its use in home receivers, but is not a serious drawback for public address systems. As advantages for the electrostatic speaker; it is simple in construction and economical in cost. The large, flat surface of the vibrating plate is also better adapted for the even radiation of sound than a horn or cone because it is not so directional.

6. **CRYSTAL SPEAKERS.** Speakers of this type operate on the Piezo-electric principle. This principle is that which expresses the relationship between certain crystal formations and electrical phenomena. It has been found that an accurately prepared crystal of quartz, tourmaline, or Rochelle salts has the property of producing an electrical voltage across two of its faces when compressed, twisted, or bent. Conversely, each of these same crystals will undergo a mechanical change; that is, become compressed, twisted, or bent, when an electrical voltage is applied to it. This is known as the "Piezo-electric effect" and forms the basis for the operation of several devices, such as speakers, phonograph pickups and

microphones.[1] Rochelle salts crystals are more adaptable for use in speakers, phonograph pickups, and microphones than the others mentioned. Crystals of Rochelle salts may be grown chemically under suitable conditions and when cut in slabs can be used as an efficient convertor of electrical energy into mechanical energy and vice-versa.

In crystal speakers, a small slab of Rochelle salts is used as the driving unit. It is cut and mounted in such a manner as to vibrate mechanically (due to its Piezo-electric properties) when voltage variations are applied to it. The crystal's vibrations are then used to drive the speaker cone and produce the sound waves. The small size of the crystal unit and cone makes this speaker unusually efficient in reproducing the higher audio frequencies. They are generally known as "tweeters" because of their ability to reproduce high notes and inability to reproduce lows. When operated in conjunction with a good low-frequency speaker (large dynamic), the entire audio spectrum may be faithfully reproduced by the combination. Several manufacturers use the crystal tweeter on their more expensive high-fidelity receivers for this reason.

Fig. 10 shows two views of a Piezo-electric crystal speaker. When connecting this speaker to a receiver, no coupling transformer is necessary. A small impedance matching transformer is built inside of the speaker case so as to effectively match the impedance of the crystal speaker unit to the output circuit of the receiver.

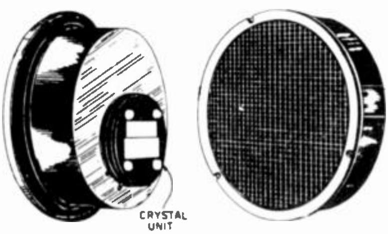
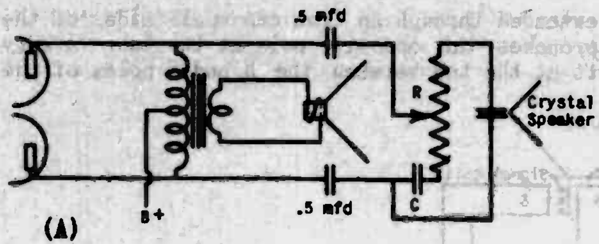


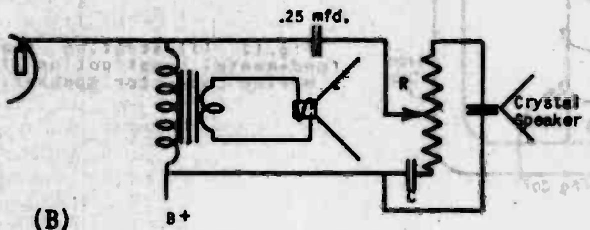
Fig.10 Two views of a crystal speaker.

There are several ways of connecting the crystal tweeter to the output of a receiver. These are shown at A, B and C in Fig. 11. In each of these diagrams, the resistor R serves as the volume control for the high-frequency crystal speaker. It should be understood that a crystal speaker must be operated in conjunction with the dynamic speaker that is already on the radio receiver, thus making a total of two speakers on the set. Nearly all dynamic speakers begin to fall off in frequency response around 3,000 cycles. Since the crystal tweeter is designed to reproduce only the higher frequencies. it starts at about 2,500 cycles, then carries on through the high frequency range to approximately 8,000 cycles. The A.F. reproduction is made fairly flat over the greater portion of the audio spectrum by this combination.

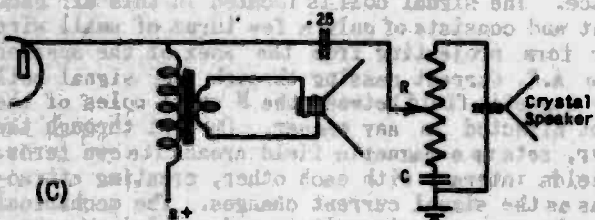
[1] The Piezo-electric effect is fully discussed in Lesson 2, Unit 3.



Output Tubes	R (Ohms)	C (MFD)
45 - 50	25,000	.1
47 - 42	20,000	.03



Output Tubes	R (Ohms)	C (MFD)
45 - 50	25,000	.05
47 - 42	25,000	.015
2A5	20,000	.015



Output Tubes	R (Ohms)	C (MFD)
45 - 50	25,000	.05
47 - 42	25,000	.015
2A5	20,000	.015

Fig.11 Methods of connecting a crystal speaker to the output of a receiver when various tubes are used.

7. **MOVING CONDUCTOR SPEAKERS (DYNAMIC).** Moving conductor driving units for the conversion of electrical into mechanical energy are more popular in modern radio receivers and public address systems than any other type. Such a unit consists fundamentally of a non-magnetic conductor placed in a strong magnetic field whose lines of force are perpendicular to the direction in which motion is desired. A sketch of its fundamental construction is shown in Fig. 12. In this type of moving conductor speaker, a strong, steady magnetic field is established by the passage of a DC current through a magnetizing coil. Moving conductor speakers which obtain their initial, steady field in this manner are generally called "electrodynamic speakers." Permanent magnet dynamic speakers will be discussed later.

Referring to Fig. 12, as the DC current passes through the magnetizing coil winding, the central core is highly magnetized. The direction of magnetization is of little importance; it has the top N and the bottom S in Fig. 12. The path for the lines of force around the coil is extended through an iron cup on all sides of the central core and approaches the opposite pole at the top. A very small air gap is left at the top between the N and S poles of the

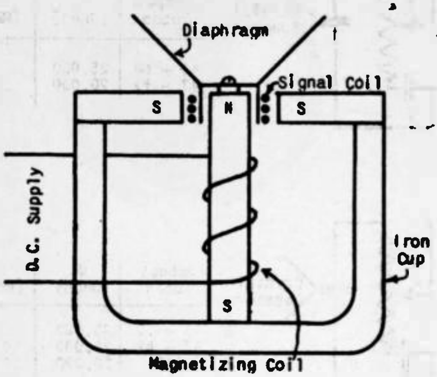


Fig.12 Illustrating the fundamental construction of a moving conductor speaker.

electromagnet; hence, an extremely dense, steady magnetic field is produced in this space. The signal coil is located in this air gap. It is light in weight and consists of only a few turns of small wire wound on a circular form projecting from the apex of the speaker diaphragm. With no A.F. current passing through the signal coil winding, the steady magnetic field between the N and S poles of the electromagnet is not affected in any manner. Current through the signal coil, however, sets up a magnetic field around its own turns. The two magnetic fields interact with each other, creating attractions and repulsions as the signal current changes. The mechanical forces developed by the magnetic attractions and repulsions causes the signal coil to move in direct accordance. The signal coil is securely attached to the diaphragm so its movement results in a similar vibration of the diaphragm. Sound waves, corresponding in amplitude and frequency to the signal current are thus produced.

The magnetizing winding in a dynamic speaker is more generally known as the "field winding" and the signal coil is generally called the "voice coil." These terms will be used henceforth in this lesson.

The essential parts of a typical electrodynamic speaker are shown in Fig. 13. A metal cone bracket such as shown at A is used to support the diaphragm shown at B. On the rear of the diaphragm is a circular, fibrous form. The voice coil is wound on this form. The two leads from the voice coil winding are shown extending along the side of the cone. It is important to note that the voice coil is permanently attached to the cone. The field winding, which supplies the steady, strong magnetic field for the dynamic speaker, is shown at D, Fig. 13. This winding is composed of several thousand turns of relatively small wire, thus enabling it to develop several hundred ampere-turns of magnetizing force when a DC current passes through it. C shows the field "cup" or "pot" which holds the field winding. The field coil is dropped into the cup over the iron core that protrudes through the center. The field winding fills all the

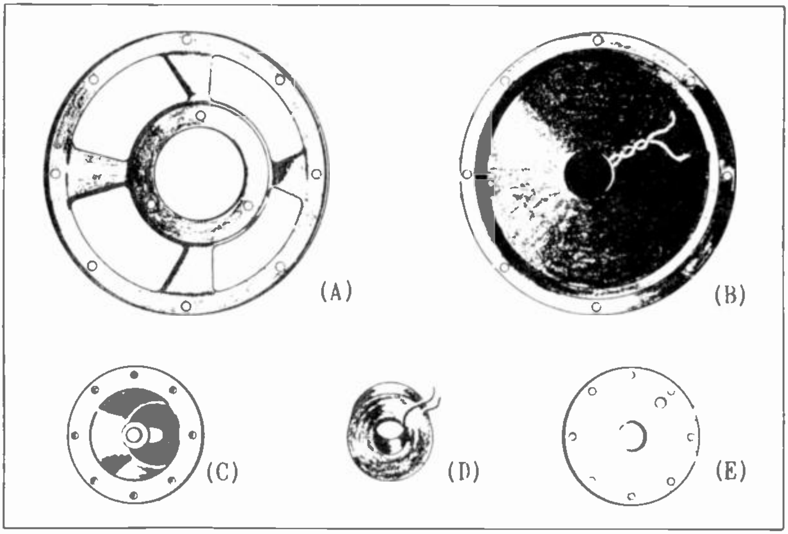


Fig.13 Illustrating the various parts of a typical moving-conductor (dynamic) speaker.

space between the center core and the inside of the cylindrical cup. The cup is made of iron and so provides an easy path for the lines of force set up around the field winding. After the field winding is inserted in the cup, the top cover plate, shown at E, is then bolted to the flange on the top of the cup. The top cover plate has a hole in the center which permits the central core of the field pot to protrude. The center hole in the cover plate is $\frac{1}{8}$ to $\frac{3}{16}$ inch larger in diameter than the diameter of the center core, so a small circular air gap is left between the center core and the cover plate. The magnetic field will be extremely dense in this small, circular gap. A DC current is always passed through the field winding, so the strength of this field remains constant and always in one direction. The voice coil is located directly in this strong, steady magnetic field. The diameter of the voice coil winding is such that when assembled, it fits perfectly in the air gap between the central core and the cover plate, without touching either of them. When A.F. current changes pass through the voice coil, the magnetic field variations set up will interact with the steady DC field, thus developing the mechanical forces which cause the voice coil and diaphragm assembly to vibrate in accordance.

The drawing at A in Fig. 14 shows an assembled, cross-section view of an electrodynamic speaker. Notice how the cone and voice coil "float" in the small gap between the cover plate and the central core leg. The outer edge of the diaphragm is glued to a flexible cloth or chamois skin ring which in turn is securely held to a metal cone bracket. The flexible edge is necessary around the outer circumference of the cone so as to permit perfect freedom of motion.

(A) (B) (C)

Fig.14 (A) Cross-section view of a dynamic speaker
(B) Rear view of a dynamic speaker
(C) Front view

The photograph at B, Fig. 14, shows a rear view of a typical electrodynamic speaker. Notice the cup on the rear which encloses the field winding; also, the metal frame which holds the outer edge of the cone. C in Fig. 14 is a different view to show the location of the cone with respect to the metal frame.

The two fundamental parts of a dynamic (moving-conductor) speaker are the field winding and the voice coil winding (with the cone attached). The quality of reproduction and the power handling capacity of a speaker depends largely upon the design of the field winding. The stronger the steady magnetic flux produced in the radial air gap by the current passing through the field winding, the greater will be the movement of the cone for a given audio signal and the louder the sound produced. Thus, it is advantageous to obtain as high a flux density as possible in the air gap. The strength of this field, however, must be selected consistent with economy and power consumption from the field exciting source. Speakers used to produce loud volume, such as on public address installations, must be supplied with a strong magnetizing force, even though it is more expensive. The smaller dynamic speakers, such as those used on home receivers, need not be so elaborately constructed because they are seldom required to reproduce exceptionally loud volume. As an average, 1,000 to 2,000 ampere-turns of magnetizing force must be supplied by the field winding in large speakers, and about 800 to 1,000 ampere-turns for the smaller speakers as used in radio receivers. The size of the wire used and the number of turns on the field winding are governed almost entirely upon the type of DC supply available for the field excitation. Various methods will be discussed in a later section of this lesson.

The thin, tubular form used for the voice coil winding must be extremely accurate in size, so as to fit perfectly in the small air gap between the center core and the cover plate. This gap is never made more than just enough to permit free movement of the voice coil, with only a few thousandths of an inch clearance on either side. The voice coil itself is generally wound with less than 100 turns of small, enameled wire; wound in several layers on the tubular form. An even number of layers are used, because the two leads must emerge from the same end of the coil. These two leads are generally glued to the side of the cone, then connected to the secondary of the output transformer. The small clearance between the voice coil and the central core makes it necessary to employ a flexible "spider" arrangement to rigidly maintain the voice coil in an accurately centered position. A typical "spider" used for this purpose is shown in Fig. 15.

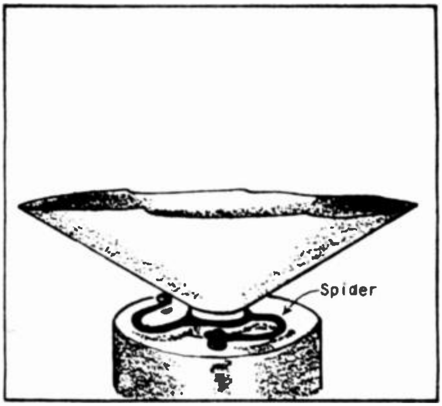


Fig.15 Drawing to show the "spider". A "spider" is used to hold the voice coil in a centered position in the midst of the electromagnetic field.

Since the voice coil consists of only a few turns, its inductance is very small. Therefore, the resistance of the winding is very nearly equal to its impedance at audio frequencies below 3,000 cycles. Ordinarily, the total impedance of a voice coil is between 1 and 15 ohms. To transfer audio power from the power stage of a receiver into a voice coil, it is necessary to use an output transformer which has only a few turns on the secondary winding. This means the output transformer must be of the step-down type wherein its primary impedance loads the plate circuit of the power stage when the voice coil is connected across the secondary winding. The impedance of the voice coil remains practically constant at most audio frequencies; therefore, the primary impedance of the output transformer will also remain fairly constant. This fact is especially important for the reproduction of low audio frequencies. In magnetic-armature type speakers, the highly inductive speaker winding presents a varying load impedance to the power tube, falling off rapidly at low audio frequencies, thus seriously impairing the low frequency reproduction from the speaker. This is not true with a moving conductor (dynamic) type of speaker, because the constant impedance of the small voice coil winding maintains a constant load impedance in the plate circuit of the power stage. The power stage is thereby enabled to produce normal power output throughout most of the audio range.

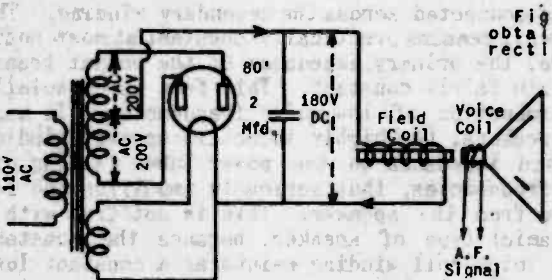
8. METHODS OF FIELD SUPPLY. There are several ways of obtain-

ing the DC exciting voltage necessary to magnetize the field coil. The method used is generally determined by that which is most convenient.

(A) Vacuum Tube Rectifier Circuits. A typical vacuum tube rectifier circuit for obtaining DC voltage excitation to the field coil is shown in Fig. 16. Here, a step-up transformer produces an AC voltage of approximately 200 volts each side of center tap which in turn is applied to the plates of the type 80 rectifier tube. A second winding on the secondary supplies filament power to the rectifier tube. A 2 mfd. condenser is connected across the output of the rectifier tube. It works in conjunction with the high inductance of the field coil to filter the pulsating DC into a nearly pure DC current through the coil winding. Deducting the voltage drop through the internal resistance of the rectifier tube, the DC voltage applied to the field coil is approximately 180 volts. The resistance of the field coil must be high enough to limit the current to the proper value, which, in this case, is approximately 25. ma. This requires a resistance of 7,200 ohms. By winding about 38,000 turns of #36 wire on the field coil, a resistance of this value will be secured. With 25 ma. passing through 38,000 turns, the ampere-turns magnetomotive force produced is 950. As stated previously, a magnetizing force of this value is sufficient for ordinary size dynamic speakers.

Should the field resistance be less than 7,200 ohms, a lower AC voltage is required across the transformer secondary to produce the same ampere-turns of magnetomotive force. Of course, a fixed resistor could be inserted in series with the field coil to limit the current, but the heat dissipated in the resistance is a loss of power and should be avoided. If the loudspeaker is used on a public address system where it must handle a large amount of audio power, it is necessary to supply more DC power to the field coil to insure freedom from distortion. For example, if the field coil is wound with about 20,000 turns of #28 wire and a current of 120 ma. passed through it, then the magnetomotive force is 2,400 ampere-turns, which is sufficient to handle 20 watts of audio power.

Fig. 16 Field excitation obtained from a vacuum tube rectifier circuit.



(B) Contact Rectifier. Fig. 17 shows a contact rectifier being used to rectify 12 volts AC into a DC voltage for exciting

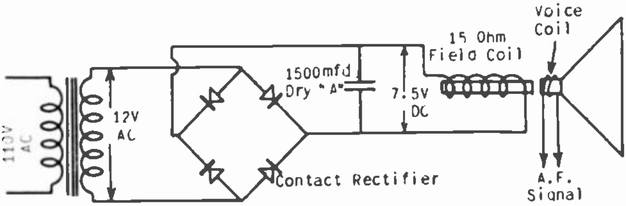


Fig.17 Securing the field exciting power from a contact rectifier circuit.

the field coil winding. Contact or "dry-plate" rectifiers do not have the ability to rectify a high AC voltage; however, their current carrying capacity is quite high. Field coil windings that are to be excited from contact rectifiers are designed to secure their magnetomotive force with a high current passing through a few turns. As an example, if a 15-ohm field winding is connected across a 7½-volt DC source, then ½ ampere of DC current will pass through the winding. If 2,000 turns are wound on the coil, then the ampere-turns magnetomotive force will be 1,000.

A 15-ohm field coil will have a fairly low inductance, so it is necessary to use a high-capacity condenser across the output of the contact rectifier to secure a nearly pure DC current through the field. The condenser in Fig. 17 is a 1500 mfd. dry "A" condenser. Electrolytic condensers of this type are manufactured especially for the purpose. They will not withstand a very high voltage, (generally 15 volts is the maximum) and must be connected in the circuit properly with respect to their polarity.

(C) DC source of voltage. When a pure DC voltage source is available, it may be connected directly across the field winding, providing it is of the proper value. If the DC source is pulsating, a filter must be included to smooth out the ripples. In automobile receivers, the six-volt supply from the storage battery is always used for the field excitation. In most of the auto receivers, the field resistance is 7½ ohms, which permits approximately 1 ampere of current to pass through the winding. With 1,000 turns of the proper size wire on the field coil, the magnetomotive force will be sufficient for average power output without danger of overloading.

In some localities, 110 volts DC is available. This may be used for field excitation by connecting it across a field coil having about 2500 ohms resistance. Approximately 45 ma. of current will then flow through the field coil, so about 22,000 turns of #34 wire should be wound on the coil to give the correct resistance and obtain 1,000 ampere-turns of magnetomotive force. A 32 volt DC supply may also be used with a properly designed field coil.

It is possible to purchase a loud speaker having a field resistance of nearly any value desired. They are designed to operate from voltages as low as 6 volts to as high as 250 volts. The popular field resistance values are 6, 7.5, 650, 1,000, 1,800, 2,500, and 5,000 ohms. In each case, the field winding is energized by passing the proper amount of DC current through it. If the number of turns on the winding is not known, the manufacturer's specifications should be consulted to determine the amount of current necessary for proper excitation.

(D) As choke in power supply. In nearly all AC operated receivers, the field excitation is obtained by connecting the field coil in the filter circuit of the power supply system. Fig. 18 illustrates how the field coil winding may be substituted in place of the second filter choke. The field winding provides the necessary inductance for the filter circuit to efficiently smooth the pulsating DC into a pure DC. Since the current drawn by all of the tubes in the receiver must pass through the field coil, it will be properly excited. In this way, the problem of field excitation is solved in a simple manner and the cost of a second choke in the filter system is saved. For the field coil to work satisfactorily in this position, it must have a resistance of from 1500 to 2500 ohms. Depending upon the design of the receiver, the total current drawn through the field winding is from 50 to 100 ma.; hence, if it has the proper number of turns, the correct magnetomotive force will be produced.

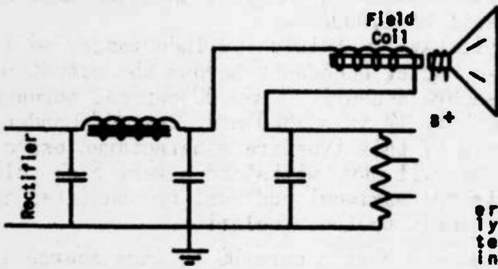
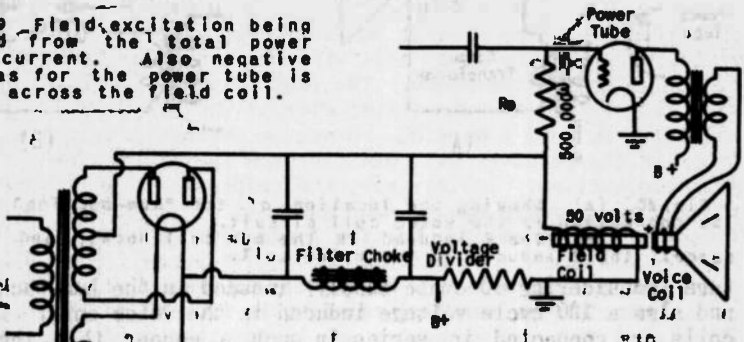


Fig.18 A dynamic speaker's field coil is generally excited in an AC operated set by connecting it in the filter circuit.

Another method of connecting the field coil is shown in Fig. 19. This is used in a number of the "midget" receivers where space is at a premium and the cost of construction must be kept as low as possible. The field coil is inserted in a lead from chassis (ground) to the center-tap of the high voltage winding on the power transformer. Thus, all the current that is drawn by the voltage divider and the tubes in the set must pass through the field coil upon flowing from the center tap of the high voltage winding. The current flowing through the field coil will be in such direction as to produce a voltage drop with the grounded side positive and the other side negative. If the field resistance and the total current are of the proper value to produce the correct voltage drop across the field, that voltage, in turn, may be used for grid bias on the power tube. In Fig. 19, the cathode of the power tube is grounded and the bottom of the grid leak resistance is connected to the negative side of the field coil winding. Thus, the grid of the power tube is placed at a negative potential with respect to the cathode by an amount equal to the voltage drop across the field coil. If the recommended grid bias on the power tube (or tubes) is 50 volts, then a field coil should be selected having the proper resistance value to produce that voltage drop when the total current passes through it.

Fig.19 _ Field excitation being obtained from the total power supply current. Also negative grid bias for the power tube is secured across the field coil.



9. **HUM-BUCKING COILS.** The current passing through the field coil must be a pure DC; otherwise, the strength of the magnetic field in the circular air gap between the center core and the cover plate will vary. Since the voice coil is situated in the midst of this dense magnetic field, any flux variations will cause a corresponding voltage to be induced in the voice coil winding. Voltages induced in it, due to this varying field, will result in a current of corresponding frequency flowing through the voice coil and output-transformer secondary circuit. The diaphragm will vibrate at that frequency and a hum is heard from the speaker. Obviously, this must be avoided.

Except when the DC voltage supply is a battery, the current passing through the field coil is that obtained from a rectifier circuit. If a 60 cycle supply voltage is being used, the current pulsations in the output of the rectifier will be 120 cycles. Likewise, a 25 cycle line supply will give a 50 cycle "ripple" current. It is this 120 or 50 cycle "hum" that is heard from the loudspeaker when the magnetizing field current is not sufficiently filtered. To reduce (or eliminate) the hum from the speaker, additional filtering may be supplied or a "hum-bucking" coil may be used. The filtering is generally quite expensive when it entails the use of more than one additional condenser. So, in the majority of receiver loudspeakers, the hum-bucking coil is used for the solution.

This hum-bucking coil is wound directly on the top of the field coil winding and consists of from 50 to 100 turns. It is not connected to the field coil in any way, merely placed in inductive relationship with it. As the insufficiently filtered current passes through the field winding, the cyclic variations of the magnetic field will cause a voltage to be induced in the hum-bucking coil of corresponding frequency. The hum-bucking coil is connected in series with the voice coil and output transformer secondary. This is shown in Fig. 20. If the DC field varies, there will be a 120 cycle vol-

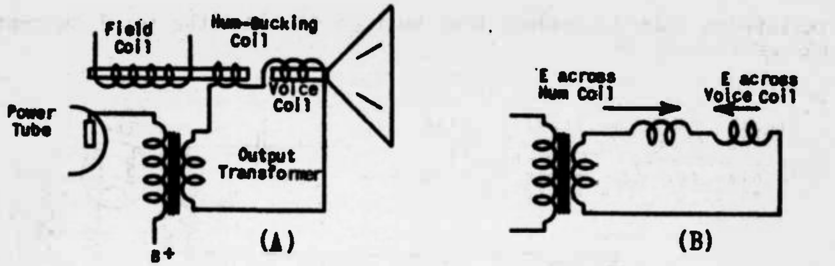


Fig.20 (A) Showing the location of the "hum-bucking" coil and its connection in the voice coil circuit.
(B) The E induced in the hum coil bucks, and tends to cancel, the E induced in the voice coil.

tage (considering 60 cycle supply) induced in the hum-bucking coil and also a 120 cycle voltage induced in the voice coil. These two coils are connected in series in such a manner that the two 120 cycle voltages buck against each other. With complete cancellation, there will be no flow of current around through the secondary circuit at the hum frequency; hence, no hum will be produced from the speaker. If, however, the hum-bucking coil is erroneously connected in series with the voice coil in such a manner that the two 120 cycle voltages add, then an excessively loud hum will be produced. Care must always be taken when connecting the hum-bucking and voice coils to the output transformer secondary; make certain that the two voltages buck against each other. Some speakers have the windings marked and others do not.

At first thought, it may appear that the signal current passing through the voice and hum coil circuits would also cancel. This is not true, however, because the voltage source for the signal current variations is the output transformer secondary and not inside the loudspeaker itself. Then, too, the magnetic fields produced around the hum-bucking coil and voice coil are not in such relationship as to interfere with each other. It is not the magnetic fields around these two coils that buck against each other and cancel, but rather the voltages induced in each of them, due to the current ripple through the field winding. The signal current will pass through both the voice coil and hum-bucking coil with no retardance except the impedance of the two windings.

It is well to point out that hum voltage cancelled by the hum-bucking coil is due only to that produced by the unfiltered current passing through the field coil. In a single-ended power output stage, if the current passing through the primary of the output transformer is not sufficiently filtered, then the 120 cycle field variations (assuming 60 cycle supply) set up around the primary will induce a 120 cycle voltage in the secondary and it will be reproduced from the speaker. There are no provisions made for cancelling the hum voltage that may be induced in the output transformer secondary so it is best to make certain that the DC primary current is steady.

10. THE OUTPUT TRANSFORMER. For the operation of a dynamic

speaker; the output transformer must be designed with a primary impedance of the proper value to load the plate circuit of the power stage, and a secondary impedance that will match the impedance of the voice coil in the dynamic speaker. This requires the secondary to have only a few turns and the primary a large number of turns, so the output transformer is of the step-down type. The signal voltage variations across the primary of the output transformer (produced by the current changes in the plate circuit of the power tube) will be stepped down to a lower value across the secondary. The low secondary circuit impedance, however, permits a high signal current to flow through the voice coil, thus establishing strong magnetic field changes around the voice coil winding to interact with the steady field produced by the DC current through the field coil. The amplitude of the speaker cone's vibration depends primarily upon the *amount of current changes* through the voice coil.

As an example of this, when a type 47 tube is delivering 2.7 watts of audio power into a 7,000 ohm load with a 15 ohm voice coil connected across the secondary, there will be 425 ma. of signal current passing through the secondary and voice coil circuit. This is assuming that the turns ratio of the output transformer is 21.6 to 1, which is the correct value to give an impedance ratio of 7,000 to 15 ohms.[1]

11. PERMANENT MAGNET DYNAMIC SPEAKERS. Quite often in loud speaker installations, it is desirable to use a speaker that has good frequency response, but at the same time, it is inconvenient to obtain the field exciting current for the operation of an electrodynamic speaker. Among such applications are: battery-operated farm receivers and P.A. installations in schools, churches, apartments, etc. To satisfy this demand, permanent dynamic speakers have been perfected. They are properly classified as "moving-conductor speakers", because they employ a voice coil winding the same as the electrodynamic speaker just discussed. The essential difference, however, is that a strong permanent magnet is used to supply the steady field around the center core, rather than an electromagnet. Permanent magnet dynamic speakers possess all the advantages of electrodynamics, except that they cannot be made to handle exceptionally high audio power outputs. The maximum power handling capacity for the largest of these speakers is approximately 15 watts.

The construction of a typical permanent magnet speaker is shown in Fig. 21. Compared to an electrodynamic speaker, it can be seen that the construction is practically the same with the exception that a strong permanent magnet replaces the electromagnetic winding. To obtain sensitivity with this type speaker, it is essential that the magnetic flux, produced by the permanent magnet in the circular space between the central core and the cover plate, be as strong as possible. Various alloys of magnetic material are used to obtain the magnetomotive force necessary and to assure a lasting satisfactory performance. In one type of permanent magnet dynamic speaker, the magnet is made of a high grade steel containing about 15% cobalt.

[1] The relationship between the turns ratio and impedance ratio of a transformer will be thoroughly discussed in lesson # of Unit 3.

The first permanent magnet speakers that appeared on the commercial market were rather inefficient, due to the inferior properties of the permanent magnets then available. Recent research has resulted in new discoveries and the later permanent magnet speakers have, not only vastly improved efficiency, but the weight, size,

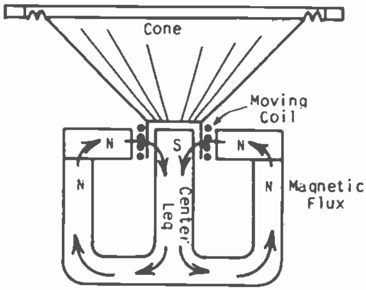
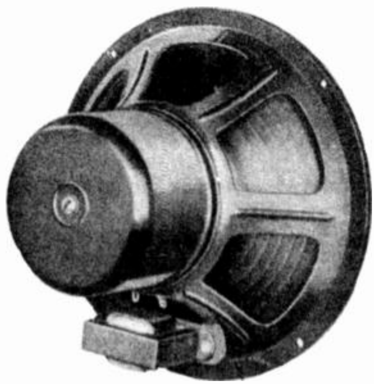


Fig.21 Drawing to illustrate the construction of a permanent magnet dynamic speaker.

and cost have been reduced. Modern P.M. dynamics have an unusually short dimension from front to back, thus making it applicable in numerous cases where an electrodynamic would be cumbersome and inconvenient. A remarkable saving is also made in power consumption, because no field winding is used. The frequency response characteristics of the newer P.M. speakers are fully equal to the electrically energized dynamic speakers having the same size cone. Electro and P.M. dynamic speakers are identical in essential design features, the only difference being that a permanently-magnetized field structure is used instead of an electrically-excited coil. The tone quality is practically the same, so a selection between the two types of speakers depends mostly on convenience and the expense involved to provide field coil power.

(A)



(B)

Fig.22 (A) 12" Wright Decoster permanent magnet dynamic speaker.
(B) 12" Jensen permanent magnet dynamic speaker.

A 12" Wright Decoster P.M. speaker capable of handling 15 watts of audio power is shown at A in Fig. 22. In this speaker, the voice coil impedance is 5.5 ohms at 400 cycles. A 12" Jensen P.M. dynamic is shown at B in Fig. 22. It is capable of handling from 12 to 13 watts and has a voice coil impedance of 8 ohms at 400 cycles.

New alloys are constantly being developed by speaker manufactures for use in P.M. speakers. With all of this development process, the objective is to obtain stronger permanent magnets that are capable of maintaining their original magnetism over long periods of time. Through research, they are also attempting to reduce their size and weight. No doubt P.M. dynamic speakers will be quite popular in future loudspeaker applications.

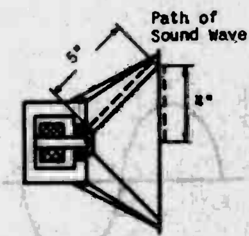


Fig. 23 Eight inch loudspeaker without a baffle.

12. **BAFFLES.** A "baffle" is a flat or box-shaped piece of solid, non-resonant material used to increase the external measurable distance from the front to the rear of the speaker cone. Baffles are necessary to obtain good low frequency reproduction from a speaker, because they serve to prevent a cancellation of the front and back waves emitted from the vibrating cone. Fig. 23 shows a

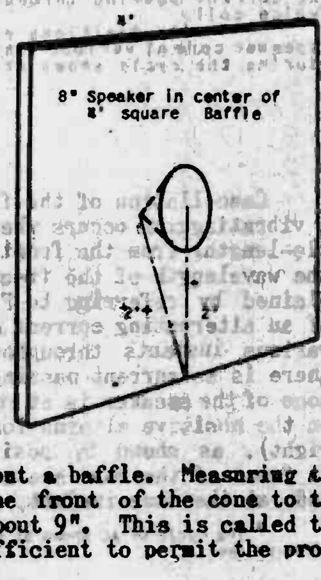


Fig. 24 Eight inch speaker in the center of a 4 foot baffle board.

typical 8" electrodynamic speaker without a baffle. Measuring the actual distance from the center of the front of the cone to the center of the rear, it is found to be about 9". This is called the "baffle-length". This distance is insufficient to permit the proper reproduction of audio frequencies less than about 300 cycles. Higher audio frequencies will be reproduced properly, but when a partial or complete cancellation of the low frequencies occurs, the speech and music sounds very "tinny" and unnatural. If the 8" speaker shown in Fig. 23 is placed in the center of a baffle board 4 feet square (shown in Fig. 24), then upon measuring the shortest distance from the front to the rear of the cone, it is found to be slightly more than 4 feet. This allows all audio frequencies down to about 70 cycles to be reproduced without undue cancellation. For 30 - cycle reproduction, a baffle - length of about 11 feet is necessary.

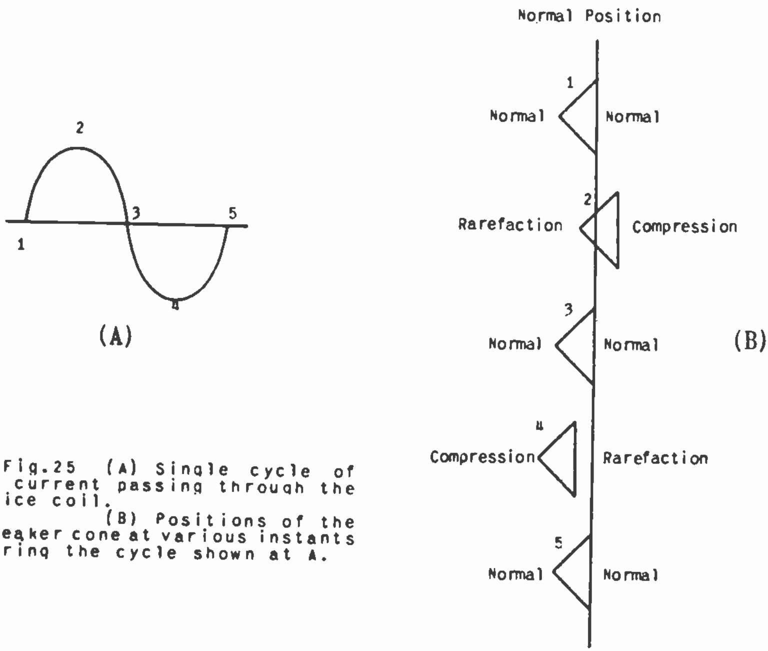


Fig.25 (A) Single cycle of AC current passing through the voice coil.
(B) Positions of the speaker cone at various instants during the cycle shown at A.

Cancellation of the front and back pressure waves emitted from a vibrating cone occurs when the shortest measurable distance (baffle-length) from the front to the rear of the cone is less than ¼ the wavelength of the frequency being reproduced. This can be explained by referring to Fig. 25. At A in this figure, one cycle of an alternating current is shown. At B the cone positions at the various instants throughout the cycle are indicated.[1] First, when there is no current passing through the voice coil (point A), the cone of the speaker is at its normal position. The current increase on the positive alternation causes the cone to move forward (to the right), as shown by position 2 in B. The air molecules directly in front of the cone are compressed as it moves in this direction and, at the same instant, a rarefaction of the air molecules at the

[1] The cycle of AC shown at (A) is assumed to be passing through the voice coil of the speaker.

back of the cone occurs. Decrease of the voice coil current from 2 to 3 (in A) causes the speaker cone to return to normal, as shown by position 3 in B. Then, the reversal of the voice coil current causes the cone to be moved back from its normal position, thus creating a rarefaction of the air molecules at the front of the cone and a compression at the rear. The return of the voice coil current back to zero (from 4 to 5) causes the cone to return to its normal position. Throughout the one cycle of alternating current, the cone of the speaker has gone through four distinct changes. It should be noticed that the compressions and rarefactions of the air molecules occur simultaneously on opposite sides of the cone; that is, they are exactly 180 degrees out of phase. The amplitude of the cone's vibration determines the intensity or strength of both the back and front waves. Should anything occur that tends to decrease the relative strengths of the compressed and rarefied pressure waves, then the volume of sound from the speaker is decreased. This is exactly what happens when attempting to reproduce low frequencies from a speaker that is not provided with a baffle.

Both the front and back sound waves from a speaker spread out in all directions from the vibrating cone. It is easily possible for a compressed front wave to traverse the short distance around an unbaffled speaker cone to the rear and neutralize the rarefied condition of the air molecules at that instant. Likewise, a compressed rear wave can partially or completely neutralize a front rarefied wave, if permitted to reach the front of the speaker cone at the instant of rarefaction. To determine whether or not this neutralization of the front and back waves will occur, we must consider the speed and wavelength of the sound wave being reproduced. Since the speed of sound waves through air is always 1130 feet per second (at 68 degrees F), then the wavelength of the sound wave is all that requires consideration. Throughout one cycle of audio current through the voice coil, four distinct changes occur in the cone position. From 1 to 2, a front compression and rear rarefaction is being produced; from 2 to 3, the air molecules at the front and rear are returning to normal; from 3 to 4, a rear compression and front rarefaction is generated; then from 4 to 5, both waves again return to normal. *It is during the instants of these changes that cancellation must not occur.* Since there are four changes over one wavelength, the actual distance traveled by each of these changes is ¼ the wavelength. Fig. 26 illustrates the four changes. It is only during these *changes* that the front and rear waves are exactly 180° out of phase, so it is only over the distance traveled by the *changes* that a cancellation can occur. A partial cancellation results in decreased volume, but with complete cancellation, there is no sound at all.

Let us assume that the current through the voice coil has a frequency of 100 cycles per second. The wavelength of the sound wave[1] is then 1130 (velocity) divided by 100, or 11.3 feet. If the distance traveled by the complete cycle in one second is 11.3 feet, then the distance traveled by each change is ¼ of 11.3, or 2.82 feet. Thus, if the shortest path from the front to the rear of the

[1] Refer to section 7, Lesson 6.

cone is not equal to or greater than 2.82 feet, a partial cancellation of the front and rear pressure waves will occur. By placing

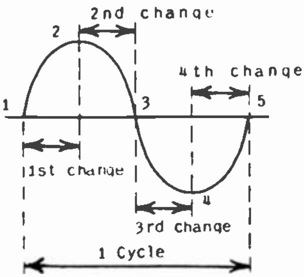


Fig.26 Illustrating the four changes of cone position on an AC wave.

the speaker in the center of a flat board or inside a box, the shortest sound wave path can be made in excess of 2.82 feet, and the 100 cycle note will be properly reproduced at normal volume.

Calculation of the baffle-length necessary to properly reproduce audio frequencies can be performed by the use of the following formula:

Baffle length = $\frac{1}{4}$ of the wave length. Since W.L. = $\frac{1130}{F}$, then

$$B.L. = \frac{1}{4} \times \frac{1130}{F}$$

$$= \frac{1130}{4 \times F}$$

$$= \frac{282}{F}.$$

Where: B.L. is the baffle-length in feet
F is the frequency in c.p.s.

By using the last formula, calculation of the baffle length is greatly simplified. For example, the baffle length necessary for 30 cycle reproduction is:

$$\frac{282}{30} = 9.4 \text{ feet}$$

For 75 cycle reproduction, the baffle length is:

$$\frac{282}{75} = 3.7 \text{ feet}$$

Higher audio frequencies require less baffle-length because the wavelength is shorter and the actual distance traveled by each change is correspondingly less. Thus, for 1,000 cycle reproduction, the baffle length need only be:

$$\frac{282}{1,000} = .282 \text{ feet}$$

Since this is only a distance of about 3", it is readily apparent that the cone itself serves as an effective baffle for high frequency reproduction.

The curve in Fig. 27 illustrates the relation between frequency and baffle-length. It may be used to expediate the determination of the baffle-length necessary for low frequency reproduction.

In console radio receivers, the large cabinet itself is generally of sufficient size to serve as a baffle for good low frequency reproduction. Of course, there are very few radio receivers wherein the shortest path from the front to the back of the cone reaches a distance of 9 feet, such as required for 30 cycle reproduction. However, these extremely low audio frequencies are seldom transmitted from the broadcast station. 75 cycles is considered the lowest common audio frequency note. In Fig. 27, it is seen that a baffle-length of about 45" (around 4 feet) will be sufficient to properly

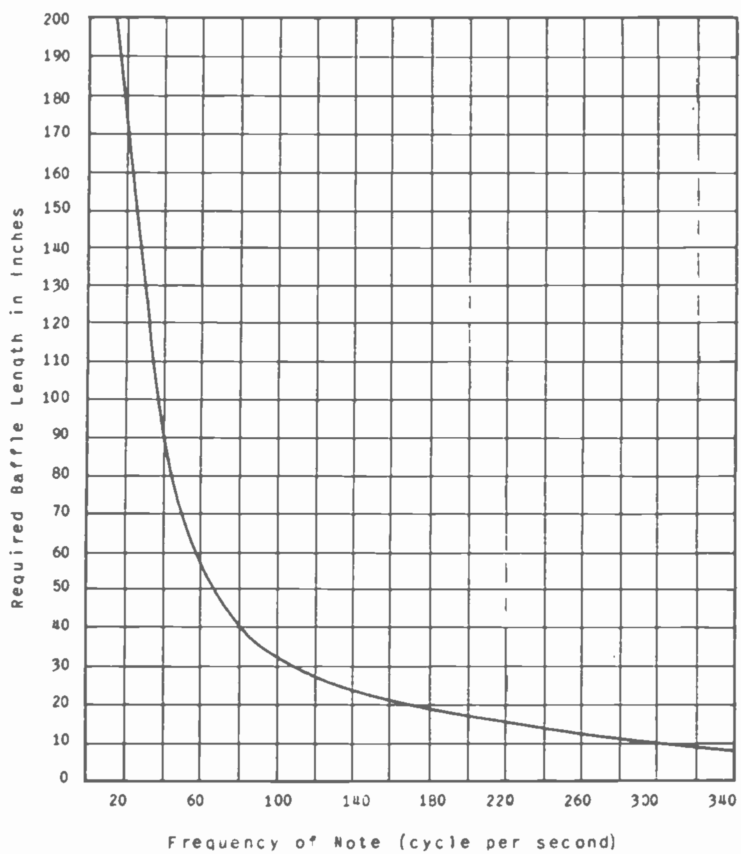


Fig.27 Graph showing the relation between frequency of a sound wave and baffle length.

reproduce an A.F. note of this frequency. The small, table models and "midget" receivers do not have sufficient baffle length to give good low frequency reproduction. Some manufacturers accentuate the low frequency gain in the A.F. amplifier to partially compensate for the impaired low frequency reproduction, however, this necessitates additional expense and is not in general use. The smaller receivers are not guaranteed nor expected to have exceptionally good tone quality.

The back of a box or cabinet type baffle should always be left open so as to permit free circulation of the air. Should the rear of a speaker be closed tightly, the backward cone movement is opposed; also, "resonance" effects are set up inside the cabinet, which result in unnatural reproduction of certain audio frequencies. An enclosed speaker does completely solve the problem of baffling, but the resonance effects that accompany such construction renders it unsatisfactory. Lately, manufacturers have devised acoustical systems such as the "Labyrinth", the "Magic Voice", etc. An acoustical "Labyrinth" type of baffle is shown in Fig. 28. The front waves are emitted from the cone, but the back waves must take a long, winding path through the Labyrinth before they emerge from

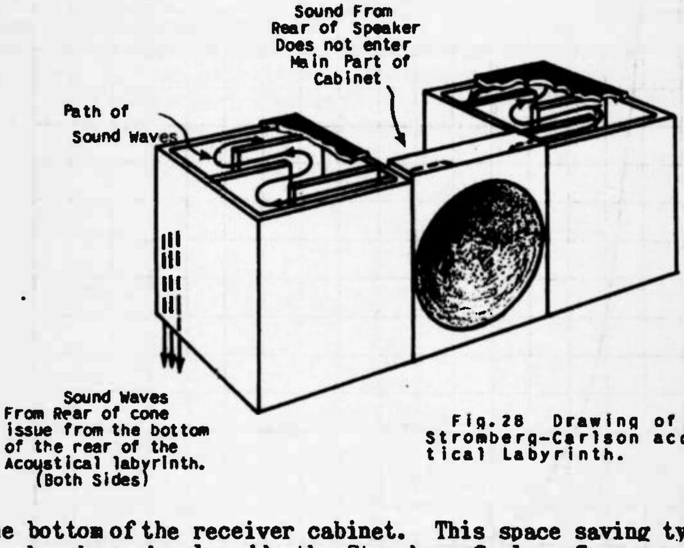


Fig.28 Drawing of the Stromberg-Carlson acoustical Labyrinth.

the bottom of the receiver cabinet. This space saving type of baffle has been developed by the Stromberg-Carlson Company. The walls of the Labyrinth are covered with sound absorbing material; thus, "resonance" effects are avoided at the higher frequencies. Non-resonant materials, such as acoustex, celotex, etc., are excellent for the construction of a baffle. In the acoustical Labyrinth, by use of the proper materials in conjunction with the cavity area, the "resonance" is made broad and over that portion of the low frequency spectrum that is deficient in the output of the A.F. amplifier. Being resonant over a broad portion of the low frequency range increases the reproduction at these frequencies; hence, the over-all frequency response of the amplifier and speaker combined is made quite flat.

Reproduction from a console type receiver is considerably different when the receiver is placed in the center of a room than when it is moved back against a wall. Its distance from a wall or a corner affects the quality of reproduction to a great extent. This is due to the angle and intensity of the back wave as it is reflected from the walls of the room. Quite often the service-engineer finds it necessary to experiment with the location of the receiver in a room, so as to determine the most desirable position. If the receiver incorporates an acoustical Labyrinth, Magic Voice, or any of the other "controlled" back wave arrangements, the receiver location is immaterial. In such receivers, the back wave is not directed from the open back of the cabinet toward any reflecting surface, so the same reproduction is obtained when it is set in the center of a room as when it is against a wall.

13. THE R.C.A. MAGIC VOICE. When a loudspeaker is housed in a console cabinet, a fairly large baffle area is provided (at least much larger than on table models), but two difficulties are encountered. First, the effective baffle area is not sufficiently great to reproduce faithfully all of the low frequencies of music and, second, the barrel resonance effect of the partially closed cabinet space back of the loudspeaker results in an over accentuation of certain parts of the low frequency register. While this does not seriously disturb the reproduction of musical selections

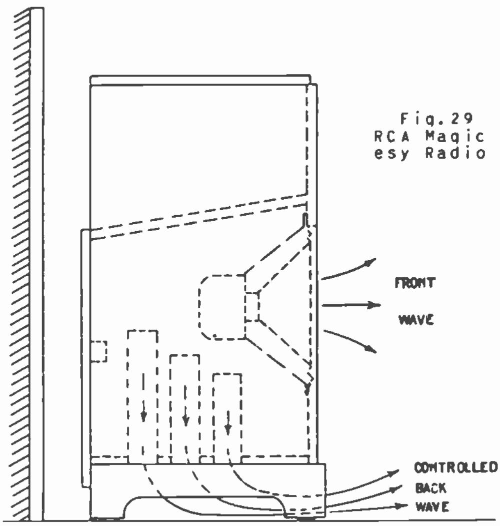


Fig. 29 Drawing of the RCA Magic Voice. (Courtesy Radio Engineering)

(in fact, it is beneficial), its effect upon the reproduction of speech, particularly certain male voices whose fundamental pitch is in the region of cabinet resonance, is to exaggerate the voice fundamental with a resultant "boomy" type of reproduction which is very undesirable.

The receiver designer is therefore faced with the necessity of compromising between the requirements of good musical reproduction and those of good speech reproduction. If the cabinet is designed so as to reproduce the lowest musical notes at their proper loudness, then the "booming" male speech will be so loud as to render the speech disagreeably unnatural, or in some cases, almost unintelligible. On the other hand, if the low frequency amplification is reduced to the point where speech sounds natural, then the lower musical notes are not properly reproduced. There has been some effort toward suppressing the back wave from the loudspeaker since this is the wave that gives the trouble from cabinet resonance effects. Another solution which has been worked out to a higher degree of satisfaction is not to try to suppress the back wave, but to control it and make it work with, rather than against, the front wave by reversing it in phase so that it may combine with and reinforce the sound from the front of the speaker. A satisfactory device which accomplishes this result has been given the commercial name of "Magic Voice". The constructional features of the device as well as a brief description of its theory are as follows.

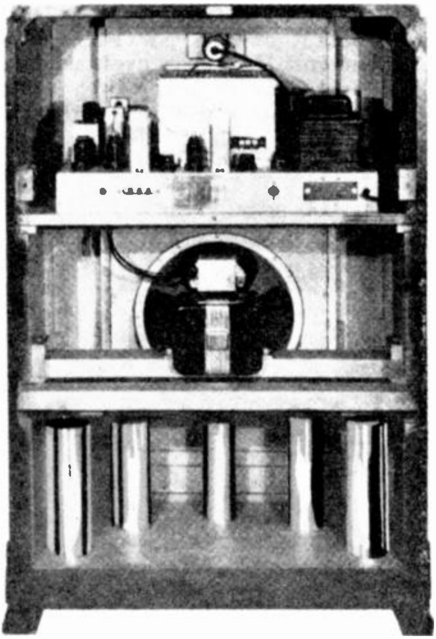


Fig.30 Photograph of an RCA receiver with the back removed to show the Magic voice pipes. (Courtesy Radio Engineering.)

In order to control the back wave, the first attempt was to rigidly enclose the cavity behind the loudspeaker. The effect of this was to completely prevent all interference between the back and front waves so that low notes, previously below the cutoff of the system and, therefore, not reproduced, may be then reproduced efficiently (neglecting resonance effects). Such an arrangement, however, was found to be inefficient in that it did not utilize the back wave from the loudspeaker. In order to utilize this back wave, it is first necessary to provide means whereby its phase might be reversed to that it would be in proper phase relation to reinforce the sound waves from the front of the speaker. This phase reversal was accomplished by using five metal tubes or pipes, situated in the bottom of the cabinet with their tops and bottoms open. Thus, they form an array of parallel paths through which the sound energy from inside the cabinet may radiate to the outside. They act in conjunction with the enclosed cavity as an acoustic-low pass filter on the sound emerging through them and are so proportioned mechanically as to cause a reversal in the phase of this sound. Reinforcement of the sound from the front of the loudspeaker is thus obtained with the resulting increased efficiency. Fig. 29 shows a sketch of the cabinet construction using the Magic Voice arrangement and Fig. 30 shows a photograph of a radio receiver employing this device, with the back removed to provide a view of the interior.

In several of the 1938 RCA Victor receiver cabinets, the "Sonic-Arc" Magic Voice construction is used. This is shown in Fig. 31. Proper control of the acoustic properties of the cabinet is obtained by the use of the curved panel of thin wood closing the back and bottom, with openings along the front bottom edge. These openings are correctly proportioned to produce the most desirable acoustic

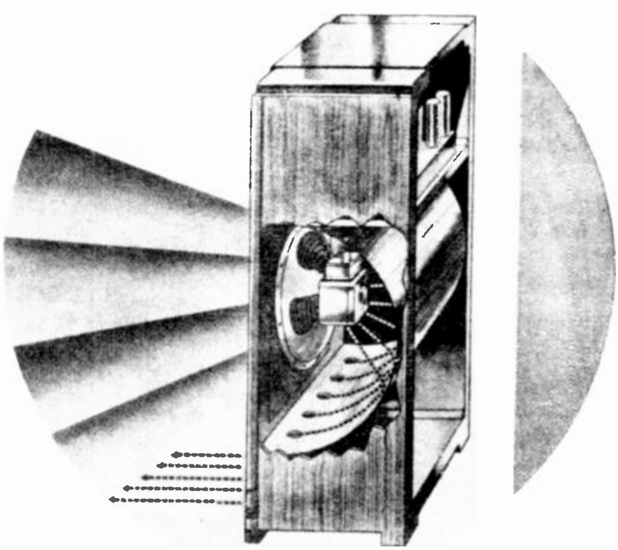
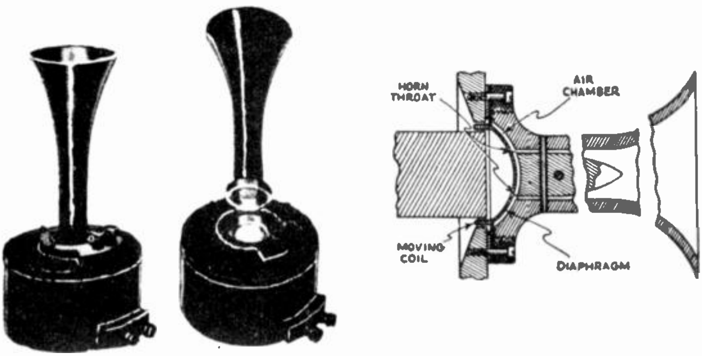


Fig.31 View of RCA receiver showing the structural details of the "Sonic-Arc".

effect. This panel confines the air in the cavity with sufficient rigidity despite its thinness, because of its curved shape which has much greater surface stiffness than a flat panel many times greater in thickness. Openings, necessary to the operation of the device, are provided in the form of a row of holes near the bottom front edge of the curved panel, together with certain openings in the corners of the cavity and around the chassis itself. These combined openings have the acoustic properties necessary to produce a maximum low frequency response. In the original Magic Voice, and in some of the 1938 combination phonograph-radio instruments, the openings are provided through pipes. The pipe construction is an alternative form more suitable in certain cabinet constructions, but the small openings without pipes give the desired effect with the Sonic-Arc construction. The principle of operation of the Sonic-Arc Magic Voice is similar to the earlier form of Magic Voice using the tubes.

14. HIGH FREQUENCY SPEAKERS. In view of the deficiency of high frequency reproduction from ordinary permanent and electrodynamic speakers, a different type of dynamic loudspeaker has been developed by the Bell Telephone Laboratories. Its construction is similar to the dynamic speakers previously discussed in that it employs a field winding for the production of a steady magnetic field and a voice or moving coil, through which the signal current is passed. It is different, however, in that it uses a moving diaphragm and horn for the emission of the sound waves rather than a vibrating cone. A photograph of such a high frequency speaker is shown at A in Fig. 32, and a detailed construction of the mechanism in the throat of the horn is shown at B. The moving (voice) coil is wound on the flanged edges of a light, parabolic diaphragm and vibrates in a small air chamber at the throat of the horn. The throat and diaphragm are designed so as to permit the reproduction of only the higher audio frequencies and the air passages at the



(A) (B)

Fig.32 (A) Photographs of high frequency electrodynamic speaker.
(B) Drawing to show the details of the "throat" in the high frequency speaker illustrated at A.

throat are proportioned so as to direct the high frequency sound waves from the flared end of the demountable horn. The speaker illustrated in Fig. 32 is designed to operate from 3,000 cycles up to and including 12,000 cycles. For the lower frequencies, a large electrodynamic speaker must be used. In conjunction with each speaker, a simple network or filter is used to allow only those frequencies which are in the efficient range of the speaker to be reproduced by that speaker. Such an arrangement is shown in Fig. 33. A two-speaker system of this type greatly improves the fidelity of reproduction from a radio receiver.

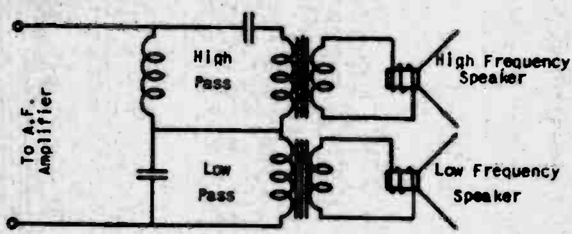


Fig. 33 Filter circuit used with dual-speaker system.

If a dual-speaker arrangement is employed, the response of the audio amplifier that drives the speaker must be exceptionally good. For proper operation, it should deliver equal audio power at all frequencies from 30 to 12,000 cycles. When turned for low volume, the low-frequency output of the amplifier should be accentuated in order to compensate for the normal deficiency of the human ear. This means that a tone-compensated volume control, or an automatic bass control circuit should be incorporated in the circuit design to realize maximum benefits from such an extensive speaker array.

A crystal speaker may also be used for reproduction of the higher audio frequencies. Filters, as shown in Fig. 33, are not generally used with a crystal speaker, but rather it is connected to the amplifier's output by one of the coupling methods illustrated in Fig. 11.

... a different loudspeaker ... high-frequency sound waves from the diaphragm of the ... frequencies ... resonance ... from 3,000 cycles up to 12,000 cycles. For the lower frequencies a large electrodynamic speaker may be used. In conjunction with each speaker, a simple network or filter is used to allow only those frequencies which are in the desired range of the speaker to be reproduced by that speaker. Such an arrangement is shown in Fig. [illegible]. A two-speaker system of this type greatly improves the fidelity of reproduction from a radio receiver.

Fig. [illegible]—Circuit used with a dual-speaker system.

If a loudspeaker arrangement is employed, the response of the audio amplifier which drives the speaker must be exceptionally good, ... It should deliver equal audio power at all frequencies from 30 to 12,000 cycles. When turned to low volume, the low-frequency output of the amplifier should be accentuated in order to compensate for the normal deficiency of the human ear. This means that a tone-compensated volume control, or an automatic bass ... circuit should be incorporated ... to realize maximum benefits from an extended ... system.

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POWER & LIGHT BUILDING, KANSAS CITY, MISSOURI

UNIT NO. 1

MULTI-ELEMENT TUBES

LESSON NO. 30

THE LAMP OF KNOWLEDGE

.......PERFORMS FEATS OF MAGIC IF YOU USE IT RIGHT.

When you were a little fellow, climbing up on your Dad's knee, you must have heard the story of Aladdin and his Magic Lamp. How he could rub his hand against its side and the 'Genie' would appear, ask what his young master desired, and it would be done.

Naturally, the story of Aladdin was a children's tale, carrying a child's imagination to untold heights. Childhood is filled with stories of magic.

But manhood is filled with stern fact. Sure, we'd like to put off facing the facts as long as possible, but it simply can't be for very long. All too soon the time comes when responsibilities stare us in the face and there isn't anything we can do about it but back down, and buckle down.

You know that. It's the reason you are studying this lesson, and the lessons that are in your book-rack, and the lessons that are still to come. You are after whatever you can get..... to gain the highest possible success consistent with your efforts.

Like Aladdin's lamp, though, Midland lessons are bound to be the means of getting results for you that you could not obtain otherwise. These lessons demand attention, the same as the Magic Lamp. But you rub them in a different way.....! Each page should be grasped near the top corner and held firmly until you have gained the knowledge it contains. Then the next page is grasped in the same way.

And one of these fine days the Genie will appear and say, 'You are a 'top' Radio man'. And being a 'top' Radio man, you'll find the facts and responsibilities that once looked so stern and impossible, are not so bad after all, BECAUSE YOU ARE READY TO MEET THEM ON THEIR OWN GROUND!

Remember always, 'RUB THOSE PAGES', and the harder you 'rub,' the bigger the 'magic'!

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Lesson Thirty

MULTI-ELEMENT TUBES

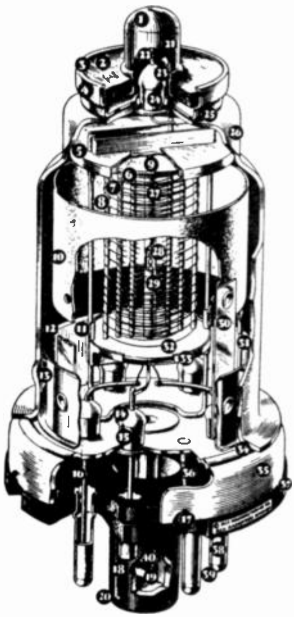
"The development of special types of multi-element vacuum tubes has made it possible to design radio receiving sets using only a very few tubes. In some cases, one of these newer tubes can efficiently replace as many as three of the older tubes.

"One of the latest advances in tube design is the "all metal" type of construction. Its construction and advantages are discussed in the first part of this lesson.

"I believe you will find the study of this lesson a fitting climax for your fundamental foundation in radio."

1. ALL-METAL TUBES. A cut-away view showing the internal structure of a typical RCA all-metal tube is shown in Fig. 1. In contrast with the metal tube construction, the assembly of a glass tube arranged in the progressive stages of construction is shown in Fig. 2. The metal tube is a type 6J7 and the glass tube illustrated is a type 6A7. Careful consideration of the fundamental structure of the all-metal tube will show wherein it differs from the glass tube.

Primarily, the function of the envelope of a radio tube is that of maintaining the high vacuum esseutial for operation of the tube. Glass performs this duty very well, but its use imposes certain limitations as to tube structure and electrical characteristics. The all-metal tube construction was designed originally by General Electric engineers. The all-metal construction not only takes care of vacuum requirements, but also avoids many of the design limitations imposed by the use of glass. For instance, the remarkable feat of resistance welding, with special welding apparatus that permits a flow of current of approximately 75,000 amperes for $\frac{1}{30}$ of a second, has been accomplished for metal tube manufacturing by the use of the General Electric thyratron tubes to control the precise timing of the weld. This permits the accurate control of a tremendous amount of heat for only a split part of a second without chang-



1—SOLDER
2—CAP INSULATOR
3—ROLLED LOCK
4—CAP SUPPORT
5—GRID LEAD SHIELD
6—CONTROL GRID
7—SCREEN
8—SUPPRESSOR
9—INSULATING SPACER
10—PLATE
11—MOUNT SUPPORT
12—SUPPORT COLLAR
13—GETTER TAB
14—GLASS BEAD SEAL
15—EYELET
16—LEAD WIRE
17—CRIMPED LOCK
18—ALIGNING KEY
19—PINCHED SEAL
20—ALIGNING PLUG
21—GRID CAP
22—GRID LEAD WIRE
23—GLASS BEAD SEAL
24—EYELET
25—BRAZED WELD
26—VACUUM-TIGHT STEEL SHELL
27—CATHODE
28—HELICAL HEATER
29—CATHODE COATING
30—PLATE INSULATING SUPPORT
31—PLATE LEAD CONNECTION
32—INSULATING SPACER
33—SPACER SHIELD
34—SHELL-TO-HEADER SEAL WELD
35—HEADER
36—SHELL CONNECTION
37—OCTAL BASE
38—BASE PIN
39—SOLDER
40—EXHAUST TUBE

Fig. 1 Internal construction of a typical all-metal tube.

ing the physical characteristics of the metal. For this reason, the process is used extensively in the manufacture of all-metal tubes. It is used for welding the shell to the header (34 in Fig. 1) and thus closes the outer container or shell with a perfect air tight seal. This type of welding is also used for welding the metal exhaust tube (40 in Fig. 1) to the header. Thus, it is possible to make a radio tube of metal construction which proves to be just as capable of holding a vacuum as the glass tube. The substitution of metal for glass also lends itself better to precision requirements of high speed tube manufacture and assembly.

In a glass tube, the glass stem is the foundation upon which the electrode structure is built. The glass stem is labeled "1" in Fig. 2. The metal type of construction eliminates the need for this stem. The purpose of the glass stem, of course, is to provide seals for the lead wires and a seal to the glass bulb. In place of the glass stem, the all-metal tube employs a flanged steel disc known as the "header." The lead wires connecting the base to the internal electrodes pass through perforations made in the surface of this header. Air tight insulation of these lead wires as they pass through the header is an important requirement and has been met by the development of a metal alloy called "fernico." This metal alloy bonds readily to certain special kinds of glass and has the same temperature coefficient of expansion as glass. Fernico eyelets are electrically welded with thyratron control into the perforations of the header. One of these eyelet connections is marked "15" on Fig.

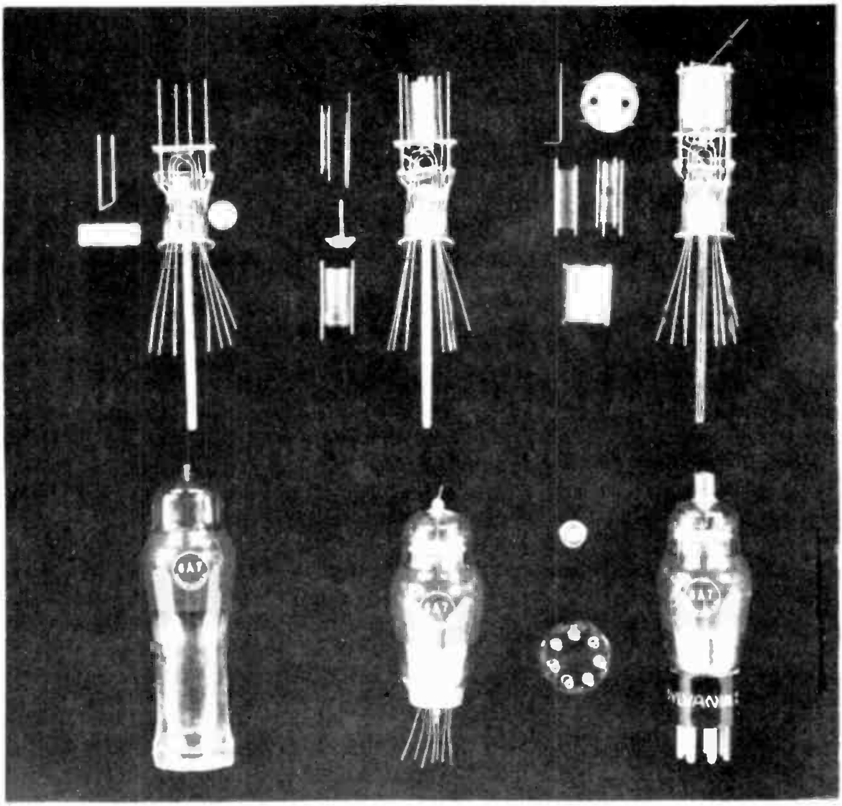


Fig.2 Assembly of a glass tube arranged in the progressive stages of construction.

1. The process is somewhat as follows: A glass beaded wire is inserted in each eyelet. The header is then heated to a temperature high enough so that the small glass beads melt and flow down into the eyelets. In cooling, both the glass and the fernico eyelet contract as one, thus making a perfect, air-tight seal and one having excellent insulation between lead wire and eyelet. The header used for the electrode support in the all-metal tube is very strong and extremely rigid because of the reinforced construction, thus making it quite satisfactory for the electrode support.

Building the electrodes directly on the header permits an additional outstanding advantage, in that the electrical connections are only about $\frac{1}{2}$ to $\frac{1}{3}$ the length of the glass type stems. The mechanical mounting, together with the circular arrangement of the leads in the header stiffens the internal construction of the tube against tendencies to bend or warp out of place. The upper part of the metal tube electrode structure is rigidly supported due to the snug fit of the grid lead shield into the dome of the steel shell. Since the metal construction of the header is unaffected by the higher temperature caused by the close proximity of electrodes, heat dissipation in the tube is amply taken care of. Actual comparison reveals that the size of the metal tube is less than half the size of a corresponding glass type tube; the result of careful engineering design. Fig. 3 shows several glass tubes with their all-metal equiv-

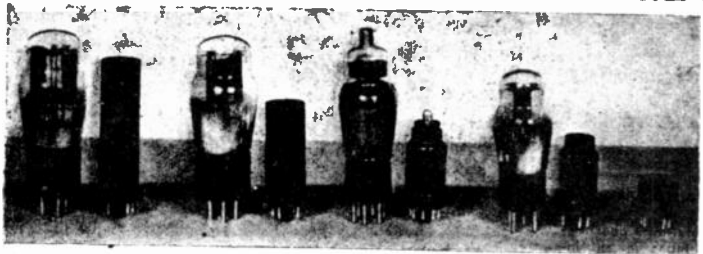


Fig. 3 Showing the contrast in sizes between metal tubes and glass tubes of corresponding rating. The metal tube on the extreme right is a duo-diode, which does not have a glass equivalent.

alents. The smaller size of the metal tube is not due to its smaller electrodes, nor have any sacrifices been made in other tube qualities. In fact, along with these structural features, certain electrical characteristics are also improved. In the metal tube, the lead connections from the electrodes of the tube to the base are much shorter than for a glass type tube. This is evidenced by the direct comparison illustrated in Fig. 4. The total length of the grid lead to the cap on the top of the tube is also shortened in the metal tube construction.

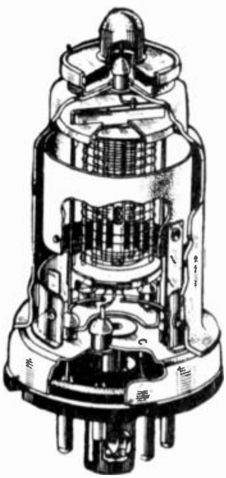
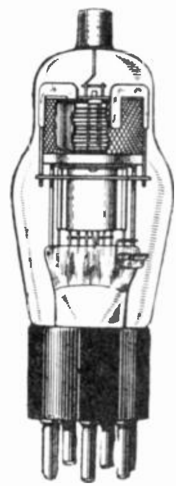


Fig. 4 Cut-away views to compare the internal structure of a metal and a glass tube.



In glass tubes, there is a tendency for an electric charge to accumulate on the inside wall of the glass envelope. The accumulation of this charge results in spontaneous discharges while the tube is operating, thus giving rise to considerable noise. In the metal tube construction, this is entirely eliminated. The reason for the accumulated charge on the inside wall of a glass tube can be explained as follows: Some of the electrons that are emitted from the ends of the cathode escape around the edges of the plate and travel toward the glass wall, due to their velocity and angle of projection. Normally, one might assume that these electrons would be attracted back to the plate. This would be true if the glass wall did not create an unusual effect. If the glass wall of the tube was only of glass material, the chances are the electrons would be attracted back to the plate. However, there is another fact which must be taken into consideration. During the process of manufacturing vacuum tubes, it is necessary to use some getter material to clean up all of the gas in the tube. When this getter, which is usually magnesium metal or some similar substance, is flashed, the glass will take on a very thin coating of the getter material. The material forming the coating on the glass wall is now capable of taking an electric charge since it is actually a very thin, metallic film. The metallic shield that always encloses the glass envelope of a glass type tube is at ground potential and the plate of most tubes is operated at about 250 volts. Thus, between the plate of the tube and the shield outside the glass envelope, there is generally about 250 volts pressure. Now note the position in this area between the shield and the plate occupied by the metal film on the glass wall. Since the film is floating free, it is not at zero potential. Also, since it is necessarily at some distance from the shield, it lies in the region of a certain positive potential with respect to ground. For purposes of illustration, let us assume that it accumulates a positive charge of about 25 volts. It may, of course, be more or less than this, depending upon conditions. Due to the metal film being at a positive potential, the electrons, even though decreasing in velocity as they move away from the plate, are traveling at a speed so that when they hit the positively charged metal film, they knock out secondary electrons. Some of these secondary electrons are drawn back to the plate, but since the number of primary electrons striking the film is less than the secondary electrons emitted, the metal film becomes more positively charged than before. Hence, we find that a positive charge is rapidly built up on the metallic film covering the inside glass wall of the tube. This in turn will tend to exert a greater attraction for the primary electrons. Eventually we will have a sufficient number of electrons attracted to this glass wall so that the electron stream to the glass wall can be treated as a resistance in the same manner that we treat the electron stream from the cathode to the plate. Also, since the metallic film is charged positively with respect to ground, we can assume that a capacity exists between the metallic film of the glass wall and the shield; likewise, a capacity exists between the plate and the metallic film.

If the plate circuit of the tube is loaded with a tuned circuit, as shown in Fig. 5, then the actual electrical conditions existing in the circuit with the accumulated charge on the glass wall of the tube would be as represented in Fig. 5b. Here, C_p is the capacity between the plate and the metal film, C_3 is the capacity between the metal film and the shield outside the glass envelope and R is the resistance of the path between the plate and the metallic film on the inside of the glass wall. If the effect is to cause the extra circuit to be more capacitive than resistive, the plate circuit is detuned with a resultant decrease in sensitivity. If it is more resistive than capacitive, you might expect a loading effect on the tuned circuit, which again would decrease sensitivity and reduce the selectivity of the tuned circuit. This, of course, is very undesirable.

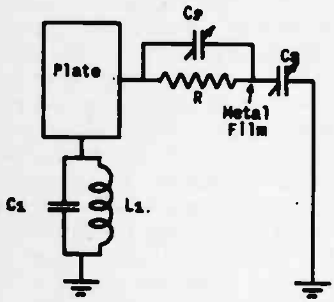


Fig.5 Equivalent electrical circuit developed by static charge accumulation in a shielded glass tube.

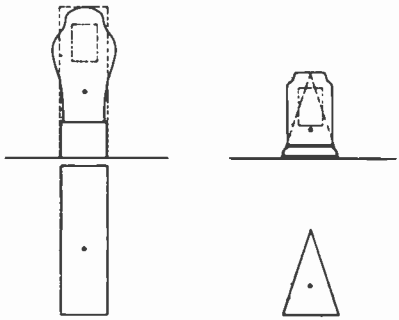
Another effect is also produced by this building up of a charge on the glass wall. The wall coating is generally not uniform and the primary electrons striking the wall actually cause more secondary electrons to be knocked off some portions of the wall than other portions. The result is that the wall will not be uniformly charged; one portion will be at a higher potential than an adjacent portion. When the potential difference between these adjacent portions becomes large enough, it is found that the charge of highest potential arcs over to the charge of lower potential. These arcs abruptly change the secondary emission current which builds up a small voltage across the tuned plate circuit. Due to the high amplification that follows the tube in which this occurs, the small voltages may ultimately appear as excessive noise in the output of the receiver.

Obviously, for glass tubes to give satisfactory operation, it is necessary that some preventive means be taken to eliminate the detrimental effects just stated. One protective method is to coat the inside wall of the glass tube with a thin layer of carbon over the region where the stray electrons land. A coating of carbon has a very rough surface which would break up any metallic film that would tend to deposit on the wall of the tube. Also, the carbon has the property of resisting secondary emission effects. This treating process is employed in some of the glass type tubes such as the 57, 58, 6C6 and 6D6.

A second protective method against the charge accumulation is to place a metal shield between the plate and the glass wall. This metal shield is either connected to the screen grid or to ground. This arrangement causes any stray electrons to be drawn either to the shield or else repelled back to the plate so that they are unable to bombard the glass wall. This method is used in glass type tubes such as the 77, 78, 6B7, etc.

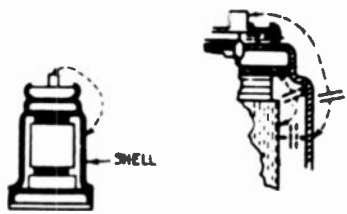
In a metal type tube, the grounded metal shell prevents this undesirable effect automatically and very efficiently. No extra parts, processes, or treatments are necessary with a metal tube. The electrons which may shoot past the plate will be at zero velocity when they reach the grounded shell and therefore cannot strike it sufficiently hard to cause secondary electron emission, but rather float around and eventually return to the plate. The charge accumulation effect is entirely eliminated with the all-metal tube.

Fig.6 Drawings to illustrate why the construction and shape of a metal tube decreases the possibility of electrode vibration.



The construction and shape of all-metal tubes permits less possibility for vibration to be set up in their internal elements. Fig. 6 shows an outline drawing of a typical glass and metal tube. The black dot indicates the center of gravity and the location of the tube elements is roughly approximated by the small dotted rectangel. The shorter and more compact structure of the metal tube avoids the tendency for motion. If the tendency for motion is avoided, then we can expect less noise due to the reduced vibration of the electrodes.

Fig.7 Showing how the grounded shell of a metal tube provides practically perfect shielding of the electrodes.



Perfect electrode shielding allows more gain to be secured before instability due to feedback through the plate-to-grid capacity is reached. In all-metal tubes, the plate-to-grid capacity is negligible in value. A drawing to illustrate the improved shielding provided by the grounded shell is shown in Fig. 7. The dotted line shows that a slight capacity will exist between the control grid and the shell, but, since the shell is grounded, the external capacity between the control grid and plate of the tube is short-circuited. The internal capacity between the control grid and plate is of negligible value due to the grounded (R.F. ground, not DC) screen grid.

The grounded shell of an all-metal tube is often called a "permanent shield." This means that the grounded shell itself serves as a shield for the internal elements and, being of strong mechanical construction, the relationship between the internal electrodes and the shell is always the same; that is, permanent. The usual tube shield placed around a glass tube is removable and ordinarily the shield support consists of some type of a flanged metal disc mounted on the chassis around the socket. Since the support is usually riveted to the chassis, the shield can get its ground connection through this flanged support. The connection to ground, of course, is due to frictional contact only. Due to the frictional contact, poor contact is often experienced. Also, this frictional contact arrangement is undesirable because of the possibility of corrosion. If the shield makes no contact whatsoever with its flanged support, the amplifying stage in which the supposedly shielded tube is contained will immediately become unstable and, no doubt, excessive oscillations will be produced. Also, if a high resistance contact (poor contact) occurs, practically the same type of operation will result. Due to these difficulties possible with the usual tube-shield can, design engineers have been limited in the past insofar as the amplification or gain in the receiver is concerned. The fact that there is always a possibility for the usual tube shield to gradually develop a high resistance ground connection requires that the gain per stage be held down initially so that instability can never occur during the normal life of the receiver. In a metal type tube, the possibilities of trouble arising from the use of shield cans is entirely eliminated. This is because the tube shell has positive and permanent contact with ground at all times. The shell is permanently welded to the header in a weld. Since in a weld the metals flow together, a perfect electrical connection is obtained. Further, the connection between the header and the base grounding pin is also welded. Also, the socket contact pressure, when the metal tube is inserted in the socket, provides perfect electrical ground connection to the plated pin, thus insuring positive contact over a long period of time. Radio engineers can then design their amplifying circuits with more gain, since they know that after a long period of use, there can be no change in the contact resistance between the metal-shell shield of the metal tube and ground. Insofar as service-engineers are concerned, it means less noise and oscillation troubles, due to imperfect shielding.

The smaller size of the metal tube and the elimination of the auxiliary shield can are desirable from the design engineer's standpoint. The elimination of the auxiliary shield saves chassis space. Then, since the all-metal tubes require less than half the space of the average glass tube, it is much easier to place them in the most advantageous position on the receiver chassis.

That the all-metal type of tube has several advantages is positively without a doubt. The only outstanding disadvantage that has been experienced with all-metal tubes up to this time is the inconsistency of the electrical characteristics in manufacturing. Improvement in constructional methods is rapidly eliminating this difficulty. The fernico eyelets used to insulate and permit the passage of the electrode leads through the header have also given some trouble. Theoretically, the coefficient of expansion of this alloy is the same as the metal used for the header; however, some trouble has been experienced wherein the actual expansion did not coincide exactly with the metal and, as a result, air was permitted to enter which destroyed the vacuum. Rapid improvements are being made in the metal tubes and some day they may entirely supplant glass tubes for receiving sets.

2. METAL-GLASS TUBES. In addition to the all-metal radio tube, most manufacturers also make glass tubes which closely correspond to the metal tubes in electrical characteristics. These are called "G" or "MG" type tubes. In most cases, these tubes are identical or at least very similar to some of the most popular glass tubes. The appearance of these G or MG tubes is also similar to certain original glass tubes, with the exception of the bases and grid caps. The bases are of the octal type with a centering or locating lug and the grid caps are of miniature size, with the same diameter as the grid caps on all-metal tubes.

The operating characteristics of most G tubes are identical to certain all-metal or conventional glass tubes. Reference, therefore, may be made to the published data on the equivalent type tubes for preliminary technical information. A group of equivalents are listed in the accompanying chart.

"G" Type	Description	Characteristics Same as:
1C7G	Pentagrid Converter	1C6
1D5G	Super Control Tetrode Amplifier	1A4
1D5GT	Super Control Tetrode Amplifier	1A4
1D7G	Pentagrid Converter	1A6
1E5G	Screen Grid R-F Amplifier	1B4
1E5GT	Screen Grid R-F Amplifier	1B4
1E7G	Double Pentode Output Tube	*
1F5G	Power Output Pentode	1F4
1F7G	Double Diode Pentode	1F6
1G5G	Power Output Pentode	*
1H4G	Amplifier and Detector	30
1H6G	Double Diode Triode	1B5/25S
1J6G	Class B Twin Amplifier	19**
1R1G	Battery Receiver Ballast	1Y1
1T1G	Battery Receiver Ballast	*
5U4G	Full Wave High Vacuum Rectifier	5Z3
5V4G	Full Wave High Vacuum Rectifier	83V
5X4G	Full Wave High Vacuum Rectifier	5Z3
5Y3G	Full Wave High Vacuum Rectifier	80
5Y4G	Full Wave High Vacuum Rectifier	80
6A5G	Power Output Triode	6A3 §
6A8G	Pentagrid Converter	6A7
6B4G	Triode Power Amplifier	6A3
6B8G	Double Diode Pentode	6B7
6C5G	Triode Amplifier	See Below
6C8G	Double Triode Amplifier	*
6D8G	Pentagrid Converter	6A7 §
6F5G	High Mu Triode Amplifier	See Below
6F6G	Power Output Pentode	42

"G" Type	Description	Characteristics Same as:
6H6G	Double Diode	See Below
6J5G	Triode Amplifier	*
6J7G	Triple Grid Amplifier and Detector	77
6K5G	High Mu Triode Amplifier	*
6K6G	Cathode Type Power Pentode	41
6K7G	Triple Grid Super Control Pentode	78
6L5G	Triode Amplifier	6C5G §
6L6G	Power Amplifier	6L6
6L7G	Heptode Mixer	See Below
6N6G	Power Output Amplifier	6B5
6N7G	Class B Power Amplifier	6A6
6P7G	Pentode Triode	6F7
6Q7G	Double Diode High Mu Triode	See Below
6R7G	Double Diode Medium Mu Triode	See Below
6S7G	Super Control Pentode	6D6 §
6T5	Triode Amplifier	*
6T7G	Double Diode High Mu Triode	6Q7G §
6U7G	Super Control Pentode	6D6
6V6G	Power Amplifier	*
6V7G	Double Diode High Mu Triode	85
6X5G	Full Wave High Vacuum Rectifier	84
6Y7G	Double Triode Power Amplifier	79
6ZY5G	Full Wave High Vacuum Rectifier	*
6Z7G	Double Triode Power Amplifier	*
25A6G	Power Amplifier Pentode	43
25B6G	Power Amplifier	43 §
25L6G	Power Amplifier	*
25Z6G	High Vacuum Rectifier and Voltage Doubler	25Z5

*New Characteristics--Refer to Characteristics data.

**Except filament current (240 Ma.)

§ Similar but not identical in characteristics.

6C5G characteristics same as 6C5 except for capacitances
6F5G characteristics same as 6F5 except for capacitances
6H6G characteristics same as 6H6 except for capacitances
6L7G characteristics same as 6L7 except for capacitances
6Q7G characteristics same as 6Q7 except for capacitances
6R7G characteristics same as 6R7 except for capacitances

All-metal and G type tubes are supplied with an octal base. An octal base has 8 pins uniformly spaced 45 degrees apart. When fewer than 8 pins are required for the tube's elements, the unnecessary ones are omitted, but the spacing of the remaining pins is unchanged. All tubes having an octal base will fit into a universal 8-hole, octal socket. A socket of this kind is shown in Fig. 8. A guiding lug protrudes from the center of all tubes having an octal base. This guiding lug, or locating pin then fits into the hole of corresponding shape in the octal socket. The tube can only be inserted in the socket in one position; therefore, it is impossible to insert the tube improperly. As shown in Fig. 8, the pin numbering is from 1 to 8, clockwise from the locating lug, when the base is viewed from the bottom. Where pins are omitted, the number for that pin position is also omitted. To become familiar with the pin connections generally used refer to the chart in Fig. 8. For

PIN #1 is ALWAYS the SHELL connection.

PIN #2 is ALWAYS one HEATER connection.

PIN #3 is ALWAYS a PLATE connection.

PIN #4 is NORMALLY the SCREEN connection except on the 6H6 it is the second CATHODE, on the 5Z4 it is the second PLATE and on the 6F5 it is the PLATE.

PIN #5 is NORMALLY a GRID connection except on the 6H6 it is the first PLATE.

PIN #6 is the first PLATE connection on the 5Z4 and the second GRID connection on the 6A8.

PIN #7 is ALWAYS the second HEATER connection.

PIN #8 is ALWAYS a CATHODE connection and in addition on the 5Z4 it is the second HEATER connection and on the 6F6 and 6L7 the SUPPRESSOR GRID connection.

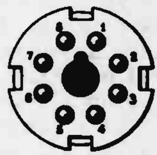


Fig.8 Metal tube pin connections.

exact pin connections however, on all the present types of tubes, refer to the tube chart in Lesson 25.

The self-aligning plug on the base of metal, G, and MG tubes, makes it possible to easily and quickly insert a new tube in the universal type socket. This design eliminates hunting for heater prongs and moving the tube around to find the pin holes.

3. NUMBERING SYSTEMS. A numbering system, which ordinarily requires three symbols to identify a tube, has been standardized by the Radio Manufacturers Association. These symbols are arranged with a numeral first, then a letter and finally a second numeral. As an example of this type designation, in the 6L7, the "6" designates that the heater voltage of the tube is between 6 and 6.9 volts, standardized at 6.3. Likewise, "5" would designate a heater voltage between 5 and 5.9 volts, standardized at 5.

The middle letter is used to designate the tube's purpose or function and is assigned arbitrarily. In rectifier tubes, the assignment is made arbitrarily with "Z".

The final numeral indicates the number of useful elements brought out to the terminals; thus the 6L6 has 6 such elements, a heater, a cathode, a control grid, a screen grid, a plate and a shield (shell).

This numbering system, as used at the present time has the serious defect that too many exceptions are involved. The first numeral, which stands for the heater voltage, is well standardized, but the letter inserted between the numerals is not always self-explanatory or enlightening as to the function of the tube. It is generally necessary to refer to the tube manual in order to determine exactly the purpose for which the tube is intended. The addition of the suffix G or MG to the tube number always indicates that it is a glass tube, having an octal base. If the tube is all-metal, or is a glass tube that does not employ an octal base, then the G or MG will be omitted.

About all that can be expected from the tube number designation is an approximate idea of its application or purpose. For exact details on its operating voltages, circuit applications, etc., an authoritative tube chart or tube manual must be consulted.

4. CLASSES OF TUBES. In this discussion, we shall divide those tubes available for receiver circuit operation into 13 classes. Division in this manner will enable a more comprehensive study of their construction and applications to radio receiver circuits. It is virtually impossible to submit a detailed description of each type of tube available; your tube manual is supplied for that purpose. The characteristics and applications of only one or two types typical of each class will be discussed. They are divided as follows:

(1) Monodes. This is a general classification including all ballast tubes. Typical tubes are the 1A1, 1B1, 1C1, etc. Ballast tubes will be studied in the next section of this lesson.

(2) Diodes. All half-wave rectifier tubes fall under the diode classification. A typical tube is the type 81. It was discussed in Lesson 16.

(3) Triodes. All three-element amplifying tubes are included in this classification. The operating characteristics for several of these tubes have been discussed in previous lessons. Typical tubes are the 56, 45, 2A3, etc.

(4) Tetrodes. This includes all of the four-element or screen-grid amplifier tubes. Lesson 25 described the construction and operation of these tubes in detail. Typical types are the 24, 35, etc.

(5) Pentodes. Tubes of this type were also discussed in Lessons 25 and 28. R.F. pentodes are commonly used for I.F. amplification and A.F. pentodes are used for the production of audio power to drive a loudspeaker.

(6) Heptodes. All of the converter and mixer-amplifier tubes are included in this general classification. Typical tubes are the 1C6, 6A7, 6L7, etc. A subsequent discussion in this lesson deals specifically with the operation of converter and mixer tubes.

(7) Pentode-Triodes. These tubes contain two separate sections, one pentode section and one triode section. A common heater-cathode assembly is used, but the electrodes in the two sections of the single tube are entirely separate. Pentode-triodes are often

used as a combined second detector and I.F. amplifier. A typical tube is the 6F7.

(8) Duo-Diodes. All of the full-wave rectifier tubes are included in this class. Typical full-wave rectifiers are the type 80, 84, 5Z4, etc. The all-metal voltage rectifier (the 6H6) is also included in this classification.

(9) Duo-Triodes. These tubes have two separate triode sections contained within the single envelope. Some of them are used as power amplifiers, such as the 53 and 6A6, whereas others (such as the 6N7) are used for phase inversion or in automatic frequency control circuits. Lesson 28 discussed the phase inverter circuit.

(10) Duo-Pentodes. These tubes have two separate pentode sections within a single envelope. They are ordinarily used as push-pull power amplifiers. A typical tube is the type 1E7G.

(11) Diode-Pentodes. The diode section in tubes of this classification is generally used as a rectifier and the pentode section as an amplifier. Two separate cathodes and a common heater are used. A typical tube is the type 12A7.

(12) Duo-Diode-Triodes. Tubes of this type have several applications; the most important being that of a diode second detector in a superheterodyne, with the triode section serving as the first A.F. amplifier. We shall show applications of this tube in later portions of this lesson. Typical types of duo-diode-triodes are: 6Q7, 6R7, 2A6, 55 and 85.

(13) Duo-Diode-Pentodes. These tubes are similar in application to the duo-diode-triodes, their construction differing only in that the amplifying section is a pentode rather than a triode. The pentode is sometimes used as the last I.F. amplifier in a superheterodyne, with the duo-diode section serving as the second detector. Typical tubes are the type 6B7, 2B7, 1F6 and 6B8.

5. **BALLAST TUBES.** There has been a steady increase in the use of ballast tubes in battery and AC-DC sets. Ballast tubes may be grouped into two major divisions based upon differences in construction and regulating characteristics. One type is employed mainly in battery-operated receivers to maintain substantially constant filament current over a considerable range of battery voltage variation. The second type is used in AC-DC receivers and 32 volt sets, where the voltage drop required may cover a wide range. Such a ballast tube affords some amount of regulation, but the characteristic is not as flat as for regulators intended for use in battery receivers.

The Sylvania ballast tubes for use in battery sets includes the types 1A1, 1B1, 1C1, 1D1, 1E1, 1G1, 1J1 and 6. These tubes are designed to permit the operation of 2-volt receiving tubes from a 3 volt battery source which may consist of two banks of dry cells in parallel, the two banks then being connected in series. The supply voltage varies from about 3.4 to 2.2 volts during the use of the battery. For this range of supply voltage, the types of ballast tubes listed above will maintain the socket terminal voltage between 1.8 and 2.2 volts. During the major part of battery life, the socket voltage will remain very close to the rated value of 2 volts.

To determine the correct filament current load in series with the ballast tube, it is necessary to include the total filament current drain of the receiver tubes plus the current drain of the dial lamp, if the latter is employed. For example, a receiver using a type 19, a type 30 and three type 34 tubes has a normal filament current drain of 500 ma. (no dial lamp). The correct ballast tube to use would be a type 1A1. The accompanying summary table furnishes data on bulbs, bases, load currents and service for Sylvania ballast tubes. The characteristic curve for a 1A1 ballast tube is shown in Fig.9. Curves on the other ballast tubes mentioned may be secured from the Sylvania Tube Manual.

TYPE	BASE	BULB	MA. LOAD CUR-RENT	SERVICE
1A1	Sm. 4 pin	ST-12	500	Battery
1B1	Sm. 4 pin	ST-12	360	Battery
1C1	Sm. 4 pin	ST-12	745	Battery
1D1	Sm. 4 pin	ST-12	240	Battery
1E1	Sm. 4 pin	ST-12	430	Battery
1G1	Sm. 4 pin	ST-12	420	Battery
1J1	Sm. 4 pin	ST-12	620	Battery
6	Sm. 4 pin	ST-12	695	Battery

The second group of ballast tubes, those for AC-DC receivers and 32 volt sets, are used where the voltage drop required may cover

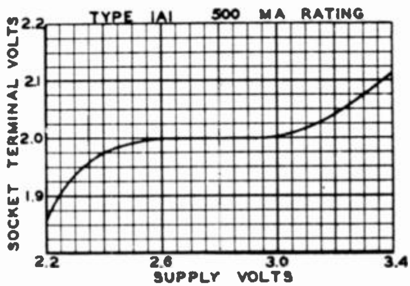


Fig.9 Characteristic curve for the type 1A1 Sylvania Ballast Tube.

a wide range. Such ballast tubes afford some amount of regulation, but the characteristics are not as flat as for the ballast tubes used in battery receivers. The following summary table furnishes data on this group.

Type	Base	Bulb	Ma. Load Current	Service
2	Medium 4 pin	ST-16	300	32 Volt
3	Medium 4 pin	ST-16	300	220 Volt AC-DC
4	Medium 4 pin	ST-16	400	220 Volt AC-DC
5	Medium 4 pin	ST-16	400	220 Volt AC-DC
7	Medium 4 pin	ST-16	300	220 Volt AC-DC
8	Medium 4 pin	ST-16	300	220 Volt AC-DC
9	Medium 4 pin	ST-16	300	110 Volt AC-DC
46A1	Small 5 pin	ST-12	400	110 Volt AC-DC
46B1	Small 5 pin	ST-12	300	110 Volt AC-DC

The graph at A in Fig. 10 shows the characteristics for the type 2, 32 volt ballast tube. The curves for the 110 volt AC-DC ballast tubes; namely the 9, 46A1, and 46B1, are shown at B in Fig. 10.

Curves for Sylvania AC-DC and 32 volt Ballast Tubes

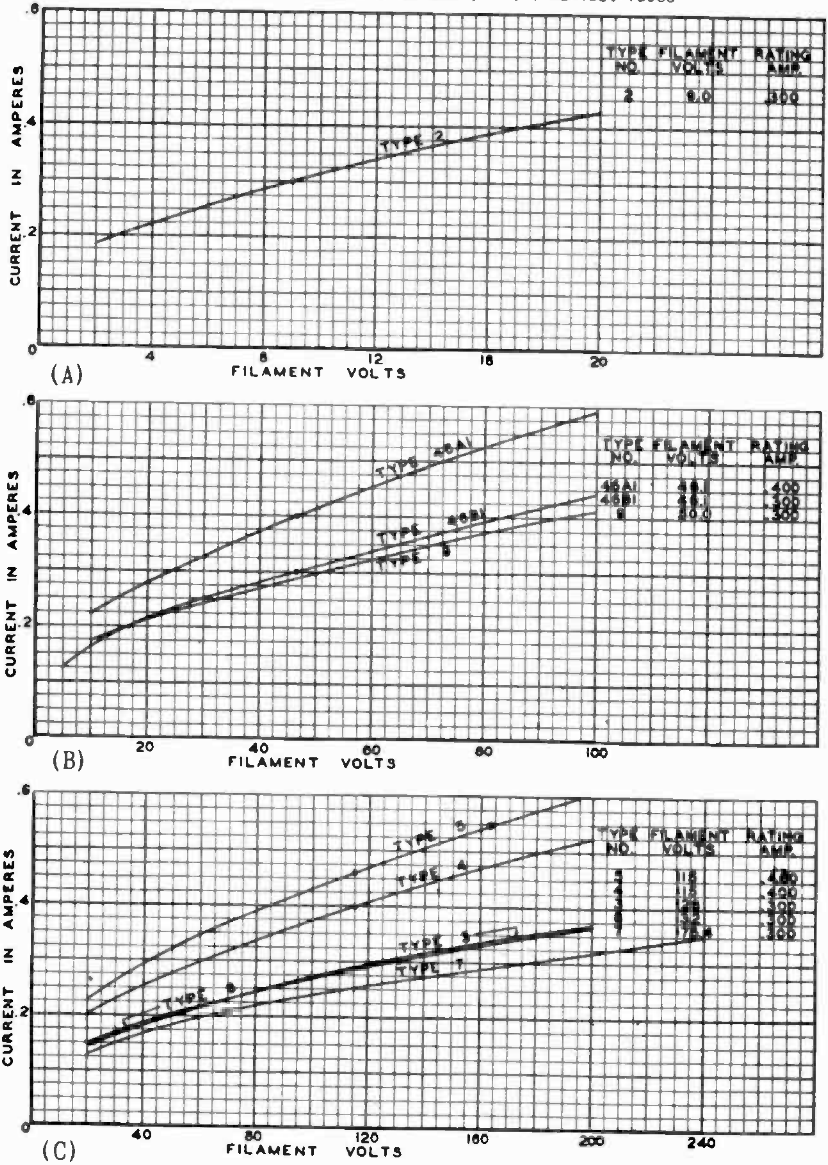


Fig. 10

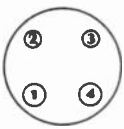
The remaining ballast tubes listed in the chart are for 220 volt AC-DC operation and the characteristic curves for these tubes are shown at C in Fig. 10.

TRIAD BALLAST RESISTOR UNITS

SPECIFICATIONS

Type	For Use With	Overall Voltage Drop	Pilot Lights			Base Wiring	
			No.	Current	Type No.	M8 Series	Glass
55A	2-6.3 & 2-25V Tubes	55	None			A	W
K55B	2-6.3 & 2-25V Tubes	55	1	.150	40	B	X
K55C	2-6.3 & 2-25V Tubes	55	2	.150	40	C	Y
K55D	2-6.3 & 2-25V Tubes	55	2	.150	40	D	
K55E	2-6.3 & 2-25V Tubes	55	3	.150	40	E	
K55F	2-6.3 & 2-25V Tubes	55	1	.150	40	F	
K55G	2-6.3 & 2-25V Tubes	55	2	.150	40	G	
K55H	2-6.3 & 2-25V Tubes	55	2	.150	40	H	
K55J	2-6.3 & 2-25V Tubes	55	3	.150	40	J	

GLASS SERIES PIN NUMBERS



Bottom View of Base

FIRST LETTER OF SERIES INDICATES TYPE OF PILOT

K for 6.3V 150 MA Lamp #40
L for 6.3V 250 MA Lamp #46
BK for 6.3V 150 MA Lamp #40 Ballast action on pilot
BL for 6.3V 250 MA Lamp #46 Ballast action on pilot

NUMBER INDICATES OVERALL VOLTAGE DROP INCLUDING PILOTS

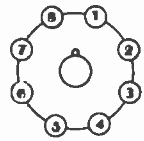
Recommended Value Based on 117 Volt Line

55 - For 2-6.3V and 2-25V Tubes
49 - For 3-6.3V and 2-25V Tubes
42 - For 4-6.3V and 2-25V Tubes

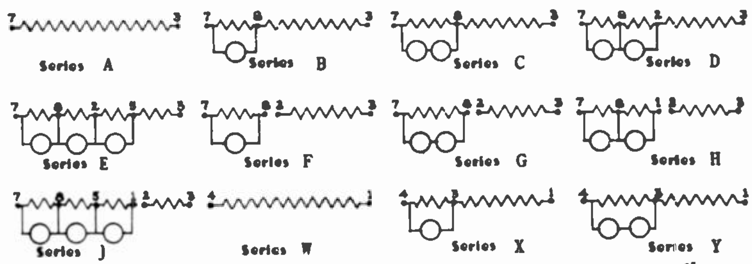
LAST LETTER INDICATES WIRING SYSTEM

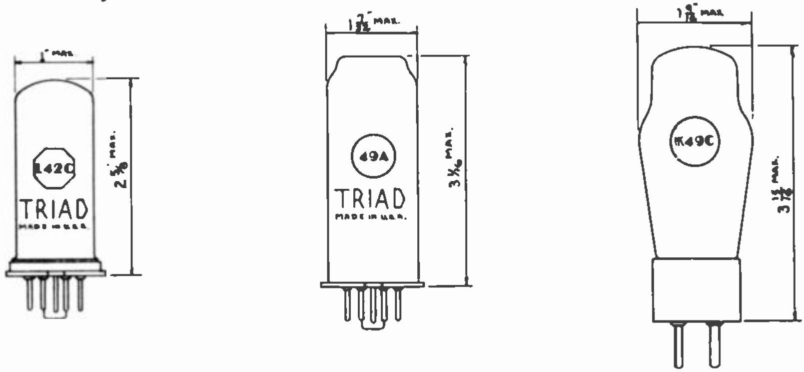
NUMBERS Indicate Pin Connections

M8 SERIES PIN NUMBERS



Bottom View of Base

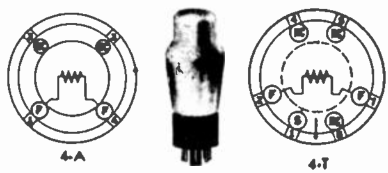




All ballast tubes belonging to this second general division should be operated as closely as possible to the standard rating in order to realize the most efficient performance. All Sylvania ballast tubes are inside frosted.

Complete information on Triad ballast resistor units is given on Page 15. In addition to the regular series of ballast units, there is another type available from the Triad Manufacturing Company which permits a ballast action on the pilot light. This method protects the pilot light from the high current surge which results when the voltage is first applied. During the heating up period of any AC-DC set, there is a current surge until the heaters are up to proper temperature. This high current flowing through the pilot light far exceeds its rated value. Thus, it is necessary to exclude the pilot light or to reduce the voltage until correct temperature is reached to prevent burn out. On those Triad ballast resistor units wherein the first letter of the series is preceded by a B (refer to Page 15), ballast action is provided for the pilot light. A number of possible connections are shown on Page 15. When the set is first turned on and the current is high, this new ballast action provides a low resistance shunt across the pilot light. This resistance increases as the tubes warm up, reaching its normal resistance just as the tubes obtain operating temperature and the heater current comes down to its normal value. In this way, the voltage across the pilot lamp is essentially constant during the heating period.

BALLAST TUBES



Five new ballast tubes have been added to the Sylvania line of tubes. The five new tubes are all intended for use in 2 volt battery receivers. Like other Sylvania battery ballast tubes, these new types are designed to hold the variation in terminal voltage within the correct filament operating range.

These new types will replace any ballast tubes having like type numbers or any ballast tubes having identical filament current load and like base pin connections. To determine the filament current load across a ballast tube it is necessary to include the total filament current requirements of all the tubes plus the current drain of the dial light.

The five new Sylvania Ballast Tubes are:

Type	Base	Ma. Load Current	Average Voltage Drop*
1F1..	4-A	720	1.0
1R1G	4-T	540	1.0
1T1G... . .	4-T	560	1.0
1Y1.. . .	4-A	540	1.0
1Z1....	4-A	900	1.0

*The voltage drop shown is for average operation and may vary according to supply voltage.

Recently, the Sylvania Tube Co. has added five new ballast tubes, the type numbers and characteristics of which are given above.

6. **PENTAGRID CONVERTERS.** During the study of superheterodyne receivers in Lesson 27, it was learned that a local oscillator must be employed to generate an unmodulated R.F. voltage which, in turn, is mixed with the incoming signal to produce the intermediate frequency in the plate circuit of the first detector. Because of the function it performs, the first detector is often called a "frequency converter."

A separate oscillator tube may be employed to generate the unmodulated R.F. voltage, then mixed with the incoming signal in the cathode circuit or applied directly to the grid of the first detector. Also, it was found that a tetrode or pentode tube could be made to perform as an "autodyne" first detector-oscillator combination. In these types of circuits, coupling of the oscillator to the first detector is secured by either inductive or capacitive means.

A pentagrid converter is for the purpose of combining the functions of the local oscillator and first detector into a single tube and, at the same time, eliminating the capacitive or inductive coupling. Coupling in a pentagrid converter is secured directly in the electron stream. This arrangement eliminates the undesired intercoupling effects between signal, oscillator and mixer circuits, and also reduces local frequency radiation.

A pentagrid converter is a vacuum tube device depending on the electron stream as a coupling agent and may be visualized as one in which the plate current is modulated by variations in cathode emission. Conceivably, the total cathode current might be modulated by variations in cathode temperature produced by filament current changes. Practically, however, this same effect can be accomplished by placing a grid and a supplementary anode grid between the cathode and the main control grid, then by using these electrodes in conjunction with the cathode to accomplish a modulation of the cathode current. With this latter arrangement, the cathode and the first two grids may be regarded theoretically as a composite cathode, which supplies a modulated electron stream. This modulated electron stream may be further controlled and utilized with voltages on the other grids and the plate.

Typical pentagrid converter tubes are the types 2A7, 6A7, 6A8, etc. A type 2A7, used in a frequency converter circuit, is shown in Fig. 11. Grid #1 is the control grid for the oscillater portion of the tube. Grid #2 is the anode for the oscillator. Grid #3 and #5 are connected together within the tube and are used to accelerate the electron stream from the cathode. In addition, grid #3 and 5 electrostatically shield the control grid #4 from the other electrodes. This shielding increases the output impedance of the tube; a desirable characteristic from the standpoint of voltage amplification.

The word "pentagrid" is a compound word made up of the Greek prefix, "pente" (or penta in the English translation) meaning five, and grid. These five grids are all indicated on the type 2A7 tube in Fig. 11. Grid #2, the oscillator anode, is made up in current practice with horizontal wires that consist only of two side rods. These two side rods are called the "oscillator anode" (meaning plate), but in circuit diagrams they are shown as a grid for simplicity.

In Fig. 11 the incoming R.F. signal is fed from L_1 into the tuned grid circuit L_2C_1; then, applied to the control grid of the tetrode section: that is, grid #4. In the oscillator section of the tube, the R.F. energy is returned through the plate circuit inductance L_4 into the tuned grid circuit, consisting of L_3, C_2, and C_4. C_2 is the main tuning condenser and C_4 is the series padding condenser. Grid bias for the tetrode section of the tube is secured by the flow of plate current through the cathode resistor R_2. The incoming signal and oscillator voltages are heterodyned (mixed) in the electron stream flowing from cathode to plate, so the output voltage will be a beat frequency equal to the difference between the incoming signal and oscillator voltages. The plate circuit of the pentagrid converter is tuned to the beat (intermediate) frequency. In Fig. 11, C_8 and L_5 form the I.F. parallel tuned circuit.

A pentagrid converter is sometimes considered to operate very much like a conventional variable-mu tetrode first detector with an associated triode oscillator. The only exception is that the oscillator triode grid is located next to the cathode and is common to both the first detector and variable-mu tetrode and the oscillator triode. The control grid voltage on the oscillator triode modulates the tetrode section of the tube in such a manner that there is no danger of driving the control grid of the tetrode positive. The electrons that are emitted from the cathode surface are influenced by all the various grid and plate voltages. It has been determined that the electrons actually divide in such a manner that grid #1 receives 7%, the oscillator anode receives 37%, grids #3 and #5 (screen grid) received 28%, and the plate of the tube receives the remaining 28%.[1]

Due to the commanding position next to the cathode occupied by the oscillator control grid, any voltages developed on the grid will affect or modulate the entire electron stream, regardless of the ultimate destination of the electrons. Let us refer to Fig. 11 to observe the action that takes place within the tube when it and the associated circuit components are operating normally.

When the heater and plate voltages are first applied to the circuit, grid #1 is at zero potential because it is tied to the cathode through the 50,000 ohm grid leak. As soon as the cathode becomes heated, it starts to emit electrons and the feedback between the oscillator plate and grid causes regeneration which immediately starts the triode circuit to oscillating. When oscillat-

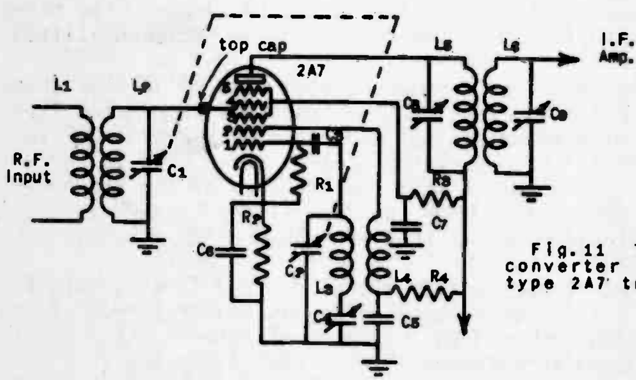


Fig. 11 Typical pentagrid converter circuit using a type 2A7 tube.

ing, grid #1 is alternately driven positive and negative. Upon being driven positive, grid current flows through the grid leak in such a direction as to make grid #1 negative with respect to the cathode. The actual voltage variations of grid #1 are generally sufficient to produce enough grid current through R_1 that a 90 to

[1] These percentages are based on normal operation.

40 volt negative bias is developed. This high negative grid bias point becomes the value about which the grid varies in amplitude alternately in a positive and then in a negative direction under the influence of the plate circuit feedback. During normal operation the maximum instantaneous negative voltage on grid #1 may be as much as from 60 to 80 volts.

The high negative excursions of the oscillator control grid would ordinarily be more than sufficient to cut off the plate current through the tetrode section entirely if it were not for a "secondary source" of electrons available to grid #4. This "second" electron source" is referred to as a "virtual cathode;" the term being selected because it acts exactly as though it were a second electron emitting cathode within the same tube. The reason for the existence of the virtual cathode is that most of the electrons at the cathode pass through grid #1 while it has a positive or slightly negative value and then are accelerated out of grid #1's field by the relatively high positive potential that is placed on grid #3. Grid #4 which is the next grid in the tetrode section has a negative bias on it at all times, so most of those electrons that have been accelerated by grid #3 are slowed down and actually form a cloud of electrons between grid #3 and grid #4. It is this cloud of electrons that constitute the virtual cathode for the tetrode section. Most of the plate current is secured from this virtual cathode during that portion of the cycle when grid #1 is at its maximum negative potential. From this, it is evident that the tetrode section works independent of the triode section, except that the tetrode plate current is modulated by the triode grid voltage. Since grid #3 is at R.F. ground potential, it shields the triode section from the tetrode section and prevents interaction. Grids #3 and #5 are connected together inside the tube so that tetrode control grid #4 is shielded from the plate by the other section of the screen grid; that is, grid #5.

From this discussion, it is evident that the plate current flowing from cathode to plate in a pentagrid converter tube is influenced by both the oscillator voltage and the incoming signal voltage and that the mixing of these two signals occurs directly in the electron stream. The plate current variations produced will then have a component equal to the difference or beat frequency. This component being modulated in direct accordance with the A.F. voltages modulated on the incoming signal. The plate circuit is then tuned to this beat frequency and, thus, the modulated I.F. voltage is secured through the process of frequency conversion.

The performance of a pentagrid converter is such that only one tube is necessary for converting the frequency of the desired signal from its original value into the I.F. frequency. To express the degree of merit with which a pentagrid converter performs this job, the "conversion transconductance" is used. The conversion transconductance (Sc) is a characteristic associated with the mixer-first detector function of a pentagrid converter tube and may be defined as the ratio of the intermediate frequency current in the primary of the I.F. transformer to the applied control grid radio frequency voltage producing it.

When the performance of a pentagrid converter is being determined, conversion transconductance is used in the same way as transconductance is used with an ordinary amplifier tube. For example, when a 1A6 tube is operated under typical conditions with 180 volts on the plate, the conversion conductance is 300 micromhos. A type 1C6 pentagrid converter, when operated under the same conditions, is approximately 325 micromhos. Due to its higher conversion conductance, the 1C6 performs the process of frequency conversion to a higher degree of efficiency than the type 1A6. The applications are slightly different; however, because the filament current of the 1C6 is twice as great as that of the 1A6.

In a complete table of tube characteristics (Lesson 25), several other pentagrid converter tubes will be found, each varying slightly from the other in filament voltage, filament current or circuit application. A pentagrid converter operates satisfactorily as a frequency converting device at medium radio frequencies, but when it is operated at frequencies higher than 15 or 20 megacycles, the conversion conductance decreases rapidly. This effect increases with frequency because of (1) the increasing ratio of incoming signal frequency to intermediate frequency, and (2) the increasing value of L to C as the receiver is tuned toward the high frequency end of the band. Even when a pentagrid converter tube is used in conjunction with a separate oscillator and the separate oscillator signal applied to grid #1, the undesirable effects at higher frequencies are still produced.

A second disadvantage of operating pentagrid converter tubes at high radio frequencies is the shift in oscillator frequency which occurs when the signal grid bias (grid #4) is varied. This frequency shift is due to a slight transconductance existing between the signal grid and the oscillator anode; that is, grids #4 and #2. The use of a separate oscillator tube coupled to the normal oscillator grid will eliminate this undesirable characteristic.

Both of these high frequency effects mentioned may be greatly minimized, with a consequent increase in gain, by replacing the pentagrid converter with an R.F. pentode amplifier whose suppressor is connected to an external oscillator. However, the plate impedance of the pentode is so low under these conditions and the oscillator voltage requirements are so high as to prohibit the use of this system in many receivers. These disadvantages may be overcome by increasing the amplifying action of the suppressor; a screen interposed between suppressor and plate will maintain the plate resistance at a satisfactory value. Another refinement may be made by inserting a grounded suppressor between the plate and the oscillator screen. A tube of this type designed especially to overcome the inherent disadvantages of the pentagrid converter is known as the type 6L7.

7. **THE 6L7 MIXER TUBE.** Fig. 12 shows the relative positions of the elements in the 6L7. As may be seen, the tube consists of a heater, a cathode, five concentric grids, and a plate. Grid #1, which is nearest the cathode, is one of the two control grids. It is of the remote cutoff type and, because the R.F. signal to be converted is applied between it and cathode (as shown in Fig. 13),

it may be referred to as the "signal grid." The remote cutoff characteristic of this grid minimizes R.F. distortion and cross-modulation effects when its bias is under the control of the AVC[1] system. Grid #2 in the type 6L7 has the same purpose as the screen in a conventional tetrode; that is, it accelerates the electrons

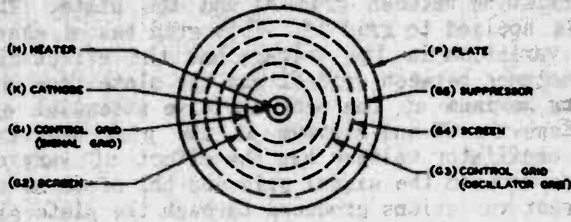


Fig.12 Illustrating the relative positions of the electrodes in the type 6L7 tube. (Courtesy Radio Engineering)

toward the plate and reduces the capacitance between grids #1 and #3 to a small value. Grid #3, interposed between grid #2 and #4, is the second control grid of the tube and has a sharp cutoff characteristic. This grid may be referred to as the "oscillator grid," because the output voltage of an external oscillator is connected to it. Grid #4 is another screen. It increases the plate resistance of the tube, reduces the capacity between grid #3 and plate and, in general, functions similarly to the screen in a conventional

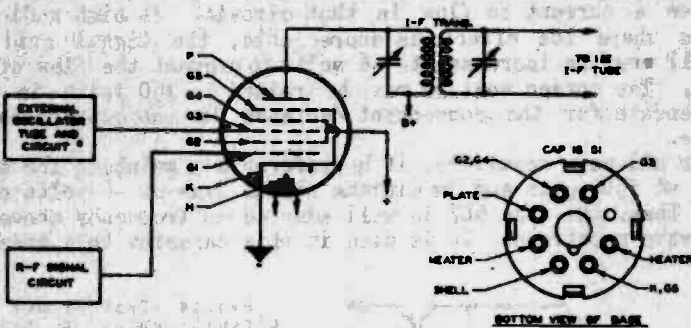


Fig.13 Connections to the 6L7 when used as a mixer. (Courtesy Radio Engineering)

tetrode. Grids #2 and #4 are connected together internally. Grid #5 is a suppressor. It is connected to the cathode internally and serves to limit the effects of secondary emission from the plate. Because of the suppressor, it is possible to operate the tube at a relatively high screen voltage.

As shown in Fig. 13, the incoming R.F. signal voltage is applied to grid #1 and the voltage from an external oscillator circuit is applied to grid #3. It should be understood that the 6L7

[1] A discussion on automatic volume control (AVC) will be given later in this lesson.

is strictly a mixer tube, designed specifically to mix the incoming and oscillator signal voltages and not to actually generate the oscillator voltage, as was done with a pentagrid converter. When an R.F. voltage is applied to grid #1, the electron stream to the plate is modulated in accordance by virtue of the transconductance existing between grid #1 and the plate. The oscillator voltage is applied to grid #3. This grid has a sharp I_p cutoff; hence, a variation in its voltage has the effect of varying the transconductance between grid #1 and the plate from zero to a maximum, being maximum at the peak positive potential of the oscillator voltage on G3 and minimum at the peak negative potential. Thus, the oscillator voltage has the effect of varying the transconductance between the signal grid and the plate so the resultant plate current variations produced through the plate circuit have a component equal to the difference frequency between the oscillator and incoming signal voltages. This is the beat or intermediate frequency and a modulated I.F. oscillating current is set up in the tuned plate circuit.

From a table of characteristics, it is seen that the manufacturer provides for a plate voltages of 250 volts and two screen voltages, 100 and 150 volts. Although, the space charge (virtual cathode) phenomena discussed previously in conjunction with the pentagrid converter is very small in the 6L7 mixer tube, it has been found that electrons repelled by the oscillator grid during its negative voltage excursions enter the vicinity of the signal grid and cause a current to flow in that circuit. At high radio frequencies where the effect is appreciable, the signal grid bias (grid #1) must be increased to -6 volts to prevent the flow of this current. The screen voltage may be raised to 150 volts in order to compensate for the consequent decrease in the conversion conductance.

For all-wave receivers, it is preferable to maintain the screen voltage at 150 volts and the minimum signal bias at -6 volts on all bands. Thus, the type 6L7 is well adapted for frequency conversion in all-wave receivers. It is used in this capacity to a great ex-

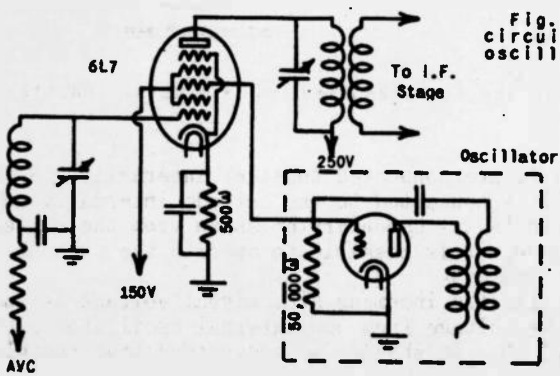


Fig.14 Typical 6L7 mixer circuit using a separate oscillator.

tent in modern sets. It should be understood that the conventional pentagrid converter works very satisfactorily at low and medium radio frequencies, but for the higher short-wave frequencies, a 6L7 mixer circuit is preferable. A typical 6L7 circuit is illustrated in Fig. 14.

8. AUTOMATIC VOLUME CONTROL. Automatic volume control is generally called AVC. At the present time, AVC is included in the design of nearly all commercial radio receivers. Automatic volume control means that the sensitivity (overall amplification) of the receiving set is automatically varied inversely with the strength of the incoming signal. This means that when a strong signal is tuned in, the sensitivity of the amplifying tubes in the receiver is reduced. And, vice versa, when a weak signal is tuned in, the sensitivity of the amplifying stages is increased. The merit of an AVC system lies in its ability to maintain a constant volume level from the loudspeaker, irrespective of the strength of the incoming signal. Of course, the manual volume control on the receiver is set to a position corresponding to the desired volume level; then, with a perfect AVC system, all signals tuned in would be reproduced from the loudspeaker at exactly the same level.

It is the intention of all AVC systems to satisfy the aforestated requirements as closely as possible. There is no such thing as a perfect AVC system; that is, one wherein all incoming signals are reproduced from the speaker at exactly the same level; but, there are several which approach this ideal condition very closely. In our discussion of automatic volume control circuits, we shall first start with those of the simpler type; then, after pointing out their disadvantages, proceed to learn the construction and theoretical operation of the ensuing circuits designed primarily to overcome the inherent disadvantages of the fundamental circuits.

Since an AVC system is a means of varying the sensitivity of the amplifying stages, it would be more correctly called an "automatic sensitivity control," rather than "automatic volume control," because its primary function lies in the variation of the receiver's sensitivity. In addition to automatically producing a fairly constant volume level from the loudspeaker when tuned from one station to another, three other distinct advantages are attained. One is the compensation for "fading" when receiving signals from distant stations. The second is that "blasting" from the loudspeaker, experienced when tuning into a local station with the volume control advanced, is eliminated. The third advantage is that with a satisfactory AVC system, it is impossible to overload the detector stage in a receiver. Detector overload always results in considerable distortion of the A.F. signal output.

Before proceeding, it must be understood that the automatic volume control action takes place entirely in the R.F. or I.F. sections of the receiver; that is, before the incoming signal is demodulated. The automatic controlling action does not affect the audio frequency amplifiers in any way whatsoever.

The action of any automatic volume control circuit depends primarily upon the variable-mu feature possessed by tubes having the super-control grid construction. Super-control tubes and their operation were discussed in Lesson 25, so it is not necessary to repeat that information. As a brief review, however, it is well to recall that in tubes of this kind, the amplification factor and transconductance are steadily decreased as the negative grid bias is increased. In most tubes, it requires a negative grid bias of approximately -40 volts to cutoff the plate current entirely; that is, to reduce the Mu and S_m to zero. Full amplification is realized from a super-control tube when the bias voltage is about -3.

In an AVC system, the circuits are so arranged that the negative grid bias applied to the grids of the super-control amplifier tubes becomes a direct function of the strength of the incoming signal. This means that a strong incoming signal produces a high negative grid bias on these tubes and, consequently, reduces their amplification. On the other hand, a weak incoming signal produces a low negative grid bias so the amplification factor and transconductance increase. In this manner, the volume level from the loudspeaker is kept fairly constant; even though the different input radio signals vary widely in strength.

Obviously, in order to vary the sensitivity of the amplifying stages, it is first necessary to automatically develop a DC voltage that is directly proportional to the average strength of the incoming signal. This DC voltage will then be used to supply the supplementary grid bias on the AVC controlled tubes. In nearly all modern superheterodynes, this AVC control voltage is developed directly in the second detector circuit. The diode detector lends itself to this application in a very convenient and efficient manner.

Fig. 15 shows a simple diode detector circuit wherein it is possible to secure an AVC controlling voltage across the resistance R that varies in direct accordance with the average strength of

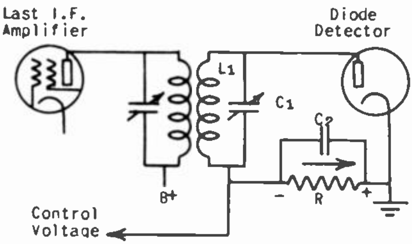


Fig. 15 Simple diode detector circuit.

the incoming signal. A strong I.F. signal delivered from the last I.F. amplifier will develop a high DC voltage across R, and a weak signal from the last I.F. amplifier will produce a low DC voltage developed across R. Let us investigate the action of this circuit.

A signal from the I.F. amplifier produces an oscillating current in the circuit L_1C_1; alternately making the top and bottom of this tuned circuit positive and negative. When the direction of the voltage developed across L_1C_1 is such as to make the plate of the tube positive, then current will flow from the cathode to the plate through L_1 and through resistor R in the direction of the arrow. When a voltage is developed across L_1C_1 in the opposite direction, the plate of the tube is made negative and no current flows. Thus, the diode detector circuit serves to rectify the alternating voltages across L_1C_1 into a pulsating direct current through the resistor R.

First, assuming that the incoming signal is unmodulated, the current established in the diode circuit will consist of two components, a DC component and an I.F. component. The condenser C_2 has sufficient capacity to bypass the I.F. component, but since it will not permit the DC component to pass, the DC must take the path through resistance R. This resistor is generally quite high in value (several hundred thousand ohms), so even though the DC component of the rectified diode current is low, an appreciable voltage will be developed across R; with the left side negative and the right side positive.

A diode is practically a linear rectifier; that is, the rectified current which flows through the diode circuit is at all times closely proportional to the strength of the R.F. voltage developed at the plate. The graph shown in Fig. 16 illustrates how the DC voltage developed across R will vary with the strength of

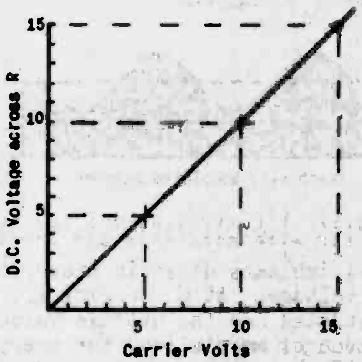


Fig.16 Graph to illustrate how the DC component of the voltage developed across R varies in direct accordance with the strength of the incoming carrier voltage.

the incoming signal. Notice that at every instant, the DC voltage across R is directly proportional to the average strength of the carrier voltage. If the carrier voltage is doubled in value, the DC voltage across R also doubles and vice-versa. The DC voltage across R may be used to supply the negative grid bias on the supercontrol I.F. amplifier tubes. If so, it follows that a strong signal through the I.F. amplifier results in a high carrier voltage being applied to the diode detector circuit, which, in turn, develops a high control voltage across the diode resistor R. This high control voltage increases the negative grid bias on the I.F. amplifier tubes, which reduces their amplification, thus automatically diminishing the volume of the receiver.

Then, in contrast with this amplification reduction, when the incoming signal is weak, the I.F. voltages delivered to the diode detector circuit are low; resulting in a low rectified current through resistor R and the development of a low control voltage. This lower control voltage is applied to the grids of the supercontrol I.F. amplifier tubes and the amplification of each is increased. Thus, additional amplification is afforded the weaker signals and a fairly constant I.F. signal voltage input to the diode detector circuit is maintained. The detector A.F. output and loudspeaker volume also remain practically the same.

So far, we have considered the operation of the diode detector circuit only when the carrier wave is unmodulated. Now let us see what happens when audio modulation is impressed on the I.F. signal.

In Fig. 17, the difference between the average value of an unmodulated and modulated carrier is illustrated. At A, the unmodulated carrier is shown; then at B, the average value of A is illustrated. It is seen that the average of the unmodulated wave is a pure DC; so a pure DC control voltage will be developed across the diode resistor R in Fig. 15. The value of this DC voltage is

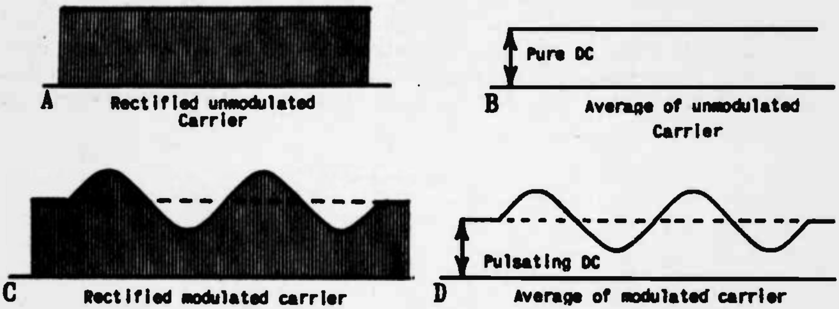


Fig.17 Illustrating the voltages produced across the diode load resistor with modulated and unmodulated carrier waves.

at all instants directly proportional to the strength of the carrier voltage. At C in Fig. 17, a rectified modulated carrier is illustrated and the average value shown at D. Obviously, with the presence of modulation, the average value of the carrier is not a pure DC, but rather varies in amplitude in accordance with the modulation. The amplitude changes represent the audio frequency or modulation component. This average of A.F. voltage is produced across the resistor R as the rectified diode current passes through it. The bypass condenser C_9 (Fig. 15) provides an easy path for the I.F. variations, thus preventing them from passing through the diode resistor. The pulsating DC (audio frequency) voltage developed across R rises and falls above and below the pure DC average value indicated by the dotted line at D in Fig. 17. Obviously, the pulsating DC voltage is not satisfactory for application to the grids of the controlled tubes in the R.F. or I.F. amplifier, because the sensitivity of these tubes would then be varied in accordance with the modulation and severe audio distortion would result. With proper filtering, it is possible to resolve the pulsating DC shown at D in Fig. 17 into its AC and pure DC components. This is illustrated in Fig. 18.

A pulsating DC voltage such as that likely to be developed across the resistor in the diode load circuit, is illustrated at A in Fig. 18. At B in Fig. 18, the AC component is shown, which represents the modulation originally impressed on the carrier and at C the pure DC component of the pulsating current is shown. To effectively resolve the pulsating DC into its two components, a

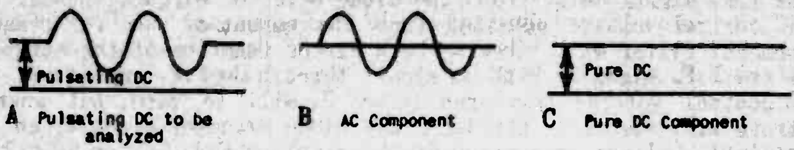


Fig.18 Analysis of a pulsating DC into its AC and pure DC components.

filter circuit must be used. Such practice is always customary in AVC circuits so as to obtain a pure DC voltage for controlling the sensitivity of the amplifying stages. The AC component is the audio modulation, so it is fed into the audio frequency amplifier.

A typical filter circuit, capable of separating the AC and DC components of the voltage produced across the diode load resistor, is shown in Fig. 19. The I.F. component of the rectified modulated current passes through C_1 and the average component passes through

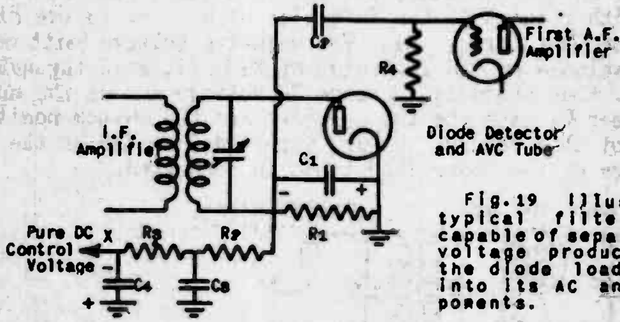


Fig.19 Illustrating a typical filter circuit capable of separating the voltage produced across the diode load resistor into its AC and DC components.

R_1 to develop a pulsating DC voltage similar to that shown at A in Fig. 18. Since the AC component represents the audio frequency, it must pass through the condenser C_2 to the grid of the first A.F. amplifier. The condenser C_2 at the same time, blocks the DC component from entering the A.F. amplifier circuit. The high resistance R_2 is called the "first filter resistance" and serves to prevent the passage of the AC component into the AVC circuit. The reactance of C_2 is made much less than the resistance of R_2, thus assisting to compel the A.F. component to take the path through C_2 to the grid of the A.F. amplifier. The actual division of the A.F. component depends on the impedance of the two respective paths, one through R_2 and C_3 and the other through C_2 and R_4. If R_2 is made sufficiently high in value; nearly all of the A.F. signal will pass through C_2 to the grid; if not, a considerable portion of the A.F. may pass into the AVC circuit. To preclude the possibility of A.F. in the AVC circuit, an additional filter section, R_3C_4 is sometimes provided. It is then definitely certain that a pure DC voltage will be secured from the output of the dual-section filter for varying the sensitivity of the R.F. and I.F. amplifying stages.

The average value (pure DC) of the pulsating voltages developed across R_1 will always be in direct accordance with the strength of the I.F. signal delivered to the diode detector circuit; hence, the AVC control voltage obtained from the output of the resistance-capacity filter will likewise be a direct function of the strength of the I.F. signal. With no signal through the I.F. amplifier, the DC control voltage developed across C_4 will be zero, but when a strong I.F. signal is applied to the diode detector circuit, an appreciable voltage, somewhere in the neighborhood of 40 or 50 volts, will be developed across C_4. This is the control voltage available for varying the sensitivity of the amplifying stages.

It should be observed that the polarity of the voltage developed across C_4 is such that the point X is negative with respect to ground. This, of course, is due to the direction of the current flow through R_1, wherein it develops a voltage with the left side negative and the right side positive. Merely because the right side is connected to the cathode and grounded, do not conclude that this side of the resistance must be at a negative potential. True, chassis ground is negative with respect to the positive side of the plate power supply voltage in the receiver, but the fact still remains that it is positive with respect to the left side of R_1, due to the direction of current flow through R_1. The negative voltage (with respect to ground) developed on the left side of R_1 is filtered through R_2, C_3, C_4 and R_3, thus producing a pure DC voltage across the output filter condenser C_4 with the top negative and the bottom positive. The polarity of this voltage is very important insofar as the sensitivity change on the controlled tubes is concerned.

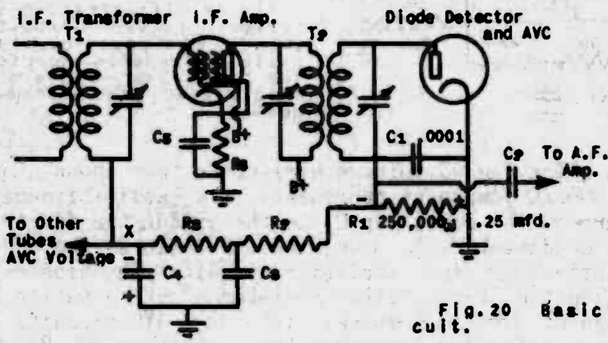


Fig.20 Basic AVC circuit.

Now to understand how a complete AVC system operates, let us refer to Fig. 20. In this circuit, several of the miscellaneous items generally included in commercial receivers have been excluded for simplicity of explanation. In later circuits, we shall add these additional parts.

The last I.F. amplifier delivers the modulated I.F. signal into the diode detector circuit through transformer T_2. Rectification occurs in the diode, so a rectified modulated I.F. current passes through the diode circuit. The condenser C_1 is rather small in capacity, having a sufficiently low reactance to bypass the I.F. component, but, at the same time, its reactance to the A.F. component of the signal is quite high. Pulsating DC voltages are then developed across the 250,000 diode load resistance R_1. The AC and DC components of the pulsating voltage across R_1 are then separated by the respective impedances offered to each; the AC component finding the least opposition through the .25 mfd. condenser C_2 into the audio amplifier and the DC component taking the path through the resistance-capacity filter circuit. This division of components occurs because the DC is blocked from the A.F. amplifier by the infinite reactance of C_2 and the AC component is prevented from passing through the filter by the high opposition offered by R_2.

The DC voltage secured across point X and ground is called the AVC voltage and may be applied to one or several amplifier grid circuits. The AVC voltage is negative with respect to ground and is directly in series with the normal grid bias developed across the cathode resistor in the amplifier circuit. Referring to Fig. 20, the plate current through R_6 develops the normal negative bias voltage for the I.F. amplifying stage. Tracing from the control grid of the tube to ground, it is seen that resistors R_3, R_2 and R_1 are all in series. Regardless of how many ohms these resistors may have, they will not affect the normal grid bias voltage developed across R_6 unless current is passing through one or all of them. (With no current through a resistor of any size, the voltage drop is zero.) The only one of these three resistors through which a current will flow is R_1; this occurring only when an I.F. signal voltage is applied to the diode detector circuit.

Without an incoming signal, the bias voltage developed across R_6 is applied directly through R_1, R_2, and R_3 to the grid of the I.F. amplifier. For example, if a normal negative bias of 3 volts is developed by the flow of plate current through the cathode resistor R_6 (with no incoming signal), this will be the negative voltage on that grid. Assuming the tube to be a super-control amplifier, its sensitivity will be quite high because of the low grid bias. Upon reception of a radio signal, a modulated I.F. voltage is delivered into the detector circuit and a rectified diode current flows through R_1. This current flow develops a voltage across R_1 with the grounded end positive and the grid side negative. The voltage developed across R_1 then adds to the normal negative bias supplied by R_6 and the total negative grid bias on the amplifier is equal to the sum of the AVC voltage and the original bias voltage.

A strong I.F. signal (produced by a strong antenna voltage) applied to the diode detector circuit will cause an appreciable DC voltage to be developed across R_1 (filtered into a DC through R_2 and R_3), and hence the grid of the I.F. amplifying tube is driven to a high negative potential with respect to its cathode. The amplification factor and transconductance of the tube are decreased to a low value, so the input to the diode detector is correspondingly decreased. The audio output of the detector is thus prevented from increasing in proportion to the strength of the incoming radio signal. This automatic action prevents blasting from the loudspeaker when tuning to a strong local station and, too, there is no possibility of overloading the diode detector circuit.

Now, assume that the manual volume control on the receiver remains fixed and the tuning dial is adjusted to a weaker station. The I.F. signal delivered into the diode detector circuit will then be low in amplitude. The DC and AC components of the rectified voltages developed across R_1 are also lower in amplitude and immediately the negative grid bias on the I.F. amplifier (and other stages) is decreased. The decreased bias simultaneously effects an increased amplification factor and transconductance. As these characteristics increase, a stronger I.F. signal is delivered to the diode detector input. In this manner, the gain of the amplifier automatically increases and the resultant A.F. output from the detector is approximately the same as when the stronger signal was being received.

This outlines the basic purpose and operation of an AVC circuit so let us now proceed to learn of the necessity for the additional items generally included in the commercial design of these circuits.

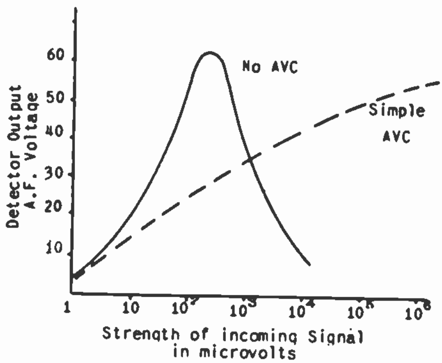
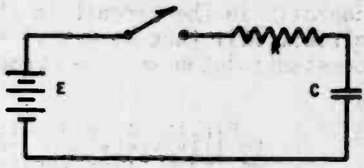


Fig. 21 Illustrating how the addition of a simple AVC circuit alters the detector output characteristics of a receiver.

An AVC circuit, such as that just discussed, is not perfect by any means in its ability to automatically maintain the detector output voltage at a constant level when the strength of the antenna signal voltage varies. Fig. 21 illustrates the results which might be expected from a simple AVC circuit and also the comparative operation of a receiver equipped the AVC action and one that is not so designed. Considering the operation of the receiver which does not incorporate AVC, it is seen that the detector output voltage rises rapidly with increasing signal strength and, at approximately 100 microvolts antenna input, the detector is overloaded. Stronger input voltages produce a decreased A.F. output from the detector with considerable audio distortion. With the AVC action, the detector output voltage rises gradually with the strength of the incoming signal. If the AVC circuit were perfect in its operation, the detector output voltage would remain absolutely constant regardless of the strength of the incoming signal. This condition cannot be satisfied with a simple AVC circuit such as just discussed, for obvious reasons. To produce a change in sensitivity of the AVC controlled tube, it is necessary to change the input to the diode detector circuit. To reduce the sensitivity of the I.F. amplifier (increase the grid bias), a slightly stronger I.F. signal must be fed into the diode detector circuit; therefore, a slightly greater A.F. output voltage will always be secured. Regardless of the gradual rise in detector output, a simple AVC circuit is beneficial in that detector "overload" is prevented and "blasting," commonly experienced when tuning through a strong local station, is eliminated. One disadvantage apparent from Fig. 21 is that the overall sensitivity of the receiver is decreased at weak signal inputs due to the AVC action. To overcome this, modern practice is to incorporate a delayed AVC system or an amplified-delayed AVC circuit. Such circuits will be discussed in following lessons.

9. **TIME CONSTANT.** One of the major factors that must be taken into consideration for the proper design of a satisfactory AVC system is the "time constant" resulting from the size of resistors and condensers used in the filtering arrangement. To explain what is meant by the "time constant" of a resistance-capacitive circuit, let us refer to Fig. 22. Here, a voltage source E is applied across condenser C when the switch is closed and the resistor R is in series

Fig. 22 Circuit to illustrate the "time constant" of a resistance - capacity circuit.



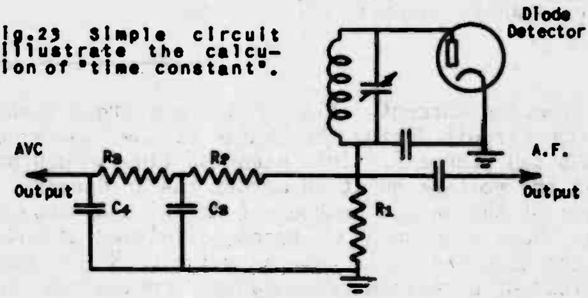
with the charging current. All of the electrons displaced around through the circuit during the charge of the condenser must pass through the resistance R. This electron flow, of course, continues only until the voltage built up across the condenser C is equal to the voltage of the supply source. A definite amount of time is required for these electrons to become displaced around through the circuit, the time increasing as the value of R is increased. *The time constant of a resistance-condenser combination is the actual time in seconds required for a condenser in series with a resistor to reach 63% of its final charge after the switch is closed.* This percentage has been derived from a fundamental electrical equation and holds true for any combination of resistance and capacity. The time constant in seconds is equal to the product of the resistance expressed in megohms and the capacity expressed in microfarads. As a formula, this is:

$$T \text{ (time constant)} = R \text{ (in megohms)} \times C \text{ (in mfds.)}$$

For example, if a 1 mfd. condenser is connected in series with a 1 megohm resistor and a battery voltage of 100 volts applied, it will require one second for the voltage across the condenser to obtain a value of 63 volts. If the original battery voltage employed was 50 volts, then one second would elapse before the condenser became charged to 31½ volts. (31½ is 63% of 50.) In all cases, the actual value of the applied voltage is immaterial and the time constant is the time in seconds required for the voltage across the condenser to attain a value equal to 63% of whatever voltage might be applied. Reducing the size of the resistor, or reducing the size of the condenser, will always result in less time being required to charge the condenser through the resistor and it is commonly said that the "time constant" is decreased. High values of capacity and resistance require a longer time for the condenser to become charged and it is generally said that the "time constant" of the combination is high.

Now let us see what effect time constant has on the operation of the basic AVC circuit illustrated in Fig. 20. First, we shall assume that the resistors and condensers in the AVC circuit have a high value. This includes R_1, R_2, R_3, C_3 and C_4. To calculate the time constant of this circuit, we must first add all the resistors together to obtain the total resistance of the circuit; then add the condensers to find the total capacity of the circuit. The AVC resistors and condensers of Fig. 20 have been redrawn into a simplified circuit, shown in Fig. 23. If we first assume that the value of each of the three resistors is 2 megohms, the total circuit resistance is 6 megohms. If C_3 and C_4 are each .25 mfd., the total capacity in the circuit is .5 mfds. The time constant of the AVC circuit will then be $6 \times .5 = 3$ seconds. This is a very high time constant; let us see how it would affect the operation of a receiver.

Fig.23 Simple circuit to illustrate the calculation of "time constant".



With large values of R and C, especially R_2 and C_3, there is little possibility that the pulsating DC developed across R_1 will reach the output of the AVC filter (on the left side of Fig. 23) and, in turn, be applied to the grids of the controlled tubes. This is desirable, but is offset with the disadvantage that too much delay occurs before the controlled tubes receive their AVC controlling voltage resulting from a change in the diode input. This means that when a receiver is tuned from a strong to a weak station, the decreased I.F. input to the diode detector circuit will develop a lower voltage across R_1, but it will be 3 seconds later before this same voltage appears on the grids of the controlled tubes and increases the sensitivity of the receiver. The weak station will probably be passed on the dial without the operator becoming aware of its existence. When an AVC circuit is this "sluggish," tuning is extremely difficult.

Then, too, when a radio set is tuned to a weak station and it is desired to receive a strong local station, upon changing the dial a "blast" will occur from the loudspeaker before the AVC circuit has had time to operate and increase the negative bias voltage on the grids of the amplifier tubes. So, in all respects (excluding the production of a pure DC AVC voltage), extremely high values for the resistors and condensers in an AVC filter circuit are impractical because the time constant is too high (or long).

Now, let us see what the effect would be if R_1, R_2, R_3, C_3 and C_4 were reduced to low values. Obviously, the opposite effects will occur, but first let us calculate the time constant. Let us assume that each resistor has a value of 50,000 ohms and each condenser has a value of .05 mfds. The total resistance in the circuit is then 50,000 × 3, or 150,000 ohms. Expressed in megohms, that is .15 megohm. To find the total capacity in the circuit, .05 + .05 = .1 mfd. To find the time constant:

$$\text{T.C. (in seconds)} = .15 \times .1 = .015 \text{ second}$$

This is an actual time of slightly longer than $\frac{1}{100}$ second. With this value of time constant, the AVC control voltage has no difficulty in responding rapidly to the varying signal strengths, such as those produced by fading and changing the dial position. The efficiency of the DC filtering, however, will be materially reduced, because for best filtering the resistance and capacity values should be high. With a time constant of only .015 second, the audio pulsations produced across the diode resistance R_1 are very apt to appear at the output of the AVC filter and thus be applied to the grids of the controlled tubes. This causes considerable audio distortion, especially when the incoming signal is modulated with low audio frequencies between 30 and 100 cycles.

Obviously, there is an optimum value of time constant between these two extreme examples that will provide adequate filtering and, yet, function rapidly enough for the AVC voltage to follow the variations of fading and tuning operations. The value used in most commercial receivers indicates that optimum conditions are reached when the time constant is approximately .1 of a second. A time constant of .1 second will result when the total resistance in the AVC circuit is 1 megohm and the total capacity is .1 mfd. Of course, other values may be used, as long as the product is equal to .1!

10. GRID FILTERS. Fig. 24 shows the basic outline of an AVC circuit as applied to three stages of a superheterodyne receiver. In this circuit, the R.F. amplifier, first detector and I.F. amplifier are all controlled by the AVC voltage. It will be noticed that in the second detector circuit, the diode load resistance R_1 is a potentiometer; this permits a control over the amplitude of the audio voltages fed into the A.F. amplifier without interfering with the operation of the AVC circuit. R is a grid leak resistance in the grid circuit of the first A.F. amplifying stage. R_1 is the

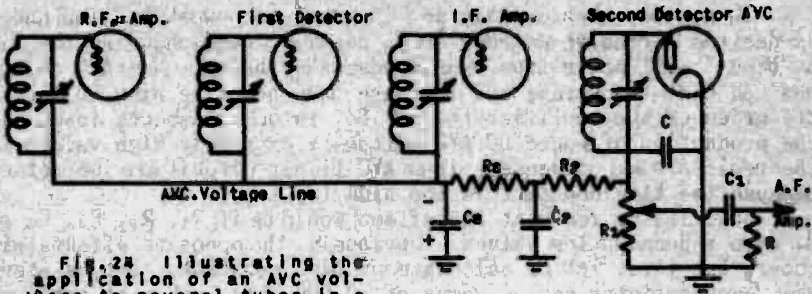


Fig.24 Illustrating the application of an AVC voltage to several tubes in a receiver.

diode load resistor and the volume control of the receiver. Condenser C by-passes the I.F. variations of the rectified modulated diode current, but the audio and DC voltages are developed across R_1. The DC voltage is filtered through the two-section filter R_7C_7 and R_8C_8, then applied to the grid circuit of each of the three controlled tubes. A receiver constructed in this manner would operate satisfactorily from the standpoint of automatic sensitivity variations, but the design is not entirely practical, because all three of the grid circuits are returned to exactly the same point. A common return makes it possible for excessive regeneration to occur between the three stages, so the circuit is apt to become very unstable, possibly breaking into oscillation. To prevent this circuit instability in commercial receivers, it is common practice to remove the second section of the AVC filter (R_8C_8), then provide an individual filter in the grid circuit of each of the controlled tubes. The revised AVC circuit then appears as shown in Fig. 25.

Fig. 25 is essentially the same as Fig. 24 except that the grid circuit of the R.F. amplifier, first detector, and I.F. amplifier is each provided with a separate filter. All these resis-

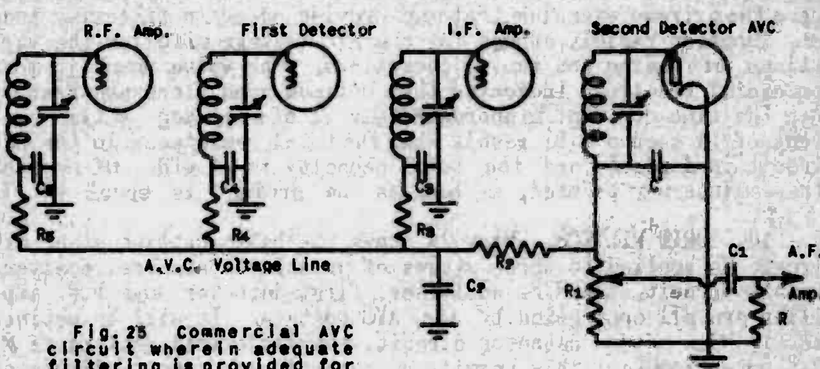


Fig.25 Commercial AVC circuit wherein adequate filtering is provided for each amplifying stage.

tors and condensers are in the AVC circuit, so they cannot all have high individual values, otherwise, the time constant will be too high for satisfactory operation. The grid condensers C_3, C_4 and C_5 must be large enough so as not to have an appreciable effect on the total capacity in the oscillating circuits. As long as these condensers are large enough, compared to the size of the tuning condensers, their presence in the tuned circuits may be disregarded, because the total capacity is reduced only a negligible amount. These condensers are used in the grid filtering circuits so as to permit application of the AVC voltage to the control grids and, at the same time, allow the rotor plates of the tuning condensers to be grounded. The ganged tuning condenser assembly is generally bolted directly to the chassis (ground) so as to prevent hand capacity while tuning.

In Fig. 25, each of the grid circuits is isolated from the other grid circuits by a filter or series "isolating" resistor. These are R_3, R_4 and R_5. When calculating the time constant in the AVC circuit, R_1, R_2, R_3, R_4 and R_5 must all be taken into consideration. Also, C_2, C_3, C_4 and C_5 must be added to find the total capacity. Since there is no current passing through the isolating resistors, the AVC voltage is not affected in any way. The only part of the entire AVC circuit through which a current flows is the diode load resistance R_1.

11. DUO-DIODE TRIODES. A duo-diode triode tube is a dual purpose tube having two separate sections enclosed in the same glass envelope. One section of the tube is a duo-diode rectifier and the other section is a triode amplifier. A common cathode is used as an electron emitter for both sections. Typical tubes of this type are 75, 85, 55, 2A6 and 6Q7. The 55 and 2A6 have low-mu triode sections and the 75, 85 and 6Q7 have high-mu triode amplifiers.

Since automatic volume control is employed in nearly all of the modern superheterodyne receivers, diode detection has come into common use. The outstanding disadvantage of a diode detector is that no amplification is obtained with the demodulation; hence, the A.F. output is low in amplitude. The dual-purpose, duo-diode triode corrects this defect; diode detection is obtained in the diode section and the triode section serves as the first A.F. amplifier. Thus, the total A.F. voltage output from the single tube is comparable to that obtained from the output of a grid leak or grid bias power detector. At the same time, the advantages of diode detection and the ease of obtaining an AVC voltage are secured.

Fig. 26 shows a duo-diode triode tube connected in a typical circuit. Here the two diode plates D_1 and D_2 are tied together and perform as a half-wave rectifier in demodulating the incoming I.F. signal. The diode load resistance is R_3 and condenser C_3 is used to by-pass the I.F. component of the rectified diode current. Pulsating voltages, following the amplitude variations of the I.F. signal, are developed across R_3. The AC component of the pulsating voltages represents the audio frequency and is coupled through C_2 to the grid of the triode section of the same tube, which serves as the first A.F. amplifier. The DC component of the pulsating voltages developed across R_3 is filtered through R_4C_4, then applied to the AVC controlled tubes. The triode section secures a negative grid bias from the voltage drop produced by the flow of plate current through the cathode resistance R_1. The voltage developed across this resistance is applied through the grid leak R_2 directly to the control grid.

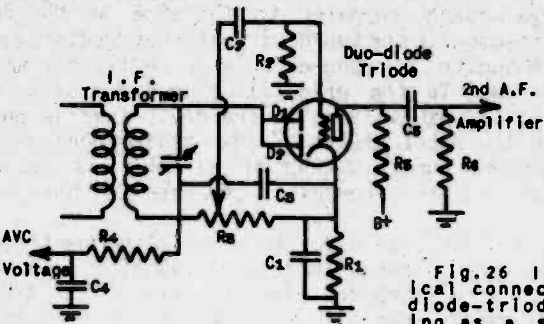


Fig.26 Illustrating typical connections of a duo-diode-triode tube performing as a second detector, AVC tube, and first AF amplifier.

The triode section operates independently of the diode section; hence, the A.F. voltages applied to the control grid cause plate current variations through R_5, thus developing the A.F. output voltage, which in turn may be applied to a second A.F. amplifier or fed directly to the power amplifier stage. The diode load resistance R_3 is a potentiometer, thus making it possible to vary the amplitude of the audio voltage applied to the control grid of the triode section. When the movable arm of the potentiometer is to the extreme right, no audio voltages are applied through C_2 to the grid, so the volume from the receiver is minimum (zero). When the movable arm of the potentiometer is on the extreme left, full A.F. voltage across R_3 is applied to the grid of the triode so the volume from the receiver is maximum.

In some duo-diode triode circuits, the two diode plates are not tied together to form a half-wave rectifier as shown in Fig. 26, but, rather, are connected in such a manner as to obtain full-wave rectification of the I.F. signal. Such practice is rather uncommon in commercial radio receivers at the present time. Delayed AVC circuits will be discussed in Lesson 9 of Unit 2. Therein it will be found that the diode plates may be used individually; one to develop a delayed-AVC voltage and the other to produce rectification of the I.F. signal. Such an arrangement has certain advantages which will be pointed out during the study of that lesson.

Typical duo-diode triode circuits will be found in the RCA Tube Manual in connection with the characteristics of the type 85 tube.

Duo-diode pentode tubes are frequently used for the same purpose as the duo-diode triodes; that is, to serve as a composite second detector, AVC tube and first A.F. amplifier. The essential difference between the duo-diode triode and the duo-diode pentode is that the amplifying section is a pentode, rather than a triode. The duo-diode section is essentially the same. Typical duo-diode pentodes are the 6B7, 2B7 and 1F6.

In some modern receivers, the pentode section of a duo-diode pentode serves as the last I.F. amplifier; then the duo-diode section performs as the second detector and to develop the AVC voltage. A separate tube must be used for the first A.F. amplifier.

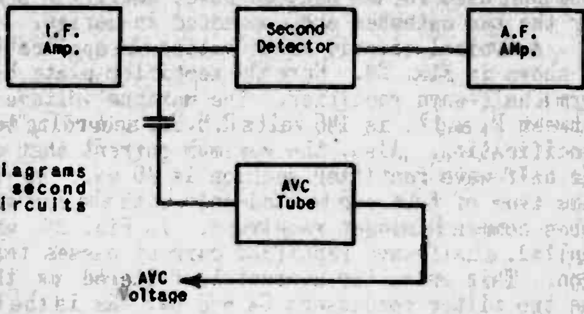


Fig. 27 Block diagrams showing how the second detector and AVC circuits are separated.

In several commercial receivers, generation of the AVC voltage is entirely separate from the process of demodulation in the second detector. Fig. 27 shows how this is done in block diagram form. The amplified output of the last I.F. amplifier is delivered into the second detector, where the signal is demodulated and is also fed (through a condenser) into a separate diode circuit which generates the AVC voltage. This has the advantages of greater stability, less possibility for audio distortion, and greater flexibility in circuit design. Frequently when this arrangement is employed, a separate amplifier is used ahead of the AVC diode so as to develop a higher automatic control voltage. A duo-diode pentode lends itself to this application very conveniently, the pentode section serving as the AVC amplifier with the diode section developing the AVC voltage. Typical tubes are the 2B7 and the 6B7.

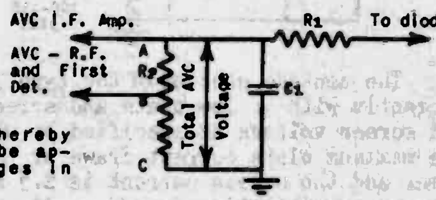


Fig. 28 Voltage divider whereby a different AVC voltage may be applied to the respective stages in a superheterodyne.

In the design of some receivers, it is desirable to apply a different AVC voltage to the I.F. amplifier than that applied to the R.F. and first detector. These deviations from the general rule are a result of other design requirements in the receiver. To show how this may be done, let us refer to Fig. 28. Here the total AVC voltage is developed across R_2, which is connected across the output of the AVC rectifier. The total voltage from A to C is available for application to the grid of the I.F. amplifier; hence, this stage is controlled to the full extent of the AVC voltage. The tap on R_2 at point B allows the application of a lower AVC voltage to the I.F. amplifier and first detector stages.

12. THE TYPE 12A7 TUBE. This tube consists of a half-wave rectifier and a pentode power amplifier, contained within a single bulb. It was commonly used in the first AC-DC operated receivers. The half-wave rectifying section of the tube has a cathode separate from that used for the pentode power amplifier stage, but the heaters for the two cathodes are connected in series.

A typical circuit illustrating the application of the type 12A7 is shown in Fig. 29. Here the rectifier plate P_1 and the cathode K_1 form a half-wave rectifier. The maximum voltage that can be applied between P_1 and K_1 is 135 volts R.M.S., according to the manufacturer's specification. Also, the maximum current that can be drawn through the half-wave rectifier section is 40 ma., so it is obvious that this type of tube can be used only with the low voltage, low current tubes common in midget receivers. In Fig. 29, when 110 volts AC is applied, a half-wave rectified current passes through the diode section. This pulsating current is filtered by the inductance L and the two filter condensers C_3 and C_4. R_3 is the bleeder resistance. The average DC voltage generally secured from this type of rectifier circuit is from 100 to 115 volts.

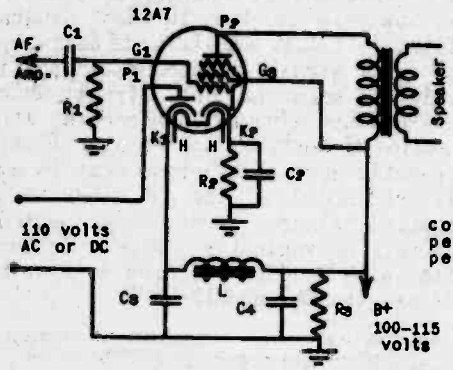


Fig. 29 Illustrating typical connections for a type 12A7 when performing as a rectifier and pentode power amplifier.

The pentode section of the type 12A7 is designed to perform efficiently with a low plate and screen voltage. The maximum plate and screen voltage as specified by the manufacturer is 135 volts. The maximum plate current drawn by the pentode power amplifier is 9 ma. and the screen current is 2.5 ma. With these values, assuming proper excitation from the audio amplifier, an undistorted power output of approximately .55 of a watt is secured. Grid bias for the pentode section is secured from the voltage drop across the cathode resistor R_2. Since cathode K_2 is entirely separate from K_1, the two cathode circuits do not interfere in any way.

The popularity of the 12A7 has diminished recently as the power supply in AC-DC receivers in favor of the more dependable voltage doubler circuits. Typical voltage doubler tubes are: 25Z5, 25Z6 and 25Z6G.

13. THE GRUNOW MODEL 4-B RECEIVER. A study of the Grunow 4-B receiver presents an excellent opportunity to illustrate the applications of multi-element tubes and the advantages thereby gained.

A circuit diagram of the Grunow 4-B is shown in Fig. 30. This is a simplified schematic diagram; some of the intricate circuit connections have been omitted for convenience. In this receiver, a type 6A7 tube is used as a combined first detector and oscillator, a 6F7 as a combined I.F. amplifier and second detector, with a 42 pentode tube serving as the output. Thus, a complete superheterodyne receiver is obtained, using four tubes; actually, only three tubes in the amplifying circuit. By using the two dual-purpose tubes, the type 6A7 and 6F7, the amplifying portion of the receiver is equivalent to a five tube set. Tuning is accomplished by a two-gang variable condenser, one section tuning the first detector grid circuit and the other tuning the oscillator circuit. Two I.F. transformers are used, one to couple from the output of the 6A7 mixer and the other to couple the output of the pentode section of the 6F7 into the triode detector section of the 6F7. Both of these I.F. transformers are indicated on Fig. 30.

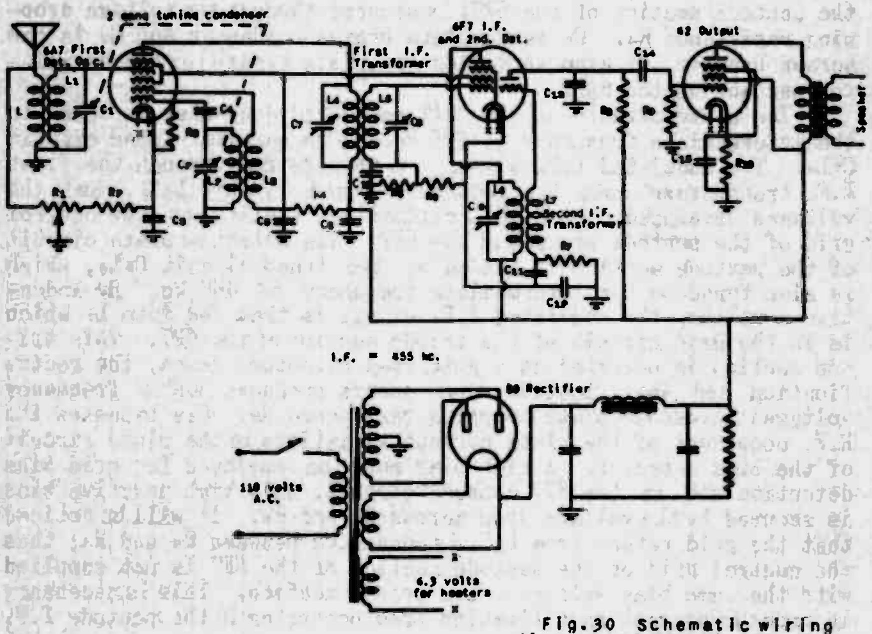


Fig. 30 Schematic wiring diagram of the Grunow 4-B receiver chassis.

A modulated signal voltage induced in the antenna causes a corresponding current to pass through the primary L to ground. By electromagnetic induction, the incoming signal is transferred into the secondary, which is tuned by the variable condenser C_1. This modulated signal voltage is then applied to grid #4 of the 6A7 pentagrid converter. This is the control grid of the pentode section. The oscillator section of the 6A7 consists of grids #1 and #2 in conjunction with the circuit components. L_3 is the plate feedback coil and L_2C_2 is the oscillator tuning circuit. The R.F. voltage developed in the oscillator tuned circuit is coupled through C_4 to grid #1, which is the control grid in the oscillator section. R_3 is the grid leak which supplies the grid bias necessary for proper operation of the oscillator circuit. The tuning condenser C_2 in the oscillator section has different size plates than the condenser C_1 used to tune the R.F. section. Both of these condensers are ganged on the same assembly and a single knob is used for tuning the receiver.

The volume control of the receiver R_1 is located in the cathode circuit of the 6A7 pentagrid converter. R_2 is a small resistance for the purpose of maintaining a minimum bias on the grid of the pentode section of the 6A7 to prevent distortion. The volume control potentiometer R_1 serves as both an antenna shunt and a cathode bias resistor. Moving the arm on R_1 to the left decreases the volume and moving the arm to the right increases the volume.

The screen voltage for the 6A7 pentagrid converter (also for the pentode section of the 6F7) is secured through the voltage dropping resistance R_4. C_6 is the plate bypass condenser and C_5 is the screen bypass. C_5 also serves as the plate bypass for the oscillator section of the 6A7.

The plate circuit of the 6A7 pentagrid converter is tuned to the intermediate frequency of 455 kc. by the parallel tuned circuit C_7L_4. The modulated I.F. signal is transferred through the first I.F. transformer into the secondary tuned circuit L_5C_8, and the voltages developed across this circuit are applied to the control grid of the pentode section of the 6F7. The output or plate circuit of the pentode section is loaded by the tuned circuit C_9L_6, which is also tuned to the intermediate frequency of 455 kc. By inductive coupling, the modulated I.F. signal is then fed into L_7 which is in the grid circuit of the triode section of the 6F7. This triode section is operated as a grid bias detector; hence, the rectification and amplification that occurs produces audio frequency voltages across the plate coupling resistance R_8. C_{13} bypasses the R.F. component of the plate current variations in the plate circuit of the bias detector. A high bias must be employed for grid bias detection and in the 6F7 cathode circuit, this high negative bias is secured by the voltage drop across R_6 and R_5. It will be noticed that the grid return from L_5C_8 is connected between R_5 and R_6; thus the control grid of the pentode section of the 6F7 is not supplied with the same bias voltage as the triode section. This is necessary in order to prevent rectification from occurring in the pentode I.F. amplifier circuit.

From the output of the triode bias detector, the audio frequency voltages are transferred through the coupling condenser C_{14} to the control grid of the type 42 pentode power output tube. This pentode is connected in a conventional manner and is capable of delivering approximately 2.5 watts of audio power into the loudspeaker.

This detailed analysis of the Grunow 4-B receiver has shown how it is possible to construct a satisfactory superheterodyne receiver using a minimum number of tubes. Both the 6A7 and the 6F7 perform a dual purpose, so the amplifier circuit is really equivalent to 5 tubes, rather than 3. Since no R.F. stage is used preceding the first detector and since only one I.F. stage is employed, the receiver sensitivity is not expected to compare with some of the larger Grunow models that have more tubes. This set, however, is very satisfactory for local reception and, since only four tubes are used, it may be built into a midget cabinet. This receiver does not use AVC and the second detector is of the grid bias type in order to obtain the greater amplification possible from that type of circuit.

14. **THE GRUNOW 5-A.** The circuit diagram of the Grunow 5-A receiver chassis is shown in Fig. 31. A study of this receiver circuit presents an opportunity to become acquainted with the operation of a 6F7 in a different circuit application and also to more clearly understand the operation of a duo-diode triode, such as the type 75.

In this receiver, the pentode section of the 6F7 is serving as the first detector and the triode section of the same tube is the local oscillator. The incoming signal from the antenna is applied to the control grid of the pentode section and the pentode plate (PP) is connected directly to the primary tuned circuit of the first I.F. transformer. The triode grid (T_g) and the triode plate (T_p) form the oscillator circuit. A typical feedback type of oscillator circuit is employed and grid bias is developed by the flow of grid current through the 100,000 ohm resistor (33134). The tuning condenser of the oscillator section is ganged with the tuning condenser for the grid circuit of the first detector. Screen grid voltage is obtained on the pentode section of the 6F7 and also on the screen of the 78 through the common 25,000 ohm dropping resistance (26514). A 50,000 ohm resistor (20929) serves as a bleeder to maintain a steady and constant screen voltage, while the .075 mfd. condenser connected across it serves as a screen bypass.[1] The voltage on the plate of the triode oscillator section of the 6F7 is reduced from the high output of the B supply through a 50,000 ohm resistance (20929).

The first I.F. transformer (27919) has the primary and secondary circuits tuned to the intermediate frequency of 455 kc. The type 78 I.F. amplifier is connected in a conventional circuit. The plate circuit of the 78 feeds the amplifier energy into the second I.F. transformer (27918). The modulated I.F. voltages developed across the secondary tuned circuit (also tuned to 455 kc.) are then applied to the diode detector and AVC circuits. Diode detection is obtained from the diode plate (P_d) connected directly to the top of the secondary tuned circuit (the one on the left). The load resistor for this plate of the duo-diode section is the 100,000 ohm resistor marked 33134. The 100 mmfd. condenser connected across this diode load resistor serves to bypass the I.F. component. The pulsating DC voltages developed across 33134 contain the AC component of the modulated I.F. signal. This AC component is the audio frequency signal and is fed through a 50,000 ohm resistor (32694) and a .01 mfd. condenser (34417) into the control grid circuit of the triode section of the 75. The potentiometer (27834) is the volume control of the receiver, because it governs the strength of the

[1] Locate these parts carefully because there are several resistors and condensers on the diagram which have the same stock number.

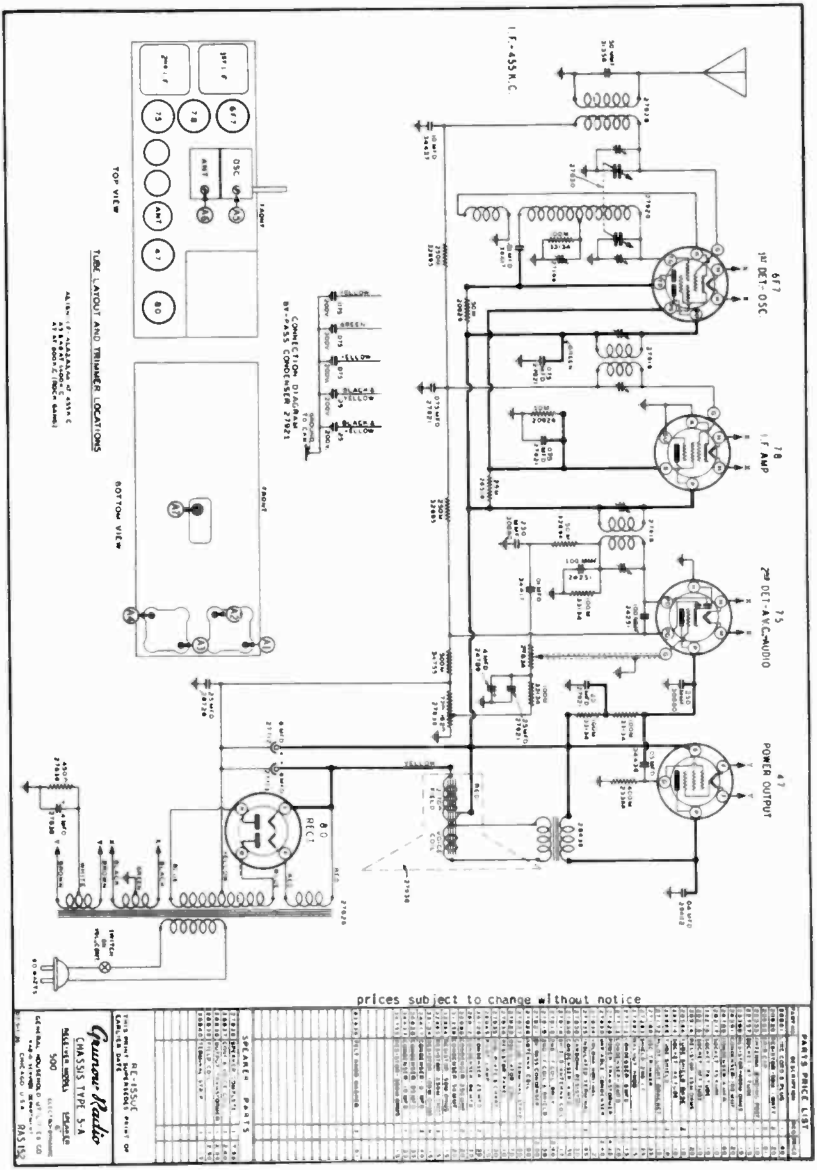


Fig.31 Complete diagram of the Grunow 5-A receiver chassis.

audio voltages fed to the grid of the triode A.F. amplifier. A 100,000 ohm resistor (33134) serves as the grid leak for the triode A.F. amplifier section of the 75. The plate circuit of the triode contains the amplified audio signal which, in turn, is coupled through a .05 mfd. condenser (34436) to the control grid of the 47 pentode power output tube.

Automatic volume control voltage is secured from the diode plate (P_d) on the right. This diode plate is supplied with an I.F. signal voltage through a 100 mfd. condenser (24251.) The rectified diode current that flows, passes through a tapped resistor (27836) and a 500,000 ohm load resistor (34755). Since the right side of the tapped resistor (27836) is connected to ground and the left side to the center tap of the high voltage winding on the power transformer, all of the current flowing from the power supply must pass through this resistor to develop a voltage across it with the left side negative and the grounded side positive. This constitutes a bucking or "delay" voltage for the AVC circuit. For a current to flow through the AVC section of the diode circuit, there must be sufficient I.F. signal voltage developed on the right diode plate to overcome this voltage produced in the opposite direction across 27836. This is called a "delayed-AVC circuit," which means that the development of an AVC voltage is retarded until the I.F. signal attains a certain minimum value. For example, if there are 10 volts developed (by the power supply current) across 27836, then at least 10 volts of I.F. signal must be applied to the right diode plate of the 75 before a rectified current will flow through this circuit and develop an AVC voltage. In other words, the action of the AVC circuit is "delayed" until the incoming signal is above a predetermined minimum value. The advantages gained by using a delayed-AVC circuit will be discussed thoroughly in Lesson 9 of Unit 2. The delayed-AVC circuit does not interfere with the process of detection.

When the I.F. signal attains a value sufficient to overcome the delay voltage, a rectified diode current passes through the 500,000 ohm resistor 34755. A .25 mfd. condenser (28728) bypasses both the I.F. and A.F. components of the voltage produced across 34755; hence, only the DC component passes through this resistor to produce a steady voltage drop. The magnitude of this DC voltage drop is always in direct accordance with the average strength of the incoming signal. The DC (AVC) voltage is filtered by a 250,000 ohm resistor (32695) and a .075 mfd. condenser (27921). The AVC voltage is then applied directly to the control grid of the 78 I.F. amplifier and also through a 250,000 ohm resistor (32695) to the control grid circuit of the pentode section in the 6F7. Note that the grid-filtering condenser has been omitted in the I.F. amplifier circuit, but is used in the first detector grid circuit. Intercircuit reactions are prevented by the insertion of a 250,000 ohm resistance (32695) between the two grid return connections to the AVC line.

In addition to showing the circuit diagram of the Grunow 5-A, Fig. 31 also indicates the tube layout and trimmer locations. Several lessons in Unit 2, which you are now ready to study, will be devoted to the methods and procedures of aligning the trimmer condensers on various superheterodyne receivers.

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