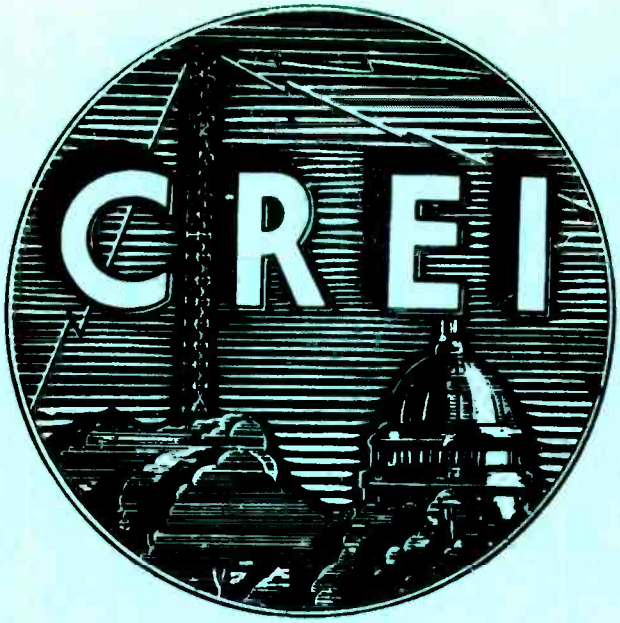

SPECIALIZED TELEVISION ENGINEERING

TELEVISION TECHNICAL ASSIGNMENT

THERMIONIC EMISSION

729E

THERMIONIC EMISSION

FOREWORD

Although major discoveries are often accidental in nature, the recognition of their importance stamps the discoverer as one of superior mental stature. When Edison, experimenting with the incandescent lamp, discovered that a current flow could be produced through the vacuum within the glass envelope between the heated filament and an auxiliary electrode, he proved his genius by getting out a patent on this phenomenon.

From the "Edison effect" was evolved the two-element vacuum tube or diode. Its importance as a rectifier, particularly for radio waves, was soon recognized, especially by Fleming, and it is a tribute to him that the diode tube is today the most widely employed type of second detector.

However, the diode now has uses in many other fields. As a rectifier of 60-cycle power, it is widely used in transmitter and amplifier power supplies, and it is also an important tool in pulse techniques, such as in square-wave generators, counter circuits, gate circuits, and the like. It will therefore be appreciated that its study is important not only because this tube is the forerunner of the multi-element amplifier tube, but because it has numerous uses in its two-element form.

This assignment begins with a discussion of thermionic emission, proceeds to a study of the effects of residual gas in the tube, the various types of filaments and cathode structures employed, the design of plate structures, and concludes with an analysis of space charge, saturation, and related matters.

Since this assignment is the first of a number on the electronic tube in all its various forms, it is apparent that its study is a must for every radioman. Your understanding of the assignments that follow will depend greatly upon your understanding of this assignment; you therefore owe it to yourself to master its contents.

E. H. Rietzke,
President.

THERMIONIC EMISSION

- TABLE OF CONTENTS -

THERMIONIC EMISSION

INTRODUCTION

The whole art of radio and television communication today is dependent upon the vacuum tube, and this device depends upon the ability of a conductor, under certain conditions, to emit electrons. Electron emission can be accomplished by any one of four general methods:

1. SECONDARY EMISSION, obtained by bombarding the metallic surface with high-velocity electrons or ions.

2. PHOTOELECTRIC EMISSION, obtained by bombarding the surface with photons of electromagnetic energy, and of a frequency exceeding the thresnhold value for the metal.

3. FIELD EMISSION, obtained by setting up a sufficiently intense electric field near the surface of the metal, and thereby extracting electrons from within the metal.

4. THERMIONIC EMISSION, obtained by heating the metal to a sufficiently high temperature to cause the free electrons within the metal to evaporate from it. This is the primary topic of this assignment, and in the following pages this phenomenon will be discussed both from a theoretical and from a practical viewpoint.

THEORETICAL CONSIDERATIONS

WORK FUNCTION.—Mention was made in an earlier assignment that atoms that have few electrons in their outermost orbit or shell, readily release these electrons to atoms that have nearly the full complement of electrons in their outermost shell, and need but a few to saturate that shell. An example is that of sodium, which has but one electron in its outermost shell, and readily releases an electron to chlorine, which has seven electrons in its outermost shell, and requires but one more electron to complete or saturate this shell. Thus, sodium and chlorine combine chemically to form sodium chloride (table salt) by this interchange of electrons.

Electrons Within a Metal.—In general, an atom that readily releases one or more electrons is called a metal, and an atom that takes on one or more electrons is called a non-metal. Sodium, potassium, caesium, iron, copper, silver, etc., are metals; chlorine, fluorine oxygen, etc., are non-metals. In addition, there are atoms that may either yield or acquire electrons; these partake of both metallic and non-metallic properties. Examples are sulphur, carbon, phosphorous, etc.

Returning to metals, it was brought out in the earlier assignment that the atoms can yield electrons within their midst without the need for a non-metal to absorb them. Thus, in a piece of copper, there are electrons wandering about between the atoms and derived from them. These electrons are called free electrons in that they are freed from the bonds holding them to any particular atom, and are therefore free to circulate in a closed metallic path or circuit and thus constitute an electrical current flow.

In a solid the atoms arrange themselves in an orderly, geometrical configuration known as a crystal. The size of a crystal is indefinite and depends upon how readily the atoms in a liquid, that is permitted to freeze, can dart about and build up the orderly crystal structure. At normal freezing rates, a chunk of material, such as copper, does not have time to form into a single crystal; instead, it forms myriads of tiny crystals interlaced to form the given chunk of metal.

Consider a single crystal. A cross section through it would show points at which atoms are located, with relatively large spaces between them. This is illustrated in Fig. 1, and it will be observed that the arrangement appears like a lattice work, and is known as a crystal lattice structure. Suppose most of the atoms have released electrons. They then have an excess of protons, and are therefore positively charged. The dots in

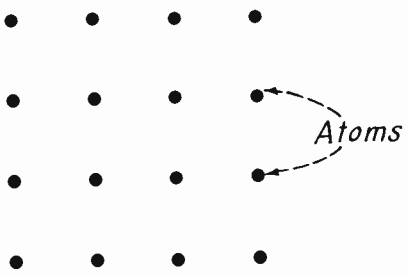

Fig. 1.—Cross section of a crystal, showing atom centers.

Fig. 1 can therefore represent points where positive charges are located.

The (free) electrons released will be attracted to these positive points in the crystal lattice structure. However, a free electron in the center of a group of positively charged atoms, or ions—as they are then called—will be attracted just as much to one ion as to another, so that the forces are balanced and it is essentially free to move in any direction it desires.

Only when it approaches close to an atom will it be more drawn to this atom than to the others, and hence captured. Even then it is not held long because the bonds are relatively weak, and it is soon freed. The force fields within a crystal can be compared to a gravitational force field. This is shown in Fig. 2. Here a plateau is pitted with depressions, into which a ball—representing a free

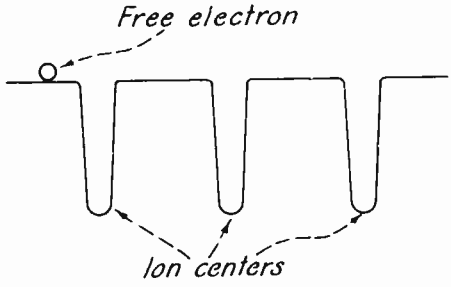

Fig. 2.—Gravitational field analogous to the force field of a crystal lattice structure.

electron—may fall. The depressions represent the ion positions, and it is clear that the ball may roll around rather freely on the plateau until it approaches to close to a pit, whereupon it may fall in. However, such is the activity within the pit that it may be readily expelled once again, to roll around on the plateau once more.

Electrons Outside of a Metal.—The readily produced motion of the free electrons in a crystal lattice

structure determines its electrical conductivity (and also its thermal or heat conductivity). However, the electrons can move freely only if they are surrounded on all sides by positive ions, because then only are the ionic forces in balance. Suppose an electron attempts to pass out of the metal. It now leaves the ions to one side of it, and their forces, instead of being in balance, are now all directed to pulling it back.

This is illustrated in Fig. 3; observe how the forces (shown in dotted lines), now all act to pull the electron to the left back into the metal. It therefore requires considerable force to push the electron through the boundary surface. This force, when multiplied by the distance through which it has to act before the electron is moved sufficiently far away from the metal to become free once more, represents *work* or energy. The amount of work required to move an electron from within a metal to a point outside where the electron is comparatively free of the

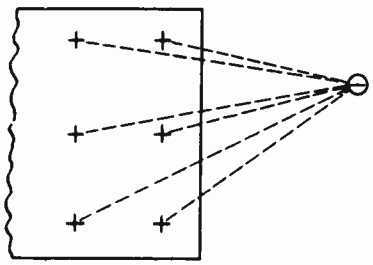

Fig. 3.—Forces acting on an electron passing through the boundary surface of a metal.

field of attraction of the metal, is called the *work function* of the metal.

It may be claimed that the

TABLE I

METAL	WORK FUNCTION VOLTS	MELTING POINT DEG. C.
Nickel	2.77	1455
Molybdenum	4.42	2620
Tungsten	4.52	3370
Tantalum	4.07	2850
Thorium	3.35	1845
Thorium on Tungsten	2.63	1900
Calcium Oxide	1.77	____
Barium Oxide	.99	____
Strontium Oxide	1.27	____

electron must be moved an infinite distance from the metal before the attractive force drops to zero, so that the work required (work function), which is the product of the force times the distance, would be infinite. This is not so, however, because as the distance of separation is increased, the attractive force decreases so rapidly that the total product approaches a finite limit; i.e., the work function is finite rather than infinite in value.

In Table I are given the work functions of various common metals, together with their melting points. Observe one striking feature, namely that the work function for thorium on tungsten is 2.63 volts, and lower than that for a pure thorium metal, which is 3.35 volts, and that it is particularly low for the oxides. This suggests that the latter materials should be especially suitable for thermionic emission.

Note that the work function is given in *volts*. This is because this unit represents *the work done on a unit charge of electricity*. In the case of the electron, if its charge is multiplied by the work function in volts, there is obtained the work or energy that has to be put into the electron to enable it to escape through the surface of the metal (to be emitted). The actual energy employed for this purpose may be radiant energy, such as light or ultraviolet light; in this case there is photo-emission. Or heat energy may be employed, in which case there is thermionic emission. It is also possible to place a very positive electrode near the surface, so as to establish a strong accelerating electric field on the electrons at the surface. In this case the emission is known as *autoelectronic* or *field* emission.

In all cases the electrons within the metal are accelerated to sufficiently high velocities (with accompanying high kinetic energy) to be able to break through the surface and be emitted. In the case of thermionic emission, the electrons acquire such velocities by being buffeted about by the vibrating atoms; their emission is very similar to the emission of vapor by a boiling liquid.

However, there is also the possibility that some of the atoms will also be emitted by the heat energy in the form of a metallic vapor. Slow, but nevertheless appreciable evaporation can take place not only below the boiling point of a metal, but even below the melting point, especially in a vacuum. Everyone has noticed the blackening of the glass walls of an incandescent lamp with particles coming from the filament, even though the filament is operating below its melting point. On the other hand, the higher the melting point (and boiling point) of a metal, the less will be the evaporation of atoms at a given temperature.

Hence, the suitability of a metal for thermionic emission depends upon at least two factors:

1. How low is its work function, and

2. How high is its melting point.

EMISSION FORMULA. —The formula for thermionic emission has been developed by Richardson and modified, in the light of modern quantum

mechanics, by Dushman. It is

$$i = A_o T^2 \epsilon^{(-\varphi e/kT)} \qquad (1)$$

where i is the emission current per square cm, A_o is a constant, T is the absolute temperature, φ is the work function of the metal, e is the electron charge (= 1.59×10^{-19} coulombs), and k is Boltzmann's constant (= 1.371×10^{-23} joule per degree). The constant A_o has a theoretical value of 120.4 amperes per centimeter, but owing to the difficulty of obtaining a perfectly clean and smooth metallic surface, its actual value in practice varies over quite a wide range.

If i is plotted against T, it will be found to increase very rapidly with increase in T, owing to the exponential term. For the

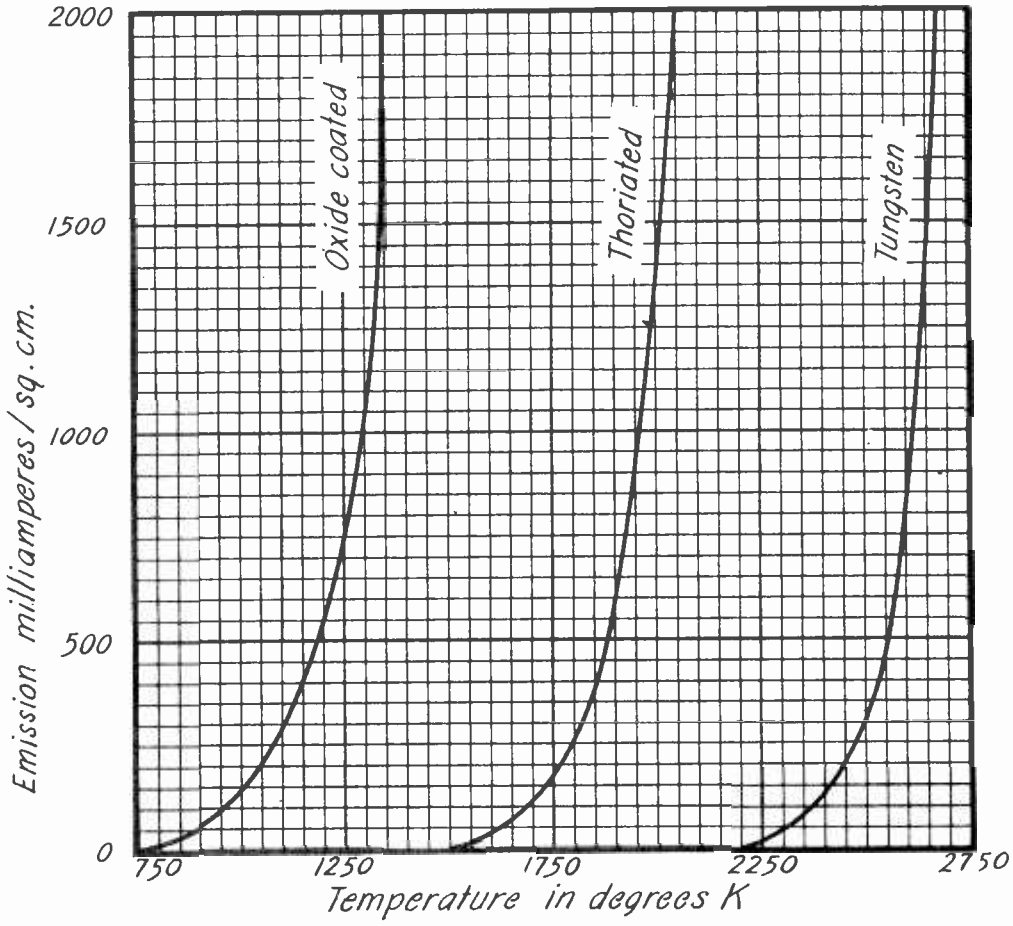

Fig. 4.—Variation of emission with absolute temperature T, for three materials having different work functions, φ.

same reason, it will vary very markedly at any given absolute temperature T if φ is varied; i.e., if different materials having different φ's are compared at the same temperature. As an example of such variation, Fig. 4 has been prepared.

Note, for any one curve, how rapidly the emission increases with but small variations in T. At first i increases slowly, but after a certain range of values for T, its increase is very marked. Thus, for the thoriated filament as an example, the emission increases from approximately zero to about 250 ma/cm^2 as the temperature is increased from 1,500° K to 1,800° K. From 1,800° K to 2,000° K, the increase is from about 250 to 1,400 ma/cm^2. Roughly a 10 per cent increase in temperature from 1,800° to 2,000° results in over 400 per cent increase in emission.

On the other hand, observe that for 1,000 ma/cm^2, the oxide-coated cathode requires a temperature of but 1,300° K; the thoriated cathode requires a temperature slightly over 1,950° K; and the tungsten cathode requires a temperature of over 2,600° K. This is because the oxide-coated cathode has the lowest work function, and tungsten has the highest work function of the three, as can be checked from Table I. From a mathematical viewpoint, the most important factor in Eq. (1) is the exponential, variations in its components—φ and T—have a more profound effect upon the emission than the factors A_o and T^2.

CHOICE OF EMITTING MATERIAL.— From the foregoing, it would appear that the choice of an emitting material would depend upon how low its work function is, and how high it can be heated before melting, or appreciably vaporizing. Unfortunately, from Table I it will will be noted that tungsten, which has the highest melting point (3,370° C), has also the highest work function (4.52 volts).

A material that has about the lowest work function—caesium—unfortunately has an exceedingly low melting point. Therefore, the choice of the material boils down fundamentally to how high is its melting point compared to its work function; that is, at a safe operating temperature consistent with a reasonable life, is its work-function sufficiently low that copious emission can be obtained.

From this viewpoint caesium is unsuitable, whereas tungsten is quite satisfactory. Tungsten is so refractory that it can be safely operated at 2,400° K for wires of small diameter, and at higher temperatures for larger wires. At this temperature the emission is sufficiently large because the high temperature T tends to balance the high work function φ in the fraction representing the exponent of the exponential in Eq. (1).

There are, of course, other practical considerations that help to determine the suitability of a material for thermionic emission. One of these considerations is heating power. Tungsten requires considerable heating power, and is therefore not as desirable as thoriated-tungsten or oxide-coated cathodes, particularly in receivers, where power cost and heat dissipation are primary factors. On the other hand, tungsten can stand up better in high-voltage transmitter tubes of large power-handling

capacity, and is therefore generally chosen for such applications. From a practical viewpoint, therefore, each cathode material has a field of application where it excels.

VACUUM REQUIREMENTS

EVACUATION.—If there is air surrounding the heated metal, the phenomenon of electron emission cannot be brought about. Tungsten, for example, if heated in air, readily combines with the oxygen in the air and a tough oxidized film forms over the surface of the metal increasing the surface potential to a point where appreciable emission cannot be obtained at any temperature below the melting point. Furthermore, if electrons could be evaporated from a metal surrounded by air, the air molecules would so impede the emission that most of the electrons would be forced back to the filament or grouped so closely to the metal that no control could be exercised by the grid or plate potentials. If a copious supply of electrons is to be emitted by the filament, and these electrons are to be readily controlled by potentials applied to other elements in the tube, the filament and other elements must be operated in a vacuum.

What is a good vacuum? The steam engineer considers a condenser pressure of 10 millimeters per square centimeter of mercury a good vacuum. Normal atmospheric pressure is 760 millimeters. At a temperature of 20° C at normal atmospheric pressure there are approximately 252×10^{17} gas molecules per cubic centimeter of space. The hydrogen atom is about 10^{-8} centimeter in diameter, and if hydrogen gas is compressed to normal atmospheric pressure at 20° C only about one millionth of the available space is occupied by gas molecules.

When a gas is compressed it is this empty space that is reduced. If the atmospheric pressure is reduced one million times or to a pressure of .00076 mm, the vacuum is said to be fair so far as vacuum tubes are concerned. *At this pressure about 1/1,000,000,000,000 of the available space is occupied by gas molecules.*

Now examine this vacuum from another point of view. At a pressure of .00076 mm, there are still 252×10^{11} gas molecules per cubic centimeter of space. *Thus, a cube .04 inch on a side will contain 25,200,000,000 gas molecules.* This indicates that the space in a fair vacuum is very much occupied. It is obvious that the word "vacuum" is only a relative term. Using modern pumps a vacuum on the order of .0005 mm/cm^2 can be obtained in a reasonable length of time. This pressure can be further reduced by means of a "getter" to be discussed later.

The importance of "good" vacuum increases with the power rating of the tube. An electron falling through a potential drop of ten volts, if unopposed, may attain a velocity in excess of a thousand miles per second. In transmitting tubes using plate potentials as high as 20,000 volts the tremendous velocities attained by the electrons are difficult to visualize. As previously stated, the electron acquires kinetic energy as its velocity increases.

If an electron should strike a gas molecule while travelling at

high velocity, the force of impact may be sufficient to drive one or more electrons out of the gas molecule. This is called ionization by collision and occurs to some extent in all tubes even at normal operating potentials. If this ionization takes place to an appreciable degree the tube becomes erratic in operation. This phase of ionization or gassing will be discussed in detail later in this assignment.

The most important effect from the filament standpoint is the creation of positive ions. When an electron knocks out one or more electrons from a gas molecule, the molecule immediately becomes positively charged and is attracted to the negatively charged cathode of the tube. These positive ions are thousands of times larger than the electron and may attain considerable momentum in the direction of the cathode, owing to its attraction for them. The ions may strike the cathode with explosive force. In power tubes that are badly gassed the cathode or filament may be blown to pieces by positive ion bombardment if the "B" supply potential is not removed immediately. It is evident that the higher the potential used in normal operation, the higher must be the degree of vacuum in the tube. The greater the vacuum, the less will be the chance of a high-velocity electron striking a gas molecule.

This is expressed scientifically by the concept of *mean free path*. This refers to the distance that an electron can travel, on the average, between successive collision with gas atoms. A vacuum tube should be evacuated to a point where the probability of an electron striking a gas atom before it strikes the plate, is exceedingly small.

In other words, the mean free path should be greater than the cathode-to-plate spacing. This still permits an appreciable number of gas atoms to be present; i.e., an absolute vacuum is not necessary, and a tube evacuated to a point where the mean free path exceeds the interelectrode spacing is nearly as good as one having a perfect vacuum.

Affinity of Metal for Gas.—All metals have a strong affinity or attraction for certain gases. Tantalum has a very great affinity for hydrogen. The gas is said to be adsorbed because it does not actually penetrate the metal but adheres only to the surface. As the metal is heated, more and more of this gas is released from the surface. If a high degree of vacuum is to be maintained throughout the life of a vacuum tube, it is essential that this occluded gas be removed during the process of evacuation.

If any adsorbed gas is released during operation of the tube, the vacuum will be reduced increasing the danger of gassing. The only practical method of removing the adsorbed gas from the tube elements is to heat them during the evacuation process to a temperature well above that ever to be expected in normal operation. The higher the temperature, the more gas that will be driven from the tube elements. The limiting temperature is the melting point of the emitter or the other elements of the tube.

The tube elements are heated during evacuation by placing the entire tube in an induction furnace. The tube is placed inside a large

inductance coil made of heavy tubing. With the vacuum pump connected and running, a large circulating radio-frequency current is introduced into the induction coil. The intense and rapidly varying magnetic field produced by this current induces eddy currents in the metallic elements of the tube structure which cause the elements to heat up. Any desired temperature can be obtained by adjusting the circulating current.

As previously explained, the larger transmitting tubes must have a very high vacuum which necessitates using very high evacuation temperatures. Only tungsten and tantalum filaments are used to any extent in modern high-power vacuum tubes because these materials have the necessary high melting point to withstand the high evacuation temperatures and at the same time produce the necessary emission.

In order to speed up the production of small tubes it was necessary to find some method of obtaining a high vacuum in a short time. Substances such as magnesium, barium, barium berylliate, phosphorous, zirconium, and others have a very strong affinity for gas. In the smaller tubes a small quantity of one of these substances is placed in a cup or secured to a plate attached to some part of the tube structure. When the pumping operation is nearly complete the substance is vaporized by heating to a high temperature for a few seconds. When the substance condenses it adsorbs or "gets" most of the remaining residual gas in the tube. The material used for this purpose is called the *getter* and accounts for the silvery or else smoky coating so common on glass-wall tubes.

In high-power tubes the plate dissipation may vaporize the getter and thereby spoil the vacuum. In such tubes tantalum can be usefully employed, since at high temperatures it adsorbs gases. Another useful metal is zirconium. At 350° C it is particularly good at adsorbing hydrogen, although it tends to liberate this gas at higher temperatures.

On the other hand, at 1400° C it will readily adsorb other gases such as oxygen, carbon monoxide and dioxide, nitrogen, etc. Hence, by employing either two filaments of zirconium operated at each of the above two temperatures, or by using one strip, one end of which is at 1400° C and the other end at about 350° C, all of the above gases can be adsorbed and the vacuum maintained.

EFFECTS OF RESIDUAL GAS.—The emission and life of pure metal filaments is seriously affected by traces of certain gases. Oxygen, nitrogen, carbon dioxide, water vapor, and various hydrocarbons are all detrimental to the filament. These gases combine chemically with the filament and tend to increase the work function. Tungsten filaments operated at a temperature below normal will tend to oxidize with a resultant decrease in emission. At normal temperature this oxidization is burned off as rapidly as it forms. Nitrogen, when ionized, is very active chemically and once it combines with the filament a "poisoned" condition may result which permanently reduces emission. Hydrogen and oxygen combine to form water vapor and it has been found that with a water vapor pressure as low as .000001 mm, emission is seriously reduced. At

high temperatures carbon dioxide and the hydrocarbons combine with the tungsten filament to form tungsten carbide which results in an increase in filament resistance. If the filament voltage is constant this results in a reduction in filament temperature and emission. In general the inert gases, argon, helium, neon, and mercury vapor have little effect on the filament chemically but may cause damage by ionic bombardment if ionized. Most of the above chemical reactions are accelerated at high temperatures and their effects are more noticeable in high power tubes for that reason. The great difference in cost of transmitting and receiving tubes is not due to the cost of additional material but is caused by the great care required in construction and necessity for removing all trace of gas from inside the tubes.

MECHANICAL STRENGTH.—A filament or cathode at normal operating temperature must possess sufficient mechanical strength to withstand the shock and vibration encountered during normal operating conditions. This is particularly the case for tubes used in shipboard transmitters, since they are subjected to continuous vibration and, in the case of naval vessels, to strong shocks during gunfire. An especially strenuous application is that of proximity fuses, where the tubes must withstand the enormous accelerating forces developed when the shell is fired from the gun.

It is important not only that the filament or heater in the tube—as the case may be—does not break, but it must not sag or bend appreciably. The same is true of the other electrodes; any relative displacement will change markedly the tube characteristics. It is preferable it have, if possible, short stubby filaments, even though an appreciable amount of the total heating power is conducted away by the nearby filament supports.

However, other factors also determine the design. Oxide-coated emitters, for example, are mounted on a base-metal support not only because of the greater mechanical strength, but also because the support acts as the resistive element that heats the oxide coating and thereby causes it to emit. Furthermore, there is reason to believe that the nature of the base-metal support determines in part the effectiveness of emission.

EMISSIVITY AND LIFE.—As stated previously, the emitter is operated at as high a temperature as is consistant with its life. This is because a small increase in temperature increases the emission so markedly that considerably less emitter is required. As a result, less *total* heating power is required in spite of the fact that the operating temperature is higher.

However, an increase in temperature also unfortunately results in a marked decrease in operating life. The reason is that the vaporization of the metal is considerably accelerated by the higher temperature, until finally the cross section of the filament is so reduced as to cause it to fail either mechanically, or as an emitter. The latter effect occurs because as the cross section decreases, the electrical resistance increases, and this in turn means less electrical power absorbed for heating *under constant voltage conditions*. Thus, the power is E^2/R; if R

increases, the power decreases, as does also the operating temperature and emission.

In practice a compromise must be made between long life and high operating temperature. For ordinary commercial purposes, a filament life of 2,000 hours is usually taken as the basis of reference. The operating temperature is usually selected so that at the end of 2,000 hours the filament cross section is reduced to 90 per cent of its original value.

However, tube life far in excess of 2,000 hours is quite common, owing to the conservative design practiced by tube manufacturers. In telephone practice, where tubes in repeater amplifiers are in continuous service, a tube life of 20,000 hours is common, and tubes capable of operating for 25 years or more are being seriously considered for submarine repeater amplifier use. Such units, hermetically sealed, could be permanently laid at the bottom of the ocean, just like the submarine cable in use at present.

Filament and cathode design in also determined by other factors. The so-called internal plate resistance or R_p of the tube (to be discussed farther on) is in part determined by the cathode emitting surface. The greater this surface, the lower is the R_p. An example of this is the 2A3 power tube. Here the filament consists of a large number of fine strands in parallel; the total emitting surface for a given heating power is much greater than that of one thick, long filament.

On the other hand, for long life in the case of a high-temperature emitter like tungsten, a single large cross-section wire would be preferable because the ratio of volume to surface is large, and a considerable amount of evaporation can occur before the cross section is appreciably reduced. Nevertheless, even in the case of such emitters, several strands in parallel are preferred.

As an example, in the Westinghouse Type AW-220 transmitting vacuum tube eight strands of tungsten, each about 14 inches long, are used for the filament. These eight strands form four loops in parallel. Each loop carries 80 amperes at 30 volts, or a total of 320 amperes. The loops are supported by tungsten springs to prevent sagging at the high operating temperatures. The AW-220 is rated at 125 kw plate dissipation and requires 9.6 kw of filament power.

EMISSION EFFICIENCY.—Emission efficiency is defined as the ratio of filament emission to filament heating power. Most of the power used to heat the filament of a vacuum tube is radiated from the filament in the form of radiant heat, and only a small portion of the total power is lost by conduction through the filament connecting leads and supports.

The amount of heat radiated from a hot body varies as the fourth power of the absolute temperature, hence the higher the operating temperature of a filament, the greater is the power lost by radiation. This means that as the operating temperature is increased more and more power will be required to maintain the filament at that temperature. This is one of the reasons for the low-emission efficiency of the tungsten filament. In the range of operating temperatures used with

tungsten filaments the emission per watt of heating power varies from 3 to 20 milliamperes. The thoriated filament at 1,900° K has an efficiency of approximately 60 ma per watt. The oxide-coated filament has the highest efficiency, ranging from 50 ma at 1,100° to 125 ma at 1,170° K per watt.

Because of the high filament heating power required for very high emission, the power rating of vacuum tubes is usually increased by designing the tubes for the highest practical plate voltage. Thus, P = EI where I is the emission current and E is the plate voltage. If I remains constant P can be increased by using a higher plate voltage. For this reason the ratio of power output to filament power is usually much greater in transmitting tubes than it is in the smaller receiving tubes.

For example, the type 2A3 tube used in small audio power amplifiers requires 2.5 volts at 2.5 amperes or 6.25 watts of filament power. As a Class A amplifier the tube has an output of 3.5 watts. The power output to filament power ratio is 3.5/6.25 = .56. Compare this with the type 862 transmitting tube which takes 207 amperes at 33 volts or 6,831 watts for filament heating. The output ranges from 25 kw to 100 kw depending on the class of operation. The power output to filament power ratio thus varies from 25/6.831 or 3.66 to 100/6.831 or 14.5. In both cases the ratio is several times greater than that of the smaller tube.

PRACTICAL EMITTERS

THE TUNGSTEN FILAMENT.—Although the tungsten filament has poor emission efficiency compared to the thoriated or oxide types, it is one of the few materials having a melting point sufficiently high to permit the high evacuation temperatures so necessary with high power transmitting tubes.

Tantalum and tungsten are the only two materials that will give satisfactory emission and still withstand these high evacuation temperatures. Tungsten also has the advantage of a strong affinity for residual gas. A tungsten filament tube that shows signs of gas may usually be cleared up by operating the tungsten filament at normal or slightly above normal filament temperature for several hours with plate voltage removed. The principle disadvantages of tungsten are short life and high power consumption. The short life is due to the high operating temperature and the high power consumption to the low emission efficiency. The operating temperature range of the tungsten filament lies between 2,000° and 2,600° K (white heat). The tungsten filament also tends to become brittle with age.

On the other hand, surface bombardment and consequent pitting of the tungsten filament by positive gas ions does not destroy its ability to emit electrons, as is the case for the composite emitting surfaces such as the thoriated-tungsten and oxide-coated cathodes. As a result, the tungsten (and tantalum) cathodes or filaments are particularly suited for high-power, high-voltage transmitter tubes, and are accordingly used almost exclusively in such tubes.

THE TANTALUM FILAMENT.—Because of its high melting point the tanta-

lum filament is also used to some extent in high-voltage transmitting tubes. Tungsten filaments are more generally used because of their lower cost and higher melting point. At the same operating temperature tantalum has approximately 10 times the emission of tungsten. However, the tantalum filament is usually operated at a lower temperature (1,800 to 2,400° K) to obtain the necessary tube life.

Tantalum is sensitive to filament overload and like tungsten tends to become brittle with operating age. Tantalum is particularly sensitive to residual gases, oxygen and water vapor combining with the filament to form tantalum pentoxide with consequent reduction in emission. Tantalum will also adsorb large volumes of gas, particularly hydrogen. Adsorbed hydrogen reduces emission and makes the filament quite brittle. The major advantage of tantalum is its emission efficiency, and it finds considerable use in the medium power transmitting tubes.

THE THORIATED FILAMENT.—The General Electric Company discovered that a small amount of thorium added to the tungsten filament would greatly reduce the tendency toward crystallization and increase the emission efficiency. In manufacture, one or two per cent of thorium oxide and a small amount of carbon are mixed with the tungsten powder. When the powder is melted and drawn into wire, the thorium oxide content is reduced to about .7 per cent. The filament is activated by heating to about 2,500° C in a vacuum for one or two minutes. This high temperature burns the oxide from the surface of the tungsten, and the chemical action between the thorium oxide and carbon reduces some of the oxide to pure thorium. Any thorium on the surface of the filament is evaporated at this temperature.

After the surface of the tungsten is cleaned the temperature of the filament is reduced to a value between 1,800° and 2,000° C and the filament cooked for several hours. The metallic thorium slowly boils to the surface and forms a layer one atom thick. The emission takes place from this monatomic layer. The emission efficiency of thorium is several times greater than that of tungsten.

In Table I it is noted that pure thorium has a work function of 3.35 volts and a melting point of 1,845° C, whereas thoriated tungsten has a work function of only 2.63 volts and a melting point of 1,900° C. This difference in work functions is due to the contact potential between thorium and tungsten. Thorium is electropositive to tungsten, and apparently the positive field created by the contact potential tends to aid the evaporation of electrons.

The strong force of cohesion between the two metals accounts for the high melting point. Thorium is very sensitive to ionic bombardment and is also very active chemically with oxygen and water vapor. For these reasons the best possible degree of vacuum is desirable with thoriated filament tubes.

Because of the low melting point of thorium and its sensitivity to ionic bombardment, the thoriated filament cannot be used in the higher power transmitting tubes, although considerable experimentation is being carried out along these lines. The operating temperature

is quite critical and lies between 1,800° and 1,900° K. If the temperature is too high the thorium diffuses toward the surface of the filament too rapidly. If the layer of thorium on tungsten becomes more than one atom thick, the outer layer evaporates very readily. This rapid dissipation of the thorium shortens the tube life.

On the other hand, if the operating temperature is too low the surface thorium evaporates faster than it is replaced by the inner supply and the emission decreases rapidly. When this condition occurs reactivation is possible if the thorium content has not been exhausted. The process is carried out by flashing the filament for about ten to twenty seconds at twice the normal filament voltage and then cooking for one or two hours at 1.2 times normal voltage. The plate voltage is removed during the reactivation process.

The life of the thoriated filament is very long if operated at the correct temperature. For example, a thoriated filament containing 1 per cent of thorium, if operated at a constant temperature of 1,800° K, has a life of 720,000 hours. At 1,900° K this is reduced to 94,000 hours, and at 2,100° to 2,900 hours. The emission per square centimeter at 1,800° K is .772 ampere, at 1,900° K 1.59 amperes and at 2,100° K 3.43 amperes. This high emission efficiency makes possible the use of a very small filament with very low power consumption. Thoriated filaments are usually operated at about 1,900° K (yellow heat). This type of filament finds extensive application in the smaller transmitter tubes designed for medium power output.

Tantalum and molybdenum can also be used as a base metal for thoriated filaments. Barium, caesium and lanthanum can be used instead of thorium with approximately the same efficiency. A single atomic layer of caesium on an oxidized tungsten base gives a slightly higher emission per unit area than thorium, but has not been found to be as satisfactory from an operating standpoint.

THE OXIDE-COATED FILAMENT.— Wehnelt in 1904 discovered that a coating of certain oxides on a metal core gave a copious emission of electrons at very low temperatures. The Wehnelt cathode, as it is sometimes called, used platinum as a base, but the high cost of this material started an early search for cheaper materials.

Tungsten has been used, but more modern oxide-coated filaments use nickel or nickel alloys. The alloy of nickel, silicon, iron, cobalt, and titanium is called "Konel" metal and when coated with barium or strontium oxide has a very low surface potential. Modern oxide-coated filaments use barium or strontium oxides although calcium oxide has been used to some extent. There is little choice between barium and strontium oxide so far as efficiency is concerned. Calcium oxide has the highest surface potential of the three.

The exact mechanics of emission from oxide-coated filaments is still a subject of controversy. The most acceptable theory is that the oxide is electropositive with respect to the base metal, and the reaction between contact potentials and work functions is such as to reduce the net work function to a very low value. The normal operating temper-

ature of the oxide-coated filament is between 1,100° and 1,300° K (dull red heat). Some cathodes give sufficient emission at temperatures below which any visible light is emitted. In manufacture the base metal of nickel or nickel alloy wire or ribbon is alternately passed through an aqueous solution containing finely divided barium or strontium carbonates and then through a drying oven containing carbon dioxide gas. The process is repeated until the filament is built up to the proper size. The completed filament is pure white in color which is excellent from the standpoint of heat conservation. (White is a poor radiator of heat.)

After the tube is evacuated the filament is heated to approximately 1,600° C, and plate voltage on the order of 200 volts is applied through a tungsten filament lamp. Sometimes it is necessary to momentarily flash the filament to start emission. As emission increases the tungsten lamp lights and when full emission is obtained the lamp burns at full brilliancy. The lamp automatically reduces the plate voltage as the emission current increases. Other methods of manufacturing are used which do not require an anode voltage.

Oxide-coated filaments and cathodes have a very high emission efficiency. The coating consists of layers of barium and strontium (commonly called barium) on a base metal of konel metal, nickel, tungsten or other material. The base metal acts as a mechanical support and also appears to have some effect on emission but probably indirectly.

The primary disadvantage of the oxide-coated filament is the low temperature at which the oxide evaporates. Only very low evacuation temperatures are practical, and it is very difficult to remove all the gas from the elements at these temperatures. This limits the tube to low plate voltages if gassing is to be avoided. This type of filament is also very susceptible to the effects of gassing. Positive ions may "blast" entire sections of the oxide coating from the base metal.

Hotspots may develop if the coating is not uniform over the surface of the base metal. Maximum emission takes place at the point where the oxide coating is thickest. Each electron in overcoming the surface potential gives up a minute portion of its kinetic energy in the form of heat. This released energy tends to increase the temperature of the filament. The greatest increase in temperature occurs at the points of maximum emission, and the oxide coating at these points tends to evaporate rapidly. The life of the oxide-coated filament is dependent upon the life of the oxide coating. Once the oxide coating is evaporated, the emission falls to that obtainable from the base metal and is usually insufficient to meet the circuit and tube requirements.

However, properly constructed and operated, the oxide filament will have a life much greater than that of the thoriated type. It is quite strong mechanically and has an emission efficiency greater than that of tungsten or thoriated filaments. Because of the high emission at low temperatures, this type of emitter is used extensively in indirectly heater cathode and rectifier tubes.

THE INDIRECTLY-HEATED CATHODE.—

With the advent of the broadcast receiver operating directly from the light socket, it became necessary to develop an emitter free from the undesirable effects of voltage variation due to the alternating current used to heat the emitter.

When alternating current is used to heat the filament of a vacuum tube, the a.c. across the filament causes voltage fluctuations between grid and filament. Also with a varying current in the filament, the emission tends to follow the current variations. Both of these effects combine to produce an undesirable hum component in the tube output circuit.

The indirectly heated or equipotential cathode was developed to eliminate these undesirable effects. The emitting surface or CATHODE consists of a small nickel or nickel alloy cylinder coated with one of the good emitting oxides. Inside the cathode *but insulated from it* is the heater wire which carries the heating current. The cathode is heated by radiation from the heater.

Fig. 5 shows three typical arrangements of the heater in the equipotential type of emitter. The actual design of the heater varies from time to time with different manufacturers. While in principle the construction is as simple as that of the ordinary electric soldering iron, in practice, due to small clearance between elements and the sensitivity of modern high gain tubes to minute internal changes, it is very difficult to design a perfect equipotential cathode.

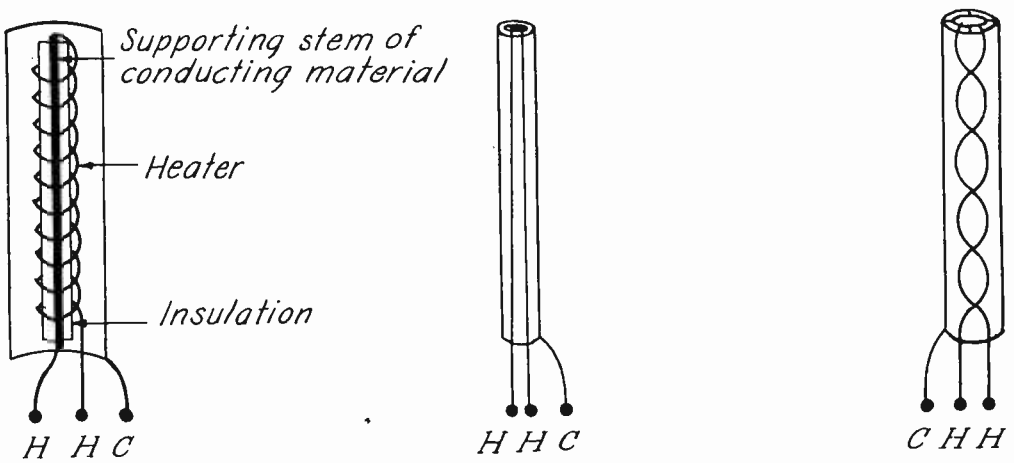

Fig. 5.—Mechanical arrangement of heaters.

A few of the difficulties met with in practice are short circuit between heater and cathode, leakage because of insufficient insulation, vibration of heater wires due to effects of alternating heating current, sag in heater wires because of expansion at high temperatures, induced currents in cathode and grid

caused by the alternating magnetic field about the heater, delay in heating, etc.

Since the cathode is heated only by radiation from the heater it must be placed as close to the heater as practical. Oxide-coated cathodes are used because there is an appreciable temperature drop through the intervening insulation, and the heater temperature must be within safe limits, so that the temperature on the surface of the insulator is relatively low—sufficient to produce emission from an oxide-coated cathode, but not from thoriated-tungsten or tungsten type.

Minimum spacing between heater and cathode is also essential to reduce the heating time, that is, the time between the application of heater power and the time when the emitter reaches normal emission. Twisted and coiled heater wires are used to reduce the external magnetic field about the heater wires. Obviously the construction of this type emitter is several times more complicated than the filamentary type.

However, the improvement of the equipotential cathode has been such that the same life as is obtained from the filament tube can now be expected. The type 24 and 27 tubes were the first of the equipotential cathode tubes. The heaters of these tubes required 2.5 volts at 1.75 amperes, and the tube required approximately one minute heating time. Compare this with the modern tubes of similar type requiring 6.3 volts at .15 ampere with a heating time of approximately 15 seconds.

To conserve filament power the heater wire is operated at a rather high temperature and hence will emit a certain number of electrons. This emission will vary with the heating current. Unless preventive measures are taken some of these heater electrons may escape from the ends of the cathode and introduce a hum component into the electron field about the cathode. If the cathode is connected directly back to the center tap of the heater transformer winding (or to the center tap of a resistor connected across that winding), the cathode forms a static shield to isolate the heater filament from the grid and plate potentials. Often this is not sufficient to prevent the electrons from escaping. In that case the cathode may be biased either positive or negative in respect to the heater.

If the cathode is made positive with respect to the heater it will attract all electrons emitted from the filament and thus prevent their entrance into the external electron field. If the cathode is biased negative the heater electrons are repelled back to the heater. The amount of bias and whether or not it should be positive or negative is best determined by test. In practice bias voltages between 3 and 20 volts are used.

Direct current may also be used as a source of supply for heater type cathodes. The 6.3-volt heater tubes were developed primarily for automotive receivers but are now used extensively in all types of receivers. The 6.3-volt heaters are connected in parallel directly across the six-volt car battery.

Tubes similar to the 25A6, 25L6, 50L6, 25Z5, etc., were developed to permit direct operation

across the supply line. Usually one or two 25-volt or greater voltage heater tubes have their heaters connected in series with one or more 12.6- or 6.3-volt tubes. 117-volt tubes are used in some sets, also 70-volt tubes. Tubes used in series must be rated for the same heater current, such as .15 amperes. The combination is then connected through a limiting resistor directly across the supply line. In many of the midget receivers the limiting resistor is built into the supply cord. In other sets it may be in the form of a ballast tube plugging into a regular tube socket. The idea is to keep the heat radiated by the resistor from underneath the receiver chassis. By using the heaters directly across the line and special rectifier voltage doubling circuits, the power transformer can be entirely eliminated from the radio set. Since the power transformer is one of the most expensive components of the receiver its elimination permits greater economy in receiver production. Rectifiers made of selenium are used to replace tube rectifiers in the smaller sets.

In modern receiver design it is customary to use indirectly heated cathode tubes in radio frequency amplifiers, detectors, and audio voltage amplifiers. In the final audio power stage the ordinary filament type of tube may be used. A slight amount of hum in the final stage is permissible since it is not further amplified. If the power stage is operated push-pull the hum component can be balanced out in the output transformer as will be explained in a later assignment.

Some battery-operated receivers utilize the "Air Cell" battery as a source of heater power. This is a primary battery with a capacity of approximately 600 ampere-hours at slightly more than 2 volts. The two-volt line of tubes was developed for use with this source of filament supply. These tubes employ a very small thoriated filament requiring about .06 ampere at 2 volts for radio frequency, detector and audio voltage amplifiers and .13 or .26 ampere at 2 volts for the power stage. Battery receivers are also designed to operate from the regular secondary 6-volt battery charged from a windcharger. Such sets usually use 6.3-volt tubes such as 6S7G, 6K6, 6D8G, etc. Later tubes of the 1.4-volt series and dry cell batteries are widely used in portable and home battery sets.

It is suggested that the student study the tube manual included with this assignment until he is familiar with the various types of tubes, their filament requirements, operating potentials and general applications. The technical data in the early pages of the receiving tube manual should be of interest.

OPERATING CHARACTERISTICS.—A FILAMENT SHOULD ALWAYS BE OPERATED AT THE EXACT POTENTIAL SPECIFIED BY THE MANUFACTURER. It is often believed that operating a filament at a voltage below normal will insure longer tube life. This is true only in the case of the oxide-coated filament. With thoriated filaments low operating temperature results in the evaporation of the surface thorium at a rate greater than it is replaced by internal diffusion. This results in a slow reduction in emission necessitating reactivation in a short time.

If the tungsten filament is operated for long periods of time below normal potential the fila-

ment will be oxidized and emission reduced. This oxidization can be burned off by operating the filament at a temperature higher than normal for several minutes. At the normal operating temperature the oxidization is burned off as rapidly as it is formed.

In the case of the larger transmitting tubes it is dangerous to operate the filament at a temperature much below normal. Such tubes use high plate potentials and apparently with emission below normal excessive mechanical strains are set up in the filament which may cause it to collapse. On the other hand, operating at a temperature higher than normal will seriously reduce the life of the filament.

In the case of the oxide-coated filament the oxide evaporates very quickly. With a considerable portion of the oxide evaporated it is necessary to always operate the filament at the higher temperature to obtain satisfactory emission. This results in further evaporation of the coating and the filament life is reduced to only a fraction of that obtained when operated at the correct temperature. In general, the emission of the oxide-coated filament falls to a very low value long before the filament burns out.

The layer of oxide on the oxide-coated filament is quite thick and over a period of time a considerable amount of oxide will be evaporated. The oxide atoms and molecules may slowly build up a conductive coating on the insulators supporting the tube elements. If the filament is operated at higher than normal temperature this condition is accelerated because the atoms are thrown off at a higher velocity. It is not unusual to find partially shorted elements in tubes that have been in service for long periods. The same condition is often found in transmitting tubes when the plate is operated at a very high temperature. Atoms are driven from the plate structure by electronic bombardment and in time build up a short circuiting layer on the plate insulating supports.

The high emission efficiency of the thoriated filament permits the use of a very fine filament only a few thousandths of an inch in diameter in the average receiving tube. In general the thoriated filament has a resistance several times greater than that of the tungsten or oxide-coated filaments in tubes of equivalent rating. Because of small size the thoriated filament is easily broken by shock or vibration and will burn out quickly if subject to a higher than normal potential for only a few minutes. Furthermore, when the thoriated filament is operated at a temperature much above normal the thorium oxide is reduced and evaporated very rapidly resulting in greatly decreased filament life.

Modern practice requires the filaments to be operated at constant potential rather than with constant current. Several years ago the reverse was true. As previously explained the cross section of the filament is gradually reduced due to slow atomic and molecular evaporation. As the cross section decreases the resistance of the filament increases. With constant current the high resistance would mean a higher operating temperature with the consequent reduction in tube life. With constant potential the filament cur-

rent will decrease as the resistance increases maintaining approximately the same operating temperature throughout the life of the tube.

Modern transmitters usually use alternating current as a source of filament power. If the line supply is alternating current, rectifiers are used to provide grid and plate potentials. If the line supply is d.c. it may be converted to a.c. by means of a rotary converter or a motor generator may be used. Direct current generators are used to supply the plate and grid potentials but the filament supply is usually taken from a special a.c. winding on one of the rotating units. In one such installation one generator supplies 2,000-volts plate potential, the other supplies 120-volts grid voltage and a special winding on the armature of the motor provides 88 volts at 88 cycles for filament heating. Transformers are used to drop the a.c. supply to the proper value for the filaments.

A three-phase supply offers several advantages at high power. More economical rectifier circuits can be used and if the filaments are arranged for three-phase operation; the actual variation between maximum and minimum in the effective magnetic field about the filament is reduced, thus reducing the hum component in the output of the tube.

DESIGN CONSIDERATIONS

GRID AND PLATE MATERIALS.—Selection of proper materials for the cold electrodes of a vacuum tube is almost as important as selection the proper filament material. The best metals for the cold electrodes are those that can easily be denuded of their gas content. Molybdenum, tantalum, tungsten, nickel and Svea metal (a pure form of Swedish iron) are extensively used for plate and grid structures of modern vacuum tubes.

Nickel and Svea metal are most commonly used in receiving tubes. These metals are not satisfactory for power tubes because both tend to crystallize at rather low temperatures, about 550° C for nickel and about 700° C for Svea metal.

Molybdenum is used in a large number of medium power tubes but tantalum and tungsten are preferred materials for high power radiation cooled tubes because of their gas adsorption qualities. By evacuating the tube at temperatures considerably in excess of those encountered in practice the tungsten and tantalum electrodes will attract and adsorb any residual gas remaining or released during operation in the tube. Both molybdenum and tantalum can be worked cold but both are hard tough metals and the life of tools and dies used to work them is very short. Tungsten must be worked hot which restricts its use to tubes where its high melting point makes it a necessity.

Graphite, a form of carbon, is used quite extensively as an anode material in radiation cooled tubes. The gas adsorption of graphite is much higher than the pure metals but by suitable treatment the gas content can be reduced sufficiently to permit evacuation in approximately the same time as the molydenum anode tube.

RADIATION EMISSIVITY.—By this is meant the ability of the plate to radiate the heat developed by

electronic bombardment. In receiving tubes this is not an important factor because the plate is required to dissipate only a very small amount of power. However, it is an important factor in power tube design because with any given operating efficiency, the power output is limited principally by the ability of the plate to radiate the power dissipated at the anode. Power tubes are rated in accordance with the heat dissipation qualities of the plate, and the plate dissipation rating is in a sense a more fundamental rating than the output power of the tube, since this depends upon the type of circuit and type of service.

The amount of energy that can be radiated from a body is approximately proportional to the fourth power of the absolute temperature if the body is operated at a temperature considerably higher than that of its surroundings. This is the condition in a vacuum tube. Therefore it is a distinct advantage to operate the anode at the highest practical temperature, because if the operating temperature can be increased, the area of the anode can be decreased for the same power dissipation and this will in turn decrease the interelectrode capacities. For example, if a given anode radiates 50 watts of heat at 500° C then at 1,000° C which is double the original temperature the plate will radiate 2^4 or 16 times 50 watts or 800 watts. The plate, if operated at the higher temperature, need only be one sixteenth as large to dissipate 50 watts.

However, there is a limit to the operating temperature that can be used. The walls of the tube must dissipate the heat radiated from the plate so in the case of radiation cooled tubes, the greater the plate dissipation the larger must be the glass bulb. Also it should be remembered that heating the plate will result in a certain electron emission from the plate. This is a very undesirable condition as will be explained later. The maximum permissible temperature of a tungsten plate is about 1,500° C. At this temperature each square centimeter of surface area will radiate approximately 14 watts with an emission current of .0456 milliampere. A higher operating temperature would cause too great an emission. Most radiation cooled power tubes are designed to operate at a temperature of approximately 1,000° C. This is a cherry red in the case of metal anodes. In general it is safe to operate graphite plates just below the temperature where a sign of color is indicated.

Another important consideration in the radiation of energy is the surface characteristics of the anode. The ideal heat radiator is a perfect black body. Graphite more nearly approaches this condition than any other anode material. The emissivity of metal anodes is increased by either carbonizing (blackening) the surface or by carborundum blasting the surface to rougher it. This latter operation increases the surface area and hence the heat radiation. Either process will increase the radiation emissivity but it will still be quite low compared to that of a black body. The carbonized surface is a better heat radiator than the roughened surface.

Sometimes fins are added to the metal anode to increase the radiation surface. Fig. 6 shows

how this procedure is applied in practice although fins are also added to internal anodes. The tube shown in Fig. 6 is an RCA 892 de-

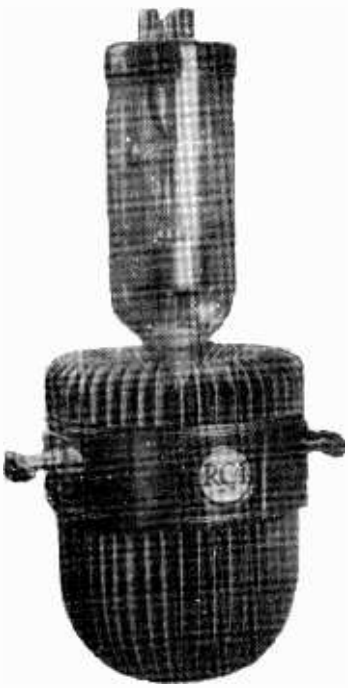

Fig. 6.—One of the standard metal-anode type tubes fitted with copper radiating fins for air cooling.

signed originally for water cooled operation but later modified to permit air cooling. To the copper anode, which extends below the glass envelope, are silver-soldered a large number of copper radiating fins. The tube so modified is given the type number 892-R. When mounted in the transmitter an airduct is clamped around the lower part of the tube and air is blown through the fins at a constant rate. Thus a blower motor and air distribution system are substituted for the water pump and cooling water system. This affords a considerable saving in the transmitter installation. The 892 as an r.f. amplifier in a Class C telegraph transmitter is capable of dissipating 10 kw whereas the 892-R in the same service is rated at 5 kw.

In connection with the desirability of high operating temperature and maximum heat radiation, it must be remembered that the heat must be radiated through the glass bulb (except for a tube like that in Fig. 6) so this definitely limits the amount of power that can be radiated. The larger the bulb the stronger it must be made to withstand the atmospheric pressure. The glass cannot be allowed to get too hot, otherwise it will soften and collapse. This is the principle reason why water cooling of the anode is ordinarily necessary for tubes of greater than 1.5-kw plate dissipation.

MECHANICAL PROPERTIES.—The mechanical properties of the anode material must be very carefully considered. The anode must retain its shape under all operating conditions if the tube is to maintain its characteristics. Even in small receiving tubes comparatively high evacuation temperatures are desirable. Nickel starts to crystallize at about 550° C and once crystallization sets in the anode becomes very soft and tends to lose its shape easily. Svea metal tends to crystallize in the same way at approximately 700° C.

Molybdenum does not soften or anneal at temperatures considerably higher than those reached during evacuation and hence is suitable for tubes of medium power. However, because electrons travel in straight lines from filament to plate the center of the anode tends to heat

more rapidly than the edges. This phenomenon may be so pronounced in some tubes that it is possible to see a bright outline of the filament on a flat metal anode. The uneven heating of the anode may cause warping unless special bracing is used.

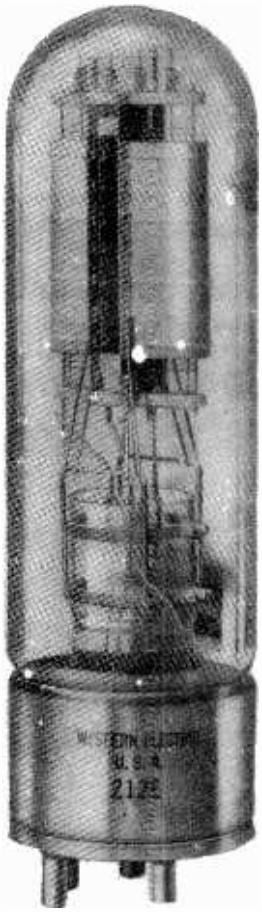

Fig. 7.—Type 212E—Filamentary air-cooled triode.

Fig. 7 shows clearly the anode construction and bracing employed in a typical air-cooled tube. This is the Western Electric 250-watt amplifier Type 212E. The small springs shown at the top of the element structure are used to counteract the tendency of the filament to expand and sag when heated.

The walls of the graphite anode are considerably thicker than those made of metal and this permits a much more uniform heat distribution. With a more uniform heat distribution a greater radiation emissivity is obtained. The walls of the graphite anode must be made thicker because of the low tensile strength of graphite. Graphite has a low coefficient of expansion so little difficulty is experienced with warping.

In small receiving tubes nickel wire is commonly used for grid structures. Molybdenum is used almost exclusively in power tube grids although tungsten wire also finds some application, particularly in water-cooled tubes.

WATER-COOLED TUBES.—Tubes rated above 1.5-kw plate dissipation are usually designed for water-cooled operation. A water-cooled tube is designed with the anode consisting of a copper tube of suitable diameter having the grid and filament assembly extending down into the anode tubing. The bottom of the cyclinder is closed and the open top is carefully joined to the glass tube, the glass being used merely permit the sealing of the top and at the same time the effective mounting and insulation of the grid and filament structures. The development of an absolutely air-tight glass to copper seal made the water-cooled tube practical. In operation the anode is mounted in a water jacket and the water is caused to circulate through the jacket at quite high velocity thus carrying away the heat developed at the

anode. Copper is used as the anode material because of its high heat conductivity.

Fig. 8.—Type 220B—Filamentary water-cooled triode.

Fig. 8 shows a typical modern water-cooled tube. The lower portion extending below the glass is the plate which fits into the water jacket. The filament and grid are inside the cylindrical plate. The two filament connections are in the form of clips extending above the upper tube level. Projecting from the center and enclosed in glass tubing is the grid stem and terminal. This tube is the Western Electric Type 220B. (Although the tube of Fig. 8 is representative of the shape and general arrangement of most water-cooled tubes, other arrangements and shapes are sometimes used, particularly in tubes designed specifically for high frequency operation.)

DESIGN OF PLATE STRUCTURES.— For a given kind of plate, the power that can be safely dissipated is a function of the plate area. For a given plate area the maximum power dissipation is function of the condition of the plate surface and the operating temperature. For radiation cooled tubes the maximum plate dissipation is from 5 to 10 watts per square centimeter of plate area.

For example, assume that a low power transmitting tube is designed with a cylindrical plate .7 inch in diameter and 1 inch high. Assuming safe dissipation of 6 watts per square centimeter, what is the maximum safe plate dissipation? It is first necessary to find the plate area in cm^2. Converting diameter and height to centimeters

$$d = 2.54 \times .7 = 1.78 \text{ cm}$$

and

$$h = 1 \times 2.54 = 2.54 \text{ cm}$$

$$\text{Circumference} = \pi d = 3.14 \times 1.78$$

$$= 5.59 \text{ cm}$$

$$\text{Area} = hC = 2.54 \times 5.59 = 14.2 \text{ cm}^2$$

The maximum dissipation will be $14.2 \times 6 = 85$ watts. The approximate power dissipation of any plate

can be calculated in like manner. If there is any question as to the factor of power dissipation/cm^2 a fairly low value should be used to allow a good margin of safety. For small tubes where the grid wires are quite close to the plate and may be injured if the plate is allowed to operate at high temperature, the allowable dissipation/cm^2 may be as low as 2 or 3 watts.

A water-cooled tube can dissipate about 75 watts/cm^2 of plate area. In order to carry away the heat from the plate of a water-cooled tube of the type 862 (100 kw) water circulation from 15 to 30 gallons per minute is required.

Two element tubes (cathode and plate) are used as rectifiers for converting alternating current to direct current. Where more complex tube operations are required as for amplifiers, oscillators, mixers, etc., additional tube elements are added in the form of wire grids between cathode and plate, to control the flow of electrons. The tube may have several grids. In every case the tube has a cathode and plate and the considerations as discussed for the simple two-element tube likewise apply to the more complex tubes. As a whole transmitting tubes are more simple in operation than receiving tubes because in transmitters a single tube is rarely expected to perform a multiplicity of functions.

SECONDARY EMISSION.—As mentioned earlier in this assignment secondary emission is also a source of electrons. Electrons may be emitted from a body (conductor or insulator) due to the impact of rapidly moving electrons. As the emitted electron travels toward the plate under the influence of the grid and plate voltages, it may attain a velocity in excess of 10,000 miles per second depending, of course, on the voltages acting on the electron.

A single electron striking the plate or grid at high velocity may cause the secondary emission of one or more electrons. The number of secondary electrons per primary electron depends on the material being bombarded, the physical conditions of the surface of the material and the velocity of the primary electron. For well cleaned degassed surfaces the number of secondary electrons per primary electron rarely exceeds two. If the material contains impurities or is not thoroughly degassed each primary electron may dislodge 3 or 4 secondary electrons. Positive ion bombardment is not a serious factor in producing secondary electrons. The velocity of the secondary electron is usually quite low, equivalent to that attained by an electron falling through a potential drop of only a few volts. The secondary electrons are emitted in all directions from the surface of the material.

Under normal triode operation secondary electrons will be drawn back to the plate immediately so no bad effects are caused by such emission. However, in certain type of tubes, particularly the screen grid type, where the screen, immediately in front of the plate is operated with a fixed positive potential, if the plate potential drops below the fixed screen potential the secondary electrons emitted from the plate will go to the screen instead of being attracted back to the plate. This seriously limits the useful output of the tube and

corrective measures have led to the design of the pentode tubes. This will be discussed in detail in later assignments.

The grid, being located between the emitter and plate, is particularly subject to the effects of secondary emission. An electron on the way to the filament may strike the grid and dislodge one or more secondary electrons. These secondary electrons will come under the greater attraction of the positive plate and many of them will go on to the plate. In some transmitter tubes the secondary emission electrons *from* the grid, with certain circuit adjustments, may exceed the electrons reaching the grid from the filament, and the grid current meter may actually show a reversed grid current.

Secondary emission is practically always undesirable in vacuum tube operation. It is reduced to a minimum by using pure elements in grid and plate structures that are well cleaned and degassed before the tube is put into operation.

There are certain modes of operation where secondary emission is made to serve a useful purpose. For example, an "electron multiplier" tube has been developed in which a few electrons due to primary emission are accelerated and caused to strike a surface having high secondary emission properties. Surfaces coated with an electropositive metal may produce 8 or 10 secondary electrons per primary electron. The original electrons *plus the greater number due to secondary emission* are accelerated and strike another surface causing a still greater increase of electrons by secondary emission, etc. By successive impacts *very high* amplification of a small initial current may be obtained. Such tubes were developed to amplify the very small currents due to photo emission in photo cells. This principle is also an important factor in the operation of various forms of television pick-up cameras, such as the iconoscope, image dissector and image orthicon.

ELECTRICAL CHARACTERISTICS

THE TWO-ELEMENT VACUUM TUBE.— After the electrons have been emitted from the filament or indirectly heated cathode they come under the influence of a number of forces, the combined effect of these forces determining the resultant electron movement and the functioning of the tube. In this discussion the terms "filament" and "cathode" may be used interchangeably.

To produce electron emission from a filament in a vacuum it is only necessary to heat the filament. This is done by passing current through the filament or through a separate heating element. The circuit consisting in its most simple form of the filament and battery is, so far as any other body is concerned, a *neutral body*. There are various differences of potential across different parts of the circuit, but the entire circuit consisting of the battery, filament and connecting leads contain just enough electrons to neutralize all the positive charges in the circuit. This being the case, if electrons are taken away from the circuit, the circuit will assume a positive charge equal to the number of electrons that were removed. Thus, if electrons are

emitted from the heated filament, the filament will assume a positive charge and therefore an attraction for electrons.

When an electron is emitted, it in general still has a certain amount of kinetic energy left over, in excess of that required to overcome the work function and allow it to be emitted. The left-over kinetic energy varies over a very wide range, although it averages about .67 electron volts for an oxide-coated cathode. Corresponding to the residual kinetic energy after emission is an *initial velocity of emission;* i.e., electrons come out of the emitter at all sorts of speeds and directions. It is the initial velocity of emission that permits an electron to overcome the attractive force of the positive charge left behind in the emitter, and to dart out into the interelectrode space in the tube.

SPACE CHARGE.—Since electrons all have negative charges, they repel one another according to Coulomb's law. As free electrons in the wire, their repelling effects on one another are balanced by the attractive forces exerted by the positive ions. When the electrons are emitted into a vacuum, and the positive ions left behind, it is clear that they now exert their repelling effects upon one another without any interference by the positive ions. The mutual repelling effect is the result of the *space charge,* which refers to the region of space filled with but one kind of charge—that of the negative electron.

In analyzing the behavior of a vacuum tube from a theoretical viewpoint, it is customary to assume first that the electrons have no initial velocities of emission, and hence merely appear on the surface of the emitter, like dew on a cold pitcher of water. The action of a voltage, applied between a second, positive electrode called the plate and the emitter acting as the cathode or negative electrode, is to cause the emitted electrons to start to move toward the plate.

As they fill the interelectrode space, en route to the plate, they form a cloud or space charge which modifies the flow to the plate. On the other hand, if the electrons have initial velocities of emission, then they form a space charge in the interelectrode space even when no positive potential is applied to the plate. In either case, the plate current flow, when plate potential is applied, is limited by the space-charge effect, and it will be of interest to study this phenomenon.

Child's Law.—Consider first the case of no initial velocity of emission. As indicated in Fig. 9, a diode (two-element) vacuum tube is connected so that the plate can

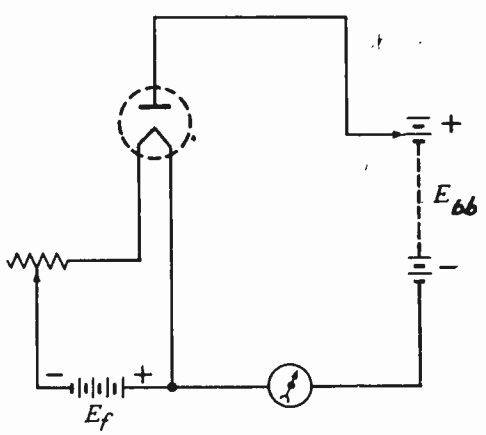

Fig. 9.—Plate current flow in a diode tube.

be given any desired positive potential E_p with respect to the cathode. When the voltage E_p is zero, no electrons are drawn over from the cathode to the plate, and the current is zero.

Now suppose E_p is made equal to some low value, such as 25 volts. Electrons begin to be drawn over to the plate. Since the interelectrode space is a vacuum, it offers no resistance or opposition to the electron flow. Furthermore, the heat energy supplied to the filament cathode has produced the thermionic emission, so that no energy is required from the plate battery for this function. It would therefore be reasonable that the 25 volts applied should pull over all the electrons emitted, and the current flow should be large and limited solely to the number of electrons emitted per second by the cathode.

Actually the current flow, for 25 volts applied to the ordinary diode, is but a fraction of the emitted, maximum value. A plate voltage considerably in excess of 25 volts is required to produce the maximum, so-called saturation value of flow. The factor that holds down the current flow is the space-charge effect.

Thus, suppose the applied voltage starts a current flow. As the electrons leave the cathode, others are emitted on its surface in place of those that have left. The first electrons that left had the full attractive electric field of the plate to pull them over. But the next electrons that are emitted find the first group between them and the plate, in the form of a negative space charge or cloud. The attractive force of the plate on the second group of electrons is now partially counteracted by the repelling space-charge effect of the first group of electrons. Suppose there is still a net attractive force. The second group will then also leave the cathode and proceed to the plate. But now a larger number of electrons is in the interelectrode space, so that the force of attraction on newly emitted electrons is decreased still further. Ultimately a point is reached where the number of electrons in transit to the plate is so great that their space-charge repelling effect balances the attraction of the plate for electrons at the cathode, and no more electrons come off.

However, the moment an electron in the interelectrode space deposits on the plate, its repelling effect is lost, and an electron is able to leave the cathode because momentarily the plate's attraction has overbalanced the repulsion of the space charge. Thus, initially the interelectrode space fills up with electrons en route to the plate, and the plate current is then limited by the balance between their repelling effect and the plate's attractive force on fresh electrons emitted at the cathode. The current flow is then determined by the number depositing on the plate, and there is a kind of dynamic equilibrium.

If more electrons attempt to enter the interelectrode space from the cathode than those depositing on the plate, the space-charge repulsion exceeds the plate's attractive force and repels the electrons back to the cathode; if more electrons deposit at the plate than are emitted at the cathode, the space-charge repulsion will be less

than the attractive force of the plate, and cathode electrons will be drawn into the interelectrode space until the space charge just balances the plate's positive charge. Thereafter the current flow is such as to maintain this equilibrium, and the necessary flow is relatively small for 25-volts plate potential.

This is illustrated in Fig. 10. An electron at the cathode—position A—has the most electrons

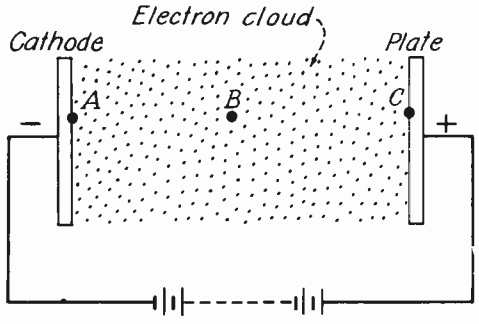

Fig. 10.—Forces acting on electrons at different positions in the interelectrode space.

intervening between it and the plate, and is therefore least attracted by the plate. For equilibrium, the net force is exactly zero.

An electron in position B has considerable electrons between it and the cathode; these electrons tend to repel it *toward the plate.* On the other hand, electrons between it and the plate tend to repel it *toward the cathode.* A net force exists urging it toward the plate. Finally, an electron at C has all the electrons to its left; they repel it toward the plate and thus help the plate draw it to itself.

Thus the forces on an electron vary with its position in the interelectrode space. As stated previously, electrons surge out into this space until the number in it is so great that the force of attraction for an electron at the cathode is reduced just to zero, whereupon there is no tendency for any more electrons to move into this space. However, as was just shown, electrons at intermediate points will have a net force tending to project them to the plate, hence they will move, and in so doing, they will deposit on the plate and reduce the space charge, whereupon equal numbers of electrons from the cathode will surge into the space to take their place. Since the action is continuous, there is a continuous flow of current.

For double the plate voltage, or 50 volts in this example, the number of electrons in the space charge must double in order to reduce the force on electrons at the cathode to zero, but the net attractive forces on electrons at positions nearer to the plate, such as at B or C in Fig. 10, will be double their previous values, hence electrons at such points will be accelerated to considerably higher velocities (actually $\sqrt{2}$ times as high as before) and will deposit out more rapidly on the plate.* The more rapid movement

*The square root of two arises as follows: For any electron at any point in the space, the force has doubled, hence the energy put into it (force times distance) is doubled, since the same distance is involved in either case. Twice as much energy put into it means that the electron has acquired twice as much kinetic energy. But this is equal to $\frac{1}{2} mv^2$. Hence the velocity must be $\sqrt{2}$ times as great, in order that its square be exactly twice as great and thereby represents twice as much kinetic energy.

of the space charge ($\sqrt{2}$ times as much) as well as its doubled density, both operate to cause $\sqrt{2} \times 2 = 2\sqrt{2} = (2)^{3/2}$ times as many electrons to deposit per second on the plate when its voltage is doubled, or in general the current varies as the three-halves power of the voltage.

Such an E-I relationship clearly does not follow Ohm's law, and accounts for some of the undesirable effects, such as distortion, produced in vacuum tube amplifiers; as well as some of the useful properties, such as modulation and the like. The three-halves power relationship was first worked out by C.D. Child in 1911, and is known as Child's law. Langmuir subsequently showed that this relationship holds for all kinds of tube electrode structures, whether plane, cylindrical, etc. Although in actual practice certain factors may cause the actual current variation to depart from this law, it is surprisingly accurate over a wide variety of conditions.

Initial Velocity of Emission.— If the electrons are emitted with initial velocities, then they will form a space charge even in the absence of plate voltage. In such a case, some will even be projected over to the plate and will constitute a current flow even when no plate voltage is applied. This was first discovered by Edison, and is known as the "Edison effect." To limit such flow, the plate must actually be given a negative potential, called a stopping potential.

Experiments of this nature indicate that theoretically there is no upper limit to the velocity of emission; although very few electrons are involved, emission velocities corresponding to hundreds of volts may be involved. This is in contrast to photoelectric emission, where the velocity has a top value proportional to the difference between the energy in a photon of the light used and the work function of the material. This is Einstein's equation, and was given in an earlier assignment.

However, the *average* velocity of emission, for an oxide-coated cathode, is about 0.67 volts, as mentioned previously. The plate current is increased by this effect as if the plate voltage were higher by 0.67 volts, which is a small increment compared to the several hundred volts used for plate potential. Hence, the initial velocity of emission is normally not an important factor in vacuum tube performance.

But this phenomenon may be of some importance in certain applications. Electrons are emitted in all directions from a cathode. In the case of a cathode-ray tube, these electrons must all be redirected to a common focal point or spot on the cathode-ray screen by suitable electron focusing means. The various initial emission speeds give rise to a distortion or blurring of the spot that is similar to chromatic aberration (color fringes) in optical lens focusing. Finally, it is to be noted that the emission of electrons in discrete steps in random directions and at random speeds causes the space charge to vary in similar erratic manner. This in turn produces random variations in the plate current, which are known as shot effect noise. It is similar to thermal noise in the input signal source, and therefore also serves

to set a lower limit to the magnitude of signal that can be amplified.

PLATE DISSIPATION.—The action of the plate voltage on electrons at different points in the interelectrode space brings out a very important factor in the operation of a tube. In ordinary wire or metallic conduction, the electrons encounter opposition to their flow all along the conductor's length. The resistance is uniformly distributed along the conductor, hence the heat is generated uniformly along it.

The heat generated in a vacuum tube, on the other hand, is localized at the surface of the plate. This is because in the interelectrode space there are no obstacles in the path of the electron flow, so that the electrons reach very high velocities by the time they arrive at the plate. They therefore strike the plate with great force and set its atoms into vibration; this is nothing more or less than thermal agitation or heat energy developed in the plate. The effect is illustrated in Fig. 11.

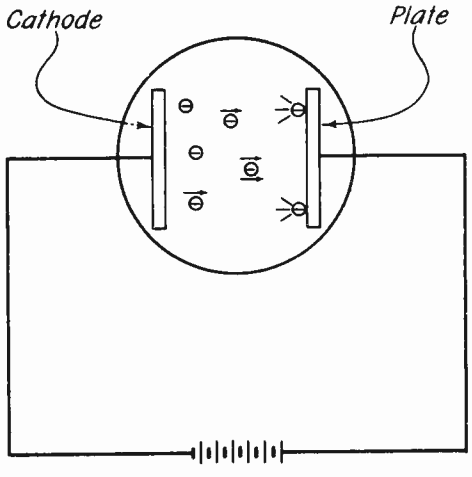

Fig. 11.—Electrons starting out from the cathode attain high velocities by the time they reach the plate, and strike it with sufficient force to heat it to a high temperature.

The amount of heat energy developed depends upon the magnitude of the current flow and the plate potential. If—for a desired current flow—the plate potential could be reduced, the heat developed and required to be dissipated by the plate, would be less. However, owing to space-charge effects, considerable plate voltage is required to cause a large current to flow. This is because such a large current produces a large electron cloud in the interelectrode space, so that a correspondingly high plate potential is required to overcome its repelling effect on the electrons just emitted at the cathode. But such a high plate potential produces a high accelerating force on electrons closer to it than the cathode.

In short, in order to be able to move electrons at the cathode, the plate voltage must be so high as to be more than sufficient to move electrons that are already in the space charge. The excess force or these electrons gives them unnecessary velocity and kinetic energy, which is then converted into useless heat energy when they strike the plate.

Gas Tubes.—If relatively fixed positive charges could be distributed throughout the interelectrode space, the negative space charge could be neutralized throughout its extent, and then very little plate voltage would be required to produce current flow. The production of such positive charges can

be readily accomplished by inserting a suitable gas or vapor in the tube.

A preferred gas is mercury vapor, produced by inserting some droplets of mercury in the tube. Sufficient vapor is formed even at room temperatures to furnish considerable quantities of atoms in the interelectrode space.

This may seem to contradict the statement made previously that the tube should have as high a vacuum as possible so as not to impede the flow of the emitted electrons. However, the number of mercury atoms introduced is not excessive; the pressure is still fairly low. The electrons have sufficient mean free path between mercury atoms to attain sufficiently high speeds so that when they collide with a mercury atom, they can dislodge one or more electrons from it, and leave it as an ionized particle.

Thus additional electrons are produced in the interelectrode space, and help to increase the current flow. But this is a minor benefit. The major benefit is from the positively charged mercury ions. These are very heavy, and therefore drift slowly toward the (negative) cathode, as shown in Fig. 12. En route, they act as attractive agents to the electrons and cancel the space charge. As a result, the plate-to-cathode voltage drop is no longer high: it cannot exceed the ionization potential for mercury, which is but 15 volts. Hence, the plate dissipation is very much less than for a high-vacuum tube.

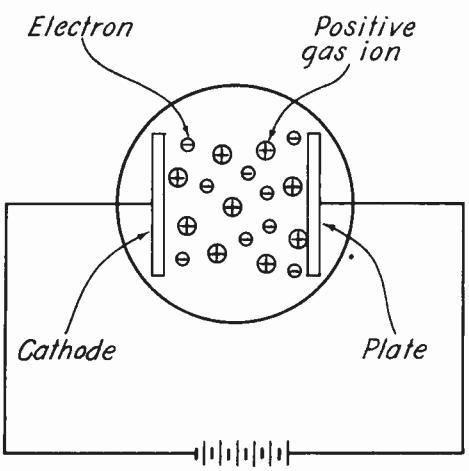

Fig. 12.—The production of gas ions in the interelectrode space counteracts the negative space charge of the electrons themselves.

The last statements are true so long as the current flow does not exceed the rate of emission of electrons from the cathode. Should the external load normally placed in series with the plate to be so low as to allow current in excess of the emission to flow, a shortage will be produced at the cathode surface, and automatically the voltage drop in the space in the vicinity of the cathode will rise.

Immediately positive (mercury) ions will be accelerated toward the cathode and strike it with sufficient force to produce additional emission. Such ionic bombardment of the usual oxide-coated cathode is very damaging to it, hence the current drawn should never exceed the thermionic emission of the cathode, and the voltage drop between cathode and plate (in the conductive direction) should never exceed about 22 volts or so.

Mercury vapor is usually preferred because it furnishes very heavy positive ions that linger long in the interelectrode space and exert maximum space charge cancelling effects; it has less tendency in the form of neutral

atoms to cling to an electron and produce a negative-ion-cluster, whose effect is opposite to that of positive mercury ions; mercury does not "poison" the ordinary oxide-coated cathode or other electrodes; and liquid mercury pellets appear to furnish just sufficient vapor to yield the optimum space-charge cancelling results, with the droplets acting as a reserve should any of the vapor be adsorbed by the electrodes.

On the other hand, for very low temperature operation, as in high-altitude flying, mercury may not vaporize sufficiently, and other gases, such as helium, argon, and even hydrogen, may be preferred. Gas tubes are normally employed as rectifiers, and have the advantage over high-vacuum diodes in that the voltage drop across them is much lower. This in turn means that more of the impressed a.c. voltage is available as d.c. voltage when rectified, and also that less heat is dissipated at the plate of the rectifier tube.

It would therefore appear that all rectifier tubes should be gas-filled. This is practically the case for high-voltage high-power applications, such as transmitters. For low-power applications, such as ordinary public-address systems and particularly radio receivers, the high vacuum tube is preferred because it produces less noise and r.f. interference.

In gas tubes the ionization occurs suddenly when the a.c. potential, rising from zero toward its crest value, passes through the ionization voltage for the gas. As a result, there is a sudden increase in current which shock-excites resonant circuits in the set and sets up oscillations. Oscillations of radio frequency can radiate to the input coils of the receiver and thus cause noise.

In passing it may also be mentioned that instead of a uniformly distributed group of positive charges, positive (or negative) electrodes may be introduced at one or more places in the tube. These electrodes will also have a profound effect upon the current flow, and moreover, their potential with respect to the cathode can be varied at will, whereas the positive gas ions have fixed charges. Hence the electrodes, normally called grids, are employed where control of the current is desired, as will be discussed in greater detail in later assignments. The important thing to note here is that whether ionized gas or grids are employed, the effect is to modify the space charge and thereby the current flow in the tube.

SPACE-CHARGE AND TEMPERATURE-LIMITED CURRENTS.—It has been mentioned that the current varies as the three-halves power of the applied voltage, so that a plot

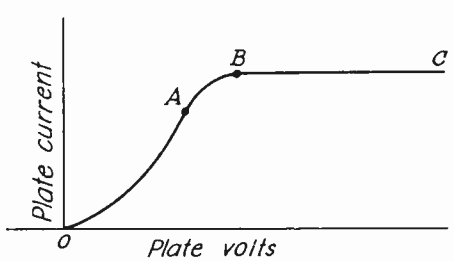

Fig. 13.—Current-voltage relation in a diode.

of the two quantities should appear as OA in Fig. 13. This portion of the complete curve is concave upward, as is to be expected of a 3/2 power law.

As the voltage is still further increased, the current ceases to rise as rapidly, and the result is portion AB of the curve. The reason for this reverse bend is that the emission is beginning to limit the current flow, rather than space-charge effects, as is the case for portion OA.

As the voltage is still further increased, curve BC is obtained. Here the current no longer increases, or at most, increases very slowly. Theoretically, if the cathode emitted a fixed number of electrons depending solely on the temperature, a sharp break in the curve would occur at saturation, there would be no knee as at AB, and BC would be horizontal; i.e., the current would cease to increase.

Actually, however, a curve somewhat like that shown in the figure is obtained, particularly with an oxide-coated cathode. There appear to be several reasons for this:

1. The rough surface of the cathode results in strong electric fields concentrated around the points and also the crevices in the surface; more plate voltage is required to remove the electrons emitted in the crevices than electrons emitted from the points.

2. At the higher plate voltages, the electric field intensity at the cathode may be sufficient to produce what is known as field emission, this is in addition to the thermionic emission.

3. The flow of plate current through the oxide-coating may produce additional heating and emission. Local "hot spots" may form on the cathode, and permit it to "run away" with the emission. The bend or knee is referred to as temperature limitation of the space current; i.e., the current is limited by emission, which in turn is limited by temperature.

A further phenomenon that is of interest is that a much greater current can be drawn momentarily from an oxide-coated cathode than can be drawn over an appreciable period of time. The reason is not at all clear, but one hypothesis is that the composite cathode structure acts somewhat like an electrolytic capacitor of high storage capacity. This capacitance effect permits a momentarily high discharge or rather emission current from the cathode and only a moderate long-term or constant current flow.

Another characteristic of importance is space-charge limitation of the space current. Suppose the cathode of a diode is heated by a small heater current, so that its temperature is low and the thermionic emission small, and suppose further a fairly high plate voltage is applied. The plate current will be limited by the emission, that is, temperature limitation will obtain.

Now suppose the cathode temperature is continuously increased, while the plate voltage is maintained constant. At first the plate current will increase, as indicated in Fig. 14 by OA. This portion of the curve resembles OA in Fig. 13, but represents a totally different relation. Here OA represents the exponential increase in temperature limited or emission

current as the cathode temperature is increased. The plate voltage is presumably sufficiently high to draw overall the electrons emitted.

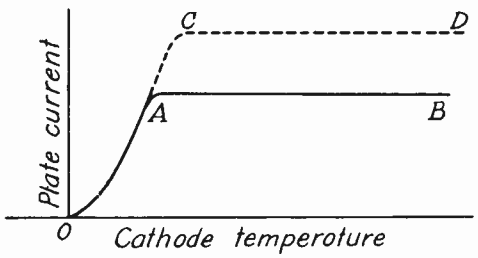

Fig. 14.—Plate current as a function of cathode temperature, for two values of plate voltage.

However, as the cathode temperature and hence emission are increased, the plate voltage is no longer able to draw over the electrons as fast as they are emitted; temperature limitation of the plate current no longer exists, and in its place space-charge limitation of the plate current occurs. In short, the plate's attraction for the electrons is now balanced by space-charge effects, and the constant current that flows (curve AB) is the result of such a balance.

If the plate voltage is increased to a higher fixed value, curve AC is at first obtained. This is merely a continuation of OA, and represents the continuing effect of temperature limitation until point C is reached. From this point on, the plate current is once more limited by space-charge effect, but of course at the higher level represented by CD.

The limitation in plate current by space-charge effect is the normal mode of operation of vacuum tubes. As an example, the average small oxide-coated cathode is operated at a temperature such that the emission is more than adequate for the peak current required. Therefore the current is limited not by emission, but by space charge.

As the tube ages, the emission decreases. When it reaches the value where it, rather than space charge, limits the peak current that can be drawn, the tube is considered worn out. This is, after all, a common sense viewpoint: the limitation to current flow in the tube should be the applied plate (and grid) voltages, and load impedance connected in series with the plate, rather than the cathode emission.

FILAMENT HEATING POWER.—The larger, transmitting-type tubes almost invariably have a filament type of cathode, since the amount of emission required is large, and cannot be economically furnished by an indirectly heated cathode. Moreover, these tubes operate at fairly high signal levels, and hum produced by an a.c. operated filament is not so important a factor in comparison with the signal level.

D.C. POWER.— Nevertheless, filaments have been heated in many cases by d.c. furnished by a motor-generator set, with or without a "floating" battery connected across the d.c. line. Where the plate current is an appreciable portion of the filament heating current, unequal heating of the filament may occur.

This is illustrated by Fig. 15. The plate battery, of voltage E_{bb}, may be connected to either side of the filament, as is indicated by the two dotted-line connections. The filament has a

voltage drop across it such that side A is negative to side B, by E_f volts. The center point C of the filament may be taken as the

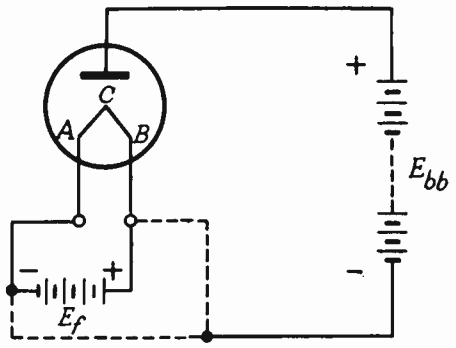

Fig. 15.—Tube with d.c. applied to filament.

point of average potential of the filament; i.e., as the zero reference point.

If the negative end of the plate battery is connected to point A, then the effective plate voltage is $E_{bb} - (E_f/2)$ *with respect to point C;* if the connection is to point B, the effective plate voltage is $E_{bb} + (E_f/2)$ with respect to point C. Thus the effective plate voltage will differ by E_f volts in the two cases. Normally, however, E_f is negligibly small compared to E_{bb}, so that the above variation in itself is of little consequence.

However, the difference in effective plate potential with respect to different parts of the filament does have an important effect upon the plate current distribution in the filament. To see this, refer to Fig. 16. For convenience, the negative end of the plate supply is shown connected to the positive end of the filament (point B). The plate current i_p (electron flow) passes through the plate battery as shown, and then divides in the filament circuit as indicated by the dotted lines.

Since end A is more negative with respect to the plate than is end B, more electrons will tend to be drawn from end A to the plate than from end B. This means that the returning plate current will leave the filament, en route once again to the plate, to a greater extent from end A than from end B.

Hence the negative end of the filament carries a heavier current than the positive end, and therefore tends to run hotter. This in turn indicates that the negative end of the filament will volatilize faster and disintegrate sooner. To avoid this, a reversing switch is placed in the filament leads so that the polarity of the filament voltage may be periodically reversed. This in turn prolongs the useful life of the filament by equalizing the wear.

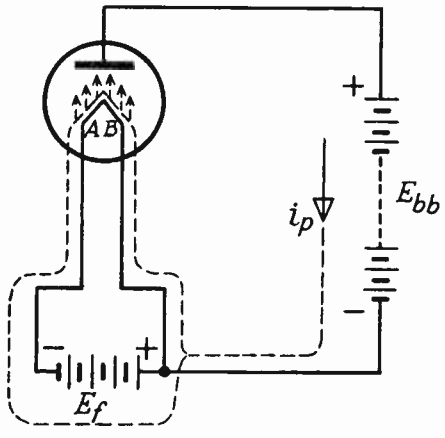

Fig. 16.—Plate current distribution in filament-type tube.

A.C. POWER.—The same effect can evidently be obtained if the filament is heated by a.c. In this case the effect of a reversing switch operating 60 times a second is obtained. This is particularly important in large power tubes, such as those used in the final stage of a transmitter, and it is here that a.c. heating is most feasible, since the signal level is highest at this point, and the hum of relatively little significance. Furthermore, a step-down filament transformer is simpler and cheaper than a motor-generator set.

The circuit is shown in Fig. 17, and is practically self-explanatory, expecially in view of the

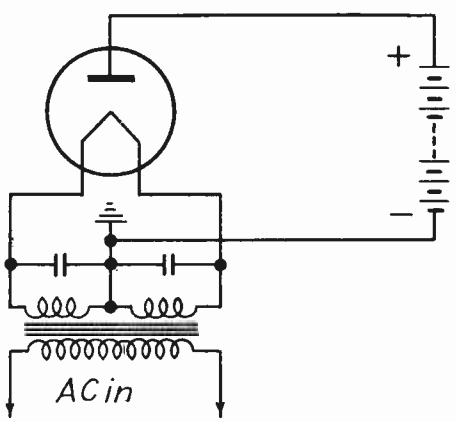

Fig. 17.—Use of a.c. to heat tube filament.

previous remarks made concerning Fig. 16. The two capacitors shown serve to by-pass high-frequency components of the plate current directly to the filament and thus avoid passage of the components through the filament leads and secondary of the filament transformer.

In short, the high-frequency components are "bottled up" in the stage, and not permitted to flow through wires and circuits common to other stages. This eliminates undesirable coupling and feedback.

Other very important reasons for the use of alternating current for heating the filaments of transmitting tubes are those of convenience and economy. Consider the case of the water-cooled power tube Type 862-A; the filament requires a continuous supply of 207 amperes at 33 volts. If more than one tube is used, multiply the current requirement by the number of tubes. If direct current is used one of two methods may be employed to furnish the power; either a 34-volt storage battery which must have a very large ampere-hour capacity to stand the heavy drain, or a direct current generator built for this low voltage and high current. The cost and up-keep of the storage battery would be absolutely prohibitive, even neglecting the space requirements of such an installation. A voltage dropping resistor would also be necessary. A direct current generator having the proper voltage and currert characteristics will be more satisfactory than the batteries, but a generator of this type is expensive and very often develops commutator trouble due to the high current passed. Such an installation also requires an expensive filter to eliminate commutator ripple.

On the other hand, some commercial source if alternating current is nearly always available, and on a ship-board installtion it is only necessary to have a small alternator which can develop 110 or 220 volts and which may be driven

on the same shaft as the high-voltage plate generator if desired. Then by the use of a small step-down transformer which costs very little and which occupies only a very small space within the transmitter, the alternator voltage may be stepped down to the required thirty-three volts for the filaments. The alternator and transformer combination when properly designed requires almost no attention and very seldom develops trouble. It will be seen that for the filament supply of transmitting tubes practically all of the arguments are overwhelmingly in favor of alternating current.

In modern broadcast transmitters, a.c. is used for filament heating with special precautions being taken to eliminate the hum. Hum elimination in the output is ordinarily accomplished by feeding into the input circuit out of phase components which balance out the hum generated in the transmitter itself. The 891 and 891-R water-cooled tubes can be used on single phase a.c., two phase a.c., or d.c. These tubes have a center-tapped filament which simplifies the connections for the various voltage sources. On d.c. only the outside connections (entire filament) are used.

CONCLUSION

This concludes the assignment on thermionic emission. Although the properties of a two-element or diode tube have also been treated here, the main topic has been that of electron emission from a heated conductor, and the criteria determining the selection of materials for this purpose.

Space-charge effects were then considered, and it was shown how this results in a three-halves power relationship between the plate current and plate voltage. Initial velocity of emission was also considered in connection with this. The effect of the introduction of a gas or vapor, and its counteracting of space-charge effects by ionization, were also analyzed.

The assignment concluded with a discussion of method of heating filaments, and compared d.c. with a.c. power for this purpose. Subsequent assignments will take up the application of diodes as rectifier elements in power supplies, and the numerous applications of multi-element tubes, such as triodes and pentodes, etc., in electronic and radio circuits.