Technical Developments Underlying the Toll Services of the Bell System

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EARLY DEVELOPMENTS

General—Telephone Instruments

TELEPHONY involves the transmission of speech to a distance by electrical means. Speech itself, physically considered, consists of rapid longitudinal variations in air pressure, or acoustic waves as they are called, traveling out from the mouth of the speaker or to the ear of the listener. Each sound has its characteristic wave form or group of wave forms and as a result these acoustic waves are of complicated and rapidly changing wave form as is illustrated by the oscillograms on Fig. 1 showing the structure of the electrical current in a telephone circuit resulting from the spoken word "Harvard," and, in more detail, the vowel in "Har." The telephonic transmission of speech requires, therefore, three fundamental elements:

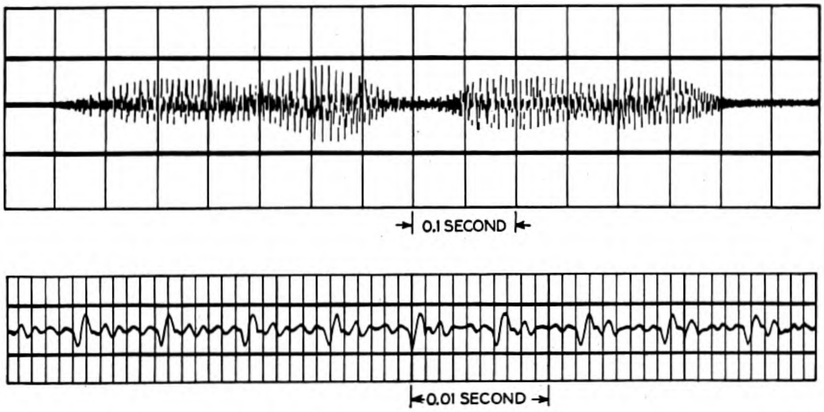

Fig. 1—Oscillograms showing electrical current in a telephone circuit resulting from spoken word "Harvard" and vowel in "Har."

(*a*) An instrument which, when acted upon by the acoustic waves of the speaker's voice, produces in an electrical circuit oscillations or waves suitable to represent the voice of the speaker. This is the telephone transmitter.

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*At the request of the Federal Communications Commission, this pamphlet was recently prepared to give the Commission a brief account of some of the principal technical developments which have led to telephone toll service as given by the Bell System. As it brings together in concise form a summary of a large amount of information of interest to communications people generally, it is being issued with a few minor editorial revisions as a supplement to the Technical Journal.

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(*b*) A circuit from the point of transmission to the point of reception suitable to transmit these complicated electrical oscillations in the proper magnitude without undue distortion of form and without interference from electrical currents from other sources. This is the telephone circuit.

(*c*) An instrument which, receiving the electrical oscillations transmitted over the line from the telephone transmitter, reproduces acoustic waves of proper loudness and quality to correspond with those produced by the speaker's voice, by means of which waves the speech is transmitted to the listener. This is the telephone receiver.

The telephone invented by Bell in 1875 corresponded in principle to the telephone receiver of today and could be used alternately as a telephone transmitter and a telephone receiver. It consists of a diaphragm of magnetic material associated with a magnet and coils of wire. When this instrument is placed before the speaker's mouth, the variations in acoustic pressure cause the diaphragm to vibrate. The instrument is so designed that this vibration in the presence of a magnet produces electrical oscillations in the coils of wire. When these oscillations are transmitted over the telephone circuit to the coils of wire in a similar instrument, they cause variations in the strength of the magnet which, in turn, cause vibrations of the diaphragm of the receiving telephone. The vibrations of the diaphragm produce acoustic waves which reproduce the speech of the talker at the distant end of the circuit.

This instrument is very inefficient as a telephone transmitter and from earliest days efforts were directed toward the development of transmitters working on a different principle. Bell himself suggested the principle most generally used. This principle is that the vibration of the transmitter diaphragm shall vary the resistance of a local electrical circuit through which current is caused to flow by a battery. The variation in resistance can cause variations in the flow of current sufficient to induce relatively powerful electrical oscillations in the telephone circuit—in fact, the oscillations so induced may have a power several hundred times as great as that of the acoustic waves produced by the speaker. The telephone transmitters acting on this principle are, therefore, powerful amplifiers.

In his early work, Bell devised a transmitter working on this principle consisting of a small platinum wire attached to a diaphragm of goldbeaters skin and dipped very slightly into acidulated water held in a conducting cup. It was with this instrument that the first complete telephone sentence, "Mr. Watson, come here, I want you," was successfully transmitted on March 10, 1876.

Almost from the first, the efforts of inventors to develop successful telephone transmitters made use of this principle, and while many variable resistance elements were tried out with some degree of success, transmitters employing granular carbon, the resistance of which varies with pressure, were the most satisfactory. Such a transmitter devised in 1878 by Hunnings of England using powdered "engine coke" was extensively used commercially. Better performance was provided by the design in 1890 by White of the Bell System of the so-called "solid-back" transmitter. This principle and the use of carbon transmitter elements have survived through numerous improvements in transmitter design and are applied to millions of telephone instruments in use today.

The telephone station of today includes, generally speaking, a transmitter of the variable resistance type, a receiver based on the principle of Bell's original discovery, both of these instruments being modern in design, includes induction coils, condensers, etc., necessary for electrically associating the transmitter and the receiver with each other and with the telephone line and, in addition, includes such items as a bell, a switchhook, etc. which are necessary for signaling and control of the telephone circuit.

Telephone Switching Systems

Very early in the practical use of the telephone, it became evident that the full usefulness of this method of communication required the development of means by which any subscriber could quickly obtain connection between his telephone and any other telephone rather than being limited in his conversations to one other subscriber or a small group of other subscribers connected together on the same telephone circuit. The difficulties which would be encountered with a telephone plant consisting of large numbers of stations connected to one circuit are obvious, the outstanding disadvantage being that only two subscribers could carry on a conversation over the circuit at one time. These difficulties led to the development of telephone switchboards at which connection could be made between lines to any two subscribers in a given town or city.

As technical developments made toll service between different cities possible, means were needed for the rapid connection of any two subscribers in different cities. It would obviously be impracticable to connect together at the same switchboard subscribers in distant cities, and switching systems were adopted so that toll connections between any two subscribers in different cities could be established over telephone lines terminating in toll switchboards located in those cities, and trunks between the subscriber switchboards and the toll boards.

As the number of subscribers and the extent of telephone service increased, it became impractical and uneconomical to connect all telephone subscribers in the larger cities to the same switchboard; impracticable because the size of such a switchboard would be so great as to make the interconnection of two lines an unwieldy and slow procedure; uneconomical because of the relatively large amount of telephone line which would be required to connect the more distant subscribers with the central office. For these reasons means of interconnecting switchboards within a city were devised whereby a station terminated on one switchboard can be connected to a station terminated on another switchboard in the same city over a telephone line or "interoffice trunk" terminating on each switchboard. The design and layout of the subscriber and switchboard plant require careful consideration in determining the maximum economy which can be realized with the proper balance between subscriber lines and interoffice trunks.

Telephone Circuits and Cables

At the beginnings of telephone service it was found that the iron wire then used for telegraph circuits was, in many cases, not satisfactory for telephony because of the losses of energy taking place in the wires and the rapid diminution in the loudness of the transmitted speech with the distance over which it was transmitted. At first no wire was available having better electrical characteristics and at the same time sufficient mechanical strength to withstand the strains it was subjected to when strung on a pole line. Thomas B. Doolittle of the Bell System, who was familiar with certain physical properties of copper, conceived that if copper were drawn cold through a series of dies, he might obtain a wire of much greater physical strength than the soft annealed copper wire then used in a small way in the making of electrical apparatus. In November, 1877 he arranged with a manufacturer to try the process and it was so successful that in 1878 a quantity of hard-drawn copper wire was placed in service in the Bridgeport, Connecticut exchange. The success of this and subsequent installations showed that a wire which was electrically efficient and mechanically strong had been obtained by means of which telephone service could successfully be given over considerable distances.

The numbers of wires required to serve telephone subscribers in large cities led at an early date to the development of means for putting the wires underground. The early experiments starting in 1878 took advantage of the known advantageous properties of lead water pipes. Insulated copper wires were drawn into lead pipes of this character. By 1886, practical means had been developed whereby lead heated to the point of plasticity could be extruded over a compacted group of insulated conductors, thus forming the pipe tightly about the conductors, and this general principle has been followed in telephone cables to the present day. By 1890 there was a general development of insulated telephone cables in the congested parts of the larger cities. In 1891 Bell System engineers introduced the use of paper for insulating cables, and this practice is still followed in cable manufacture.

Early Toll Service

The success of the early installations of hard-drawn copper wire for short lines indicated that a type of conductor had been developed by which it might be possible to extend telephone service over considerable distances. This led to a very important experiment, the construction in 1883 of an experimental toll line between New York and Boston carrying two wires.

Prior to the construction of the New York–Boston line, telephone lines, following telegraph practice, were generally of one wire grounded at both ends, the so-called "ground return circuit." However, based upon experiments with iron wires over shorter distances, particularly between Boston and Providence, J. J. Carty of the Bell System had determined that the ground return circuit was so noisy, due to interference from telegraph lines and other causes, that such circuits could not be used over long distances, and had also discovered that by using two wires connected as a metallic circuit, the interference was very greatly reduced. Carty's metallic circuit was used with success in the New York–Boston line and was adopted for all the following construction of long toll circuits. The metallic circuit principle thus developed first for toll lines extended back into local lines so that in highly developed areas all telephone circuits are now constructed on the metallic circuit principle.

This experiment successfully demonstrated the practicability of "long distance" transmission and led to the determination to extend long distance service as widely and as rapidly as the state of the art permitted and to the incorporation in 1885 of the American Telephone and Telegraph Company for this purpose. The first telephone line constructed by this new company was the New York–Philadelphia line, using hard-drawn copper wire on a metallic circuit basis. It was found that with two or more metallic circuits on a pole line, speech currents flowing in one circuit will cause similar, weaker currents to flow in the other circuits. This is called induction or crosstalk and experience with the New York-Philadelphia line showed that so much induction between telephone circuits was obtained that intelligible crosstalk resulted; in other words, one could overhear on one circuit what was said on the others. To overcome this, systems were developed whereby, by suitably interchanging positions of the wires of a circuit, the inductive effects in that circuit from an adjacent circuit would tend to neutralize. This is illustrated in Fig. 2 for a simple case of two circuits. In this figure the circuit sections "*a*" and "*b*" are equal in length, and voltages are being induced into circuit No. 2 from circuit No. 1. The arrows show the directions in which the induced current would tend to flow in circuit No. 2, the wires of which are interchanged in position between the two sections. It will be noted that the induced voltage in section "*b*" is equal in magnitude to that in section "*a*" and, by the interchanging of wires at the junction, is made to oppose that of section "*a*." The effect of this interchange or transposing of wires is such as to neutralize the induction in sections "*a*" and "*b*" appearing at the circuit terminals.

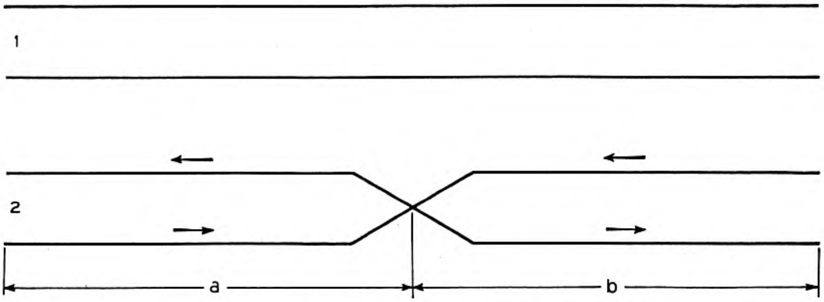
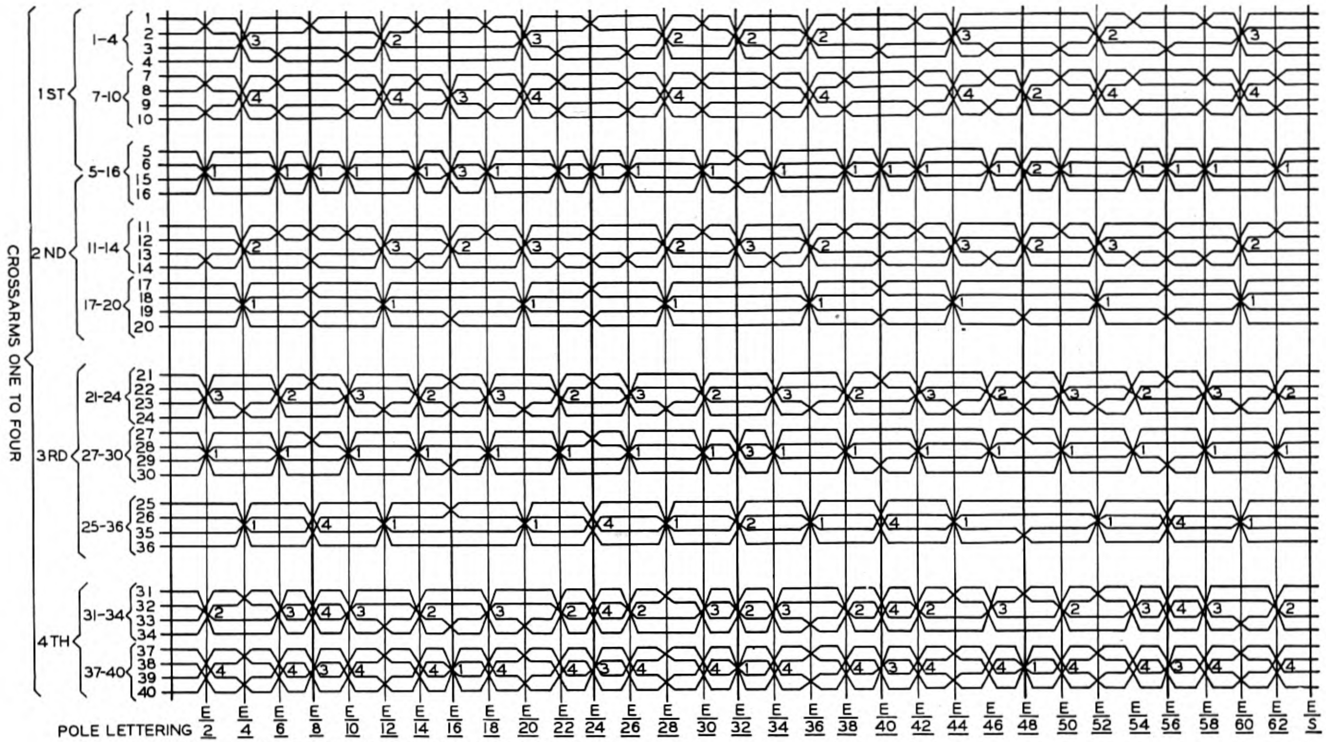


Fig. 2—Side or non-phantomed circuit transposition.

With a large number of circuits, the induction between each two circuits must be neutralized in each short section of line, and to accomplish this, more complicated arrangements, known as transposition systems, were developed. The first system of this sort was worked out by J. A. Barrett of the Bell System in 1886. The development of transposition systems has continued constantly since that time, the problem changing with the increase in the number of circuits on a line, developments in the transmission of electrical power on lines which sometimes are constructed near the telephone lines, the introduction of phantom telephone circuits, and of repeaters and carrier telephone circuits into the plant. Figure 3 shows a typical transposition system in use in the Bell System today.



NOTES: — LINE TRANSPOSED IN DIRECTION OF ARROW ⟶
THE FIGURE AT EACH PHANTOM TRANSPOSITION INDICATES THE TYPE. SPACE AS REGULARLY AS POSSIBLE

Fig. 3—Typical transposition system in use in Bell System today.

With the more extensive application of the cable developments mentioned above to local circuits, it was natural that they should be extended to the longer circuits used for toll business. In 1898 a 30-pair 16-gauge cable insulated with paper was extended eight miles from Boston toward Lynn, Massachusetts. Shortly after this a 30-pair 14-gauge cable was placed between Boston and Wakefield, Massachusetts, a distance of about 12 miles. It was found, however, that with the increasing distance in cable, the loss in transmission rapidly increased since cable circuits, because of the small size of the wires and the large electrical capacitance, had inherently poorer electrical characteristics for the transmission of telephone currents than the larger open wires strung on poles.

The Phantom Circuit

The phantom circuit has grown out of a conception of Jacob in 1883 which is illustrated in principle in Fig. 4. He conceived that by bridging resistances across each end of two parallel telephone circuits, a third circuit could be created as indicated by connecting telephones at each end between the midpoints of these resistances. These three telephone circuits could, therefore, use four wires without mutual interference. While this scheme was not practicable, it led to a proposal by Mr. Carty in 1886 to substitute balanced transformers (called repeating coils) in place of the resistances as indicated in Fig. 5.

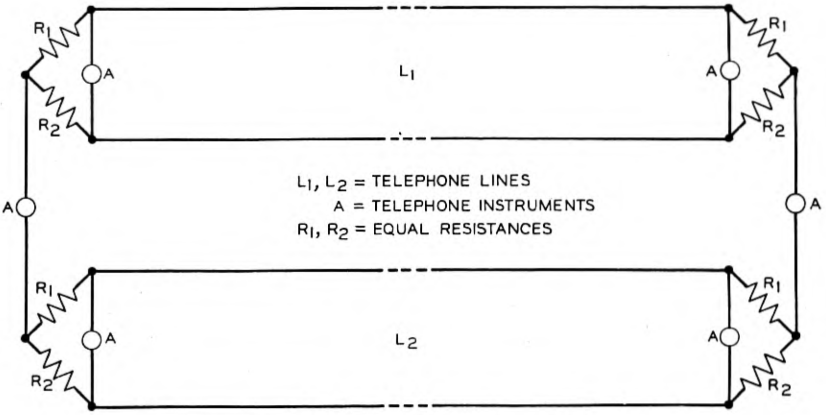


Fig. 4—Phantom circuit—conception of F. Jacob.

In order to successfully apply this idea it was necessary to develop repeating coils that were carefully balanced, that is, which had the two halves of their windings very exactly equal in electrical characteristics, so that the current from the phantom circuit would divide equally between these two halves of the windings and not influence the other circuits (called the "side" circuits). Also, an improved technique of line construction was necessary in order to avoid high resistance joints and other irregularities in construction which would result in overhearing between the phantom and the side circuits. Furthermore, in order to avoid overhearing between different phantom circuits on the same pole line, it was necessary to interchange not merely the two wires of each pair but also all four wires of the phantom group as is indicated in the transposition system shown in Fig. 4. This greatly complicated the design of transposition systems. An important feature of the problem is the high degree of balance required since the transfer from the phantom circuit to the side circuit of more than one-millionth of the electrical energy carrying the telephone currents in the phantom circuit or vice versa might be sufficient to make overhearing possible. This high degree of balance was achieved by years of painstaking work and resulted in the first successful phantom circuits in the year 1903.

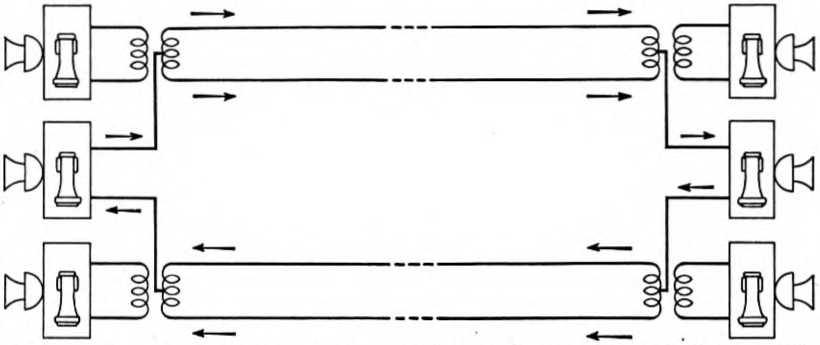


Fig. 5—Diagram of phantom circuit using balanced transformers (called repeating coils).

Today 12,400,000 miles of wire in the Bell System are installed in such a way as to be suitable for phantom operation. Without phantoming, 6,200,000 additional miles of wire would be required for the same circuit mileage.

Superposed Telegraph on Telephone Circuits

From the very beginnings of long distance telephony, the telephone wires were used also for private line telegraph service. At first, means had not been developed for using the wires simultaneously for both telephone and telegraph, and the two services were offered alternatively to the private line customers. Beginning in 1887, however, successful experiments were conducted in using telephone wires simultaneously for telephone and telegraph services by the method of superposition which is shown in Fig. 6.

The first method, called "simplexing," is an adaptation of the phantom principle for the use of telegraph on telephone circuits, the grounded telegraph circuit being introduced at the midpoint of repeating coils at the two ends of the telephone circuits, the currents dividing equally in opposite directions so that there is no interference between the telephone and telegraph circuits. The other method of simultaneous operation of telephone and telegraph circuits, however, depends upon a new principle and one which has come to be of the greatest importance in the subsequent development of telephony. This principle is the selection and separation of electric currents into different channels depending upon differences in their frequency of alternation.

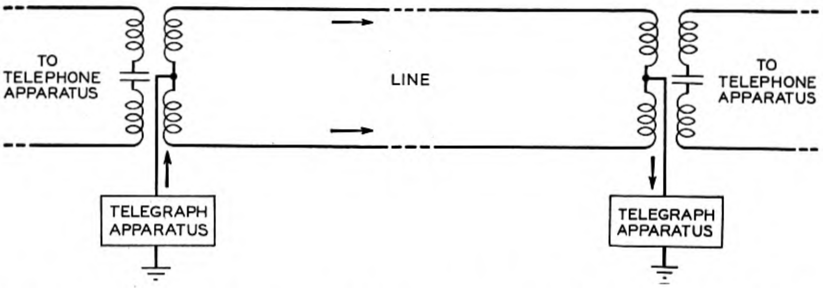


Fig. 6—Schematic of telegraph circuit superposed on a telephone circuit using the "simplex" method.

While the form of the electrical oscillations which transmit speech over a telephone circuit is extremely complicated, as indicated in Fig. 1, such oscillations can, by processes of analysis, be considered as made up of a large number of simple alternating currents of different frequencies. A simple current of this type, which is sometimes spoken of as a sine wave because of the mathematical law which expresses the variation in the flow with time, is shown in Fig. 7. Such a current by gradual variations at regular intervals reverses its direction of flow. Each double reversal is called a "cycle" and the number of such double reversals in a second is called the frequency of cycles per second.

An analysis of telephone currents shows that, in order to transmit satisfactory speech, it is necessary for all of the telephone apparatus and circuits involved to transmit with nearly uniform efficiency simple alternating currents over a considerable range of frequencies. For new designs of telephone circuits, the minimum range so transmitted is between about 250 and 2,750 cycles. The voice contains components of lower frequencies and also of high frequencies but it is not necessary to transmit them because their contribution to the clearness of the speech is relatively unimportant.

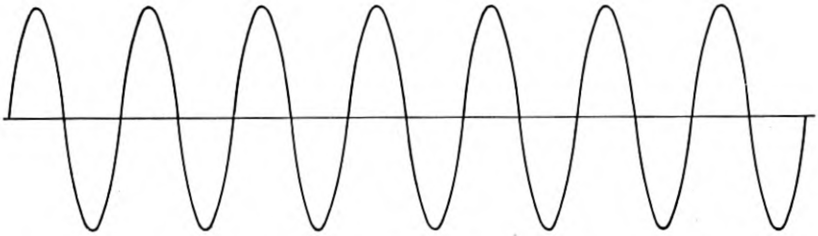


Fig. 7—Graph of a simple alternating current or "sine wave."

A similar analysis of the currents used for telegraphic transmission shows that they may be considered also as composed of simple alternating currents covering a band of frequencies—with equipment generally used in the Bell System, this band extends from zero up to roughly about 100 cycles. Components of the frequencies above about 100 cycles can be excluded from the telegraph circuit without reacting upon its efficiency of transmission with the equipment and the speeds of signaling commonly employed in private line telegraph circuits. This difference in the range of frequencies required for the transmission of telephone currents and for the transmission of telegraph currents makes possible the application of the principle of separation of electrical currents into different channels depending on the difference in their frequency of alternation mentioned above. Apparatus placed at the terminals of the circuits, which is called "composite sets," is so designed that telegraph currents and the telephone currents can be transmitted into the same wires and at the receiving end are separated into the telephone and telegraph channels, respectively, without interference. The form of this apparatus is indicated diagrammatically in Fig. 8.

The principles of simplexing and compositing have been applied extensively to the long distance circuits of the Bell System, there being now in service approximately 760,000 miles of telegraph circuit operating on these principles using wires simultaneously with their use for telephone transmission without mutual interference.

Development of the Mathematical Theory of Transmission—Loading

As telephone lines came to be extended over greater distances, it was evident that, even with the best copper telephone circuits, the loudness of speech transmitted over the circuit rapidly became less with distance, and also, particularly when the circuits were in cable, the clearness of the speech was impaired at the greater distances. At first these effects were not clearly understood, there being no adequate quantitative analysis of the effects on telephone transmission of the various electrical characteristics of the telephone circuits. Throughout all the early development period, the continued study of the mathematical theory of the transmission of currents over wires led to an increasing insight into these problems and into the conditions necessary for transmitting telephone currents over long distances efficiently and without undue distortion. The foundation was laid in the masterful, if sometimes enigmatic, papers of Oliver Heaviside published over a long period of years beginning with 1882. One result of Heaviside's work was an appreciation on his part of the unexpected fact that an improvement in transmission efficiency of telephone circuits would be brought about by an increased inductance of the telephone circuits, and he suggested in his papers that means

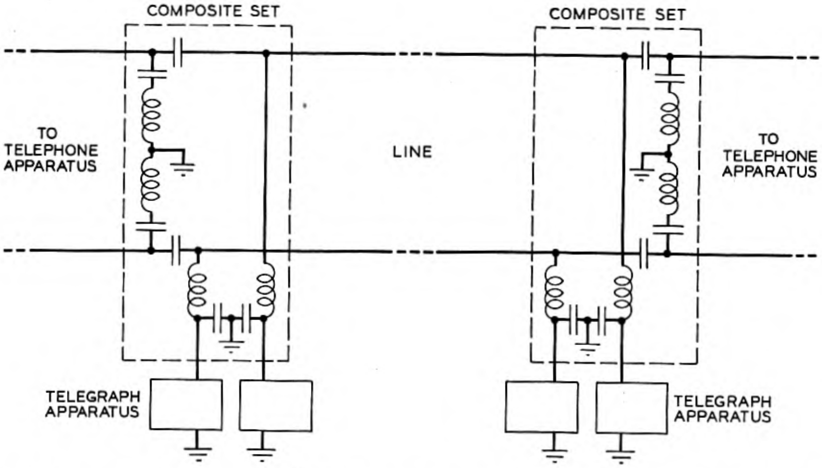


Fig. 8—Schematic of a telegraph circuit superposed on a telephone circuit using "composite sets."

might be found to increase the inductance artificially. This suggestion was taken up by two investigators in America, Professor M. I. Pupin of Columbia and Dr. G. A. Campbell of the Bell System who, working independently, proved by further mathematical development that this could be done practically and showed how to do it. These mathematical studies showed that, while the addition of inductance in large quantities at one or several points in the circuit destroyed its capability for transmitting telephone currents, the insertion of inductance in smaller quantities at regular and frequent intervals by means of highly efficient inductance coils would greatly improve the transmission efficiency.

Interurban Toll Cables

The development of practical means of applying the loading principle had been stimulated by the need for some practical means of improving the efficiency of toll cables. This principle led promptly to the extension of interurban toll cables, important items being the installation in 1906 of cables between New York and Philadelphia, a distance of about 90 miles, and between New York and New Haven, a distance of about 80 miles, and, in 1908, of a cable between Chicago and Milwaukee having a length of about 90 miles. At about this time experimental work was being actively conducted by the Bell System in the effort to develop a type of construction for toll cables which would permit the use of phantom circuits in the cables as well as in open wire. This required a new technique in cable construction, involving new principles and many refinements in detail to eliminate the interference which would exist between phantom circuits and the side circuits from which the phantoms are derived and also between phantom circuits in the same cable. The processes worked out included not only manufacturing methods but new types of electrical tests and new splicing procedures applied in the course of installation by means of which the unbalances in successive lengths of cable are made to largely neutralize each other. As a result of this work, a successful phantom cable was installed between Boston and Neponset, Massachusetts in 1910, a distance of six miles.

This work led to the inauguration in 1911 of a very important interurban cable project. At the time of the inauguration of President Taft on March 4, 1909, a sleet storm of unprecedented severity had broken down all the wire lines entering Washington and isolated the Capitol from the rest of the country. The Bell System management determined that, as soon as technical advances made it possible, means would be adopted for insuring against any future similar interruption of the communications between the United States Capitol and the rest of the nation. Upon the success of the experiments described above, it was decided to complete an underground cable route connecting Washington with Baltimore, Philadelphia, and New York, using large gauge conductors, the phantoming principle which had just been successfully demonstrated, and new systems of loading designed specifically for the new cable. The project was completed in 1912 and in 1913 this high grade cable route was extended to Boston, through New Haven, Hartford and Providence.

POSSIBILITIES AND PROBLEMS ASSOCIATED WITH THE USE OF THE TELEPHONE REPEATER

The developments discussed above had done a great deal to extend the range of telephone service making possible good commercial service between the Atlantic Seaboard and Chicago and a service of a kind as far west as Denver and providing a storm-proof cable route connecting Washington and Boston and the intermediate cities of the Atlantic Seaboard. By 1912, however, it was apparent that in addition to pushing to the utmost the advantages to be gained from the technique already developed, it would be necessary, if universal service for the entire country were to be realized, to find satisfactory means for amplifying the attenuated telephone currents on a long telephone circuit so that after transmission over one section of line they could be restored, in amplitude, transmitted into a second section, and when again attenuated restored a second time and transmitted into a third section of the line and so on, without undue distortion or change in the structure of the voice currents. The device to accomplish this is called a telephone repeater. The conclusion that improved repeaters were required was reached after a careful analysis of all of the possible means of achieving further extensions in the range of long distance transmission and as a result the energies of the research forces of the Bell System were to a greater extent than before directed to the development of improved telephone repeaters and of circuits and methods of line construction which would make possible their general use.

One of the chief problems which confronted the engineers undertaking the intensive telephone repeater development work beginning in 1912, was the development of an amplifying element for a repeater which could be used generally for telephone purposes. The telephone repeater was not new in the art at that time, since a repeater giving beneficial results had been invented by H. E. Shreeve of the Bell System and first used successfully on a circuit between Amesbury, Massachusetts and Boston in 1904. The Shreeve repeater took advantage of the amplifying characteristics of a variable resistance telephone transmitter and combined in one instrument, in refined form, the fundamental elements of a telephone receiver and a transmitter. The attenuated telephone currents entering the receiver side of the device caused the vibration of a diaphragm which, in turn, actuated a variable resistance element which transmitted amplified currents to the next section of telephone line. Figure 9 shows a cross-section of the amplifying element of this repeater, commonly known as the mechanical repeater. Repeaters of this type were used in commercial service for a number of years but since development work up to the time of the application of vacuum tubes to telephone repeaters had not overcome the fundamental difficulties of distortion, gain limitations and instability of the mechanical repeater, its use was gradually discontinued after the introduction into the telephone plant of the vacuum tube repeater. Other arrangements such as variation of the field current of a generator to produce corresponding variations in the armature voltage and the electromagnetic control of gaseous devices were tried out but were never successfully applied in any important degree to telephone circuits.

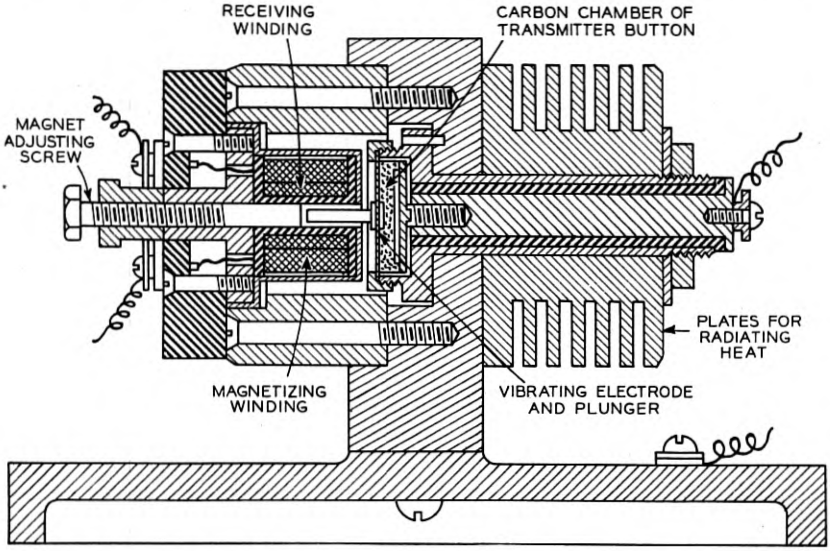


Fig. 9—Cross-sectional drawing of a mechanical type of telephone repeater.

In 1906, Lee DeForest demonstrated before the American Institute of Electrical Engineers that the discharge between a hot cathode and a plate of a thermionic tube can be controlled by a third electrode.

Immediate use of this discovery was made in improving radio telegraph receivers. The tubes and circuits thus employed were not of types that could satisfactorily be used in telephone work which required a high stability of the amplifying device and freedom from distortion of speech currents. However, an intensive study of the possibilities of this device showed that the use of such tubes based on DeForest's discovery was by far the best method of amplifying telephone currents yet developed.

Development work on vacuum tubes carried on by the Bell System has included the perfection of the tubes by the use of high vacuum, scientific proportions and new types of filaments to secure improved efficiency. The performance of vacuum tubes used in the Bell System has been improved extensively through continued development work. For example, during the last twelve years the average life of the tubes used in the Bell System has been extended by a factor of 10, and, at the same time, their power consumption has been reduced appreciably.

Vacuum tubes were first applied to telephone repeaters experimentally, and to a small degree commercially as early as 1913. One of the first important uses of vacuum tube repeaters, however, was in 1915 in connection with the first transcontinental telephone service between New York and San Francisco, a distance of approximately 3400 miles. The circuit consisted of No. 8 B.W.G. open-wire copper conductors loaded at eight-mile intervals and having vacuum tube telephone repeaters located at Pittsburgh, Omaha, and Salt Lake City.

Years of experience with early forms of telephone repeaters had shown that the successful use of repeaters depended not only upon the development of a suitable amplifier but also upon the design of suitable circuit arrangements for associating the repeater with the telephone line and on improved methods of line construction. An important consideration is the fact that a telephone circuit must operate in both directions, that is, it must permit talking to be carried on from either end of the circuit. A single telephone repeater element, however, is inherently a one-way device, receiving attenuated currents at one pair of terminals and transmitting amplified currents from the other pair of terminals. The association of such one-way elements with a two-way telephone circuit is not a simple matter because if any considerable proportion of the amplified output current of the repeater reaches the input terminals, it is again amplified and results under ordinary conditions in turning the repeater into a generator of alternating currents (an oscillator) and destroying its usefulness as a repeater.

The type of circuit arrangement most commonly used to associate two repeater elements with two sections of telephone line in such a way that the operation will be satisfactory is shown schematically in Fig. 10. This is known as a 22-type repeater. Attenuated telephone current transmitted from a distant point over the west section of line passing through the transformer *A* of a special design (sometimes called a hybrid coil) enters the input of amplifier element *B* and is amplified. From the output of amplifier element *B* it passes through a second transformer *C* associated with the east section of line and a balancing network *E*. An essential function of the repeater circuit lies in the design of the transformer in such a way that the two halves (between the midpoints of which the input to the amplifier element *D* is connected) are equal and in the design of the east line and of the balancing network *E* in such a way that they offer the same impedance to the flow of current. Coil *C* is so designed that if this condition is exactly met, none of the ouput current from amplifier element *B* is transmitted across to the input element of amplifier *D*. However, currents transmitted in from the east section of line pass through Coil *C* to amplifier *D*, are amplified and retransmitted to Coil *A* where the condition of balance also must be applied between the west line and the balancing network *W*.

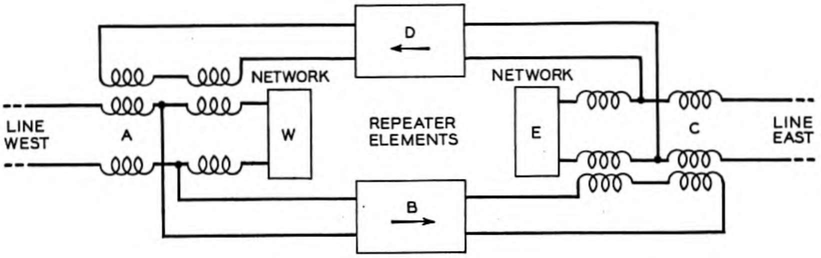


Fig. 10—Schematic 22-type telephone repeater circuit.

The complete repeater circuit includes many other things beside the bare essential elements shown in Fig. 10. Important among these are electrical filters to control the band of frequencies, potentiometers to control the amplification, transformers to efficiently interconnect different parts of the circuit, equalizers (see chapter on Associated Technical Developments) and arrangements for the supply of electric power to the vacuum tubes.

Obtaining a condition of balance requires that each section of line offer the same impedance to the flow of current as the balancing network associated with that section of line in the repeater circuit. A difficulty to be met arises from the fact that telephone currents are very complicated in wave form as previously indicated and involve components varying all the way from 200 or 300 to 2700 cycles per second or more. In order to provide for suitable operation, the condition of balance must be met within a close approximation for currents of all of the frequencies within this range. The reason why this requirement reacts on the construction of telephone lines is very simply illustrated by the curves of Figs. 11 and 12. Figure 11 shows the impedance of a long telephone circuit for all frequencies within that range when the circuit is of very uniform construction throughout. Figure 12 shows the corresponding impedance curve obtained if there are some irregularities in construction in the line. It is possible to design balancing networks which have the same characteristics as those indicated in Fig. 11 for the uniform line but it is not practicable without too great expense to design such networks having the same characteristics as the irregular line shown in Fig. 12. This is true since the characteristics of no two irregular lines are the same, the characteristics varying widely depending upon the nature and the location of the irregularities.

Means for the general use of repeaters on telephone circuits therefore involved the development by the Bell System of line balancing networks and the development of long telephone lines with uniform impedance characteristics over the range of frequencies used in telephony. In some cases this could be done by making the lines uniform in construction. For example, loading coils had to be designed so that they had, very accurately, equal amounts of inductance and had to be spaced at exact equal intervals along the line. Furthermore, it was found that the types of loading coil in previous use were affected by lightning and other causes so that the amounts of inductance changed enough to interfere with repeater operation. It was, therefore, necessary to develop new types of coils of very stable materials which would avoid this change in inductance.

In some cases, it is not possible to construct the line in a uniform way throughout. For example, it is often necessary for open-wire lines to be brought into towns and cities through sections of cable. For such cases, for each type of open-wire construction, a type of cable construction was worked out having such characteristics that it could be connected to the open wire without spoiling the impedance characteristics of the circuit. This involved the development of new loading systems for use on cables of this sort. In the case of circuits entirely in cable, improved uniformity in the manufacture of the cable

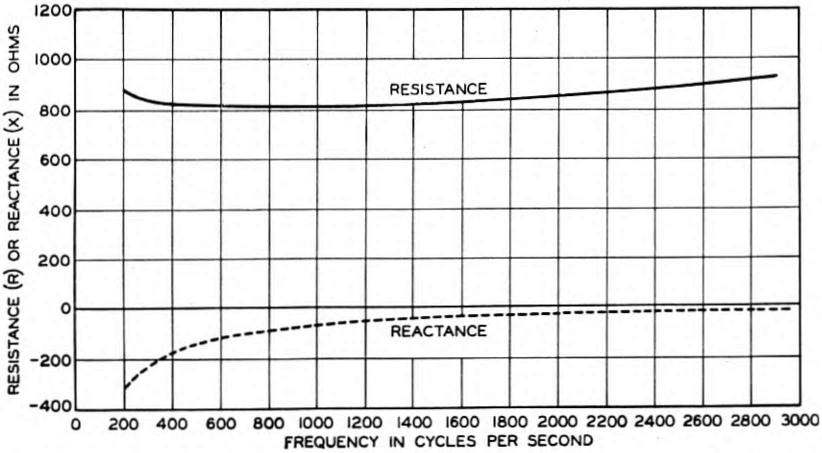


Fig. 11—Impedance-frequency characteristics of a smoothly constructed telephone line. Impedance $(Z) = \sqrt{R^2 + X^2}$.

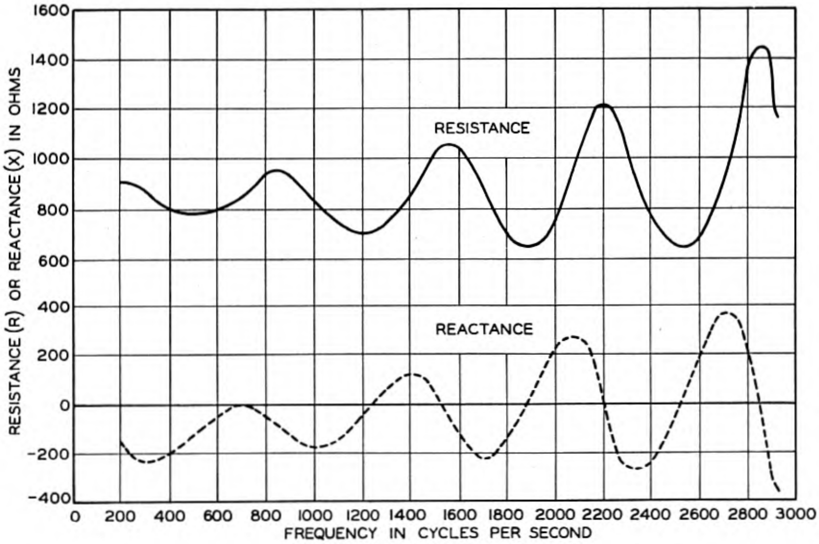


Fig. 12—Impedance-frequency characteristics of a telephone line having an impedance irregularity.

itself was required as well as improved loading coils and more exact rules for their location.

Generally speaking, repeaters are used in connection with the phantom circuit arrangements previously described, by means of which three independent telephone circuits are derived from four wires. The application of repeaters to such a group of four wires in cable (spoken of as a phantomed group or a quad) is shown schematically in Fig. 13. In this figure, the boxes denoted "Telephone Repeater" represent the complete repeater circuit shown in Fig. 10. It is necessary to separate the telephone currents of the phantom circuit from those of the two side circuits by applying to the phantom group highly balanced repeating coils, just as is done at the terminals of the circuit, and providing separate repeaters for each of the two side circuits and the phantom as is illustrated in the figure. The figure also shows a typical telegraph circuit arrangement—a metallic telegraph circuit on each pair, separated from the telephone channel by composite sets as previously described, and passing through telegraph repeaters at the telephone repeater point.

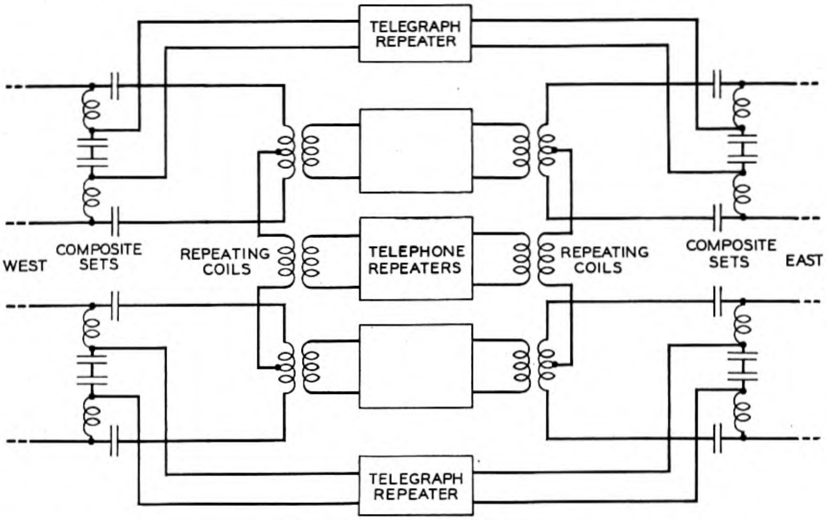


Fig. 13—Showing schematically the association of the four wires of a phantom group and composite sets, repeating coils, telephone repeaters and telegraph repeaters.

Phantom operation through cables, without crosstalk between the phantom and its side circuits and between the circuits in different quads of the cable, has involved a long train of developments in decreasing the tolerances of manufacture and increasing the uniformity in the characteristics of the cable. The cables must meet a double requirement, namely, freedom from crosstalk, which is made more difficult with the application of repeaters, and uniformity of characteristics to provide for suitable repeater operation. This double requirement has been met by niceties in design, construction, and installation, including a series of delicate electrical tests on the cable and portions of the cable during the process of installation.

With these developments, it became possible to use repeaters to provide a large improvement in the transmission efficiency of telephone circuits both in open wire and in cable, a number of repeaters where necessary being used at different points on the same circuit. The repeater element itself could be made so free from distortion that a very large number of them could be used in succession on the same circuits. The limitation in the use of repeaters, however, was determined largely by the degree of balance practicably obtainable through the more uniform construction of the telephone lines. While it was practicable to have such a degree of balance that a single repeater would amplify the telephone current often six or sevenfold, it was not generally practicable even with the use of a number of repeaters to extend the length of circuit using a given size of conductor over eight to tenfold. For transmission over very long distances or for the use of very small conductors in long toll cables, another principle was developed which was applied to toll cables and to the use of carrier systems on open wire, and will be discussed in connection with those subjects.

Toll Cable System

The success achieved in the general application of repeaters to telephone toll circuits opened the way for a great extension in the use of toll cables. Toll cables have the obvious advantage of providing a high degree of security and continuity for telephone circuits due to the fact that they are nearly immune from the effects of bad weather, particularly of sleet and of high winds which sometimes seriously interrupt open-wire telephone service by placing on the conductors and on their supporting structures loads greater than those for which they can economically be designed. Also, cables form the practical means for providing the very large numbers of circuits required to take care of the demand on very heavy routes by making it possible to crowd into one route a much greater number of circuits than could be provided by the ordinary open-wire technique.

Before the general use of repeaters became practicable, toll cables had the inherent disadvantage that, with the small conductors necessary to place a large number of circuits in one cable (until recently maximum outside diameter 2⅝ inches), the cable circuits, even when equipped with loading coils, had a very high attenuation loss per mile compared with the open-wire circuits. Even when very large conductors were used in the cable at the sacrifice of the number of circuits in order to provide circuits of high efficiency, as was done in the first cable between Washington, New York, and Boston, the losses were still high because of the close crowding together of conductors in the same circuit and of the fact that even the best insulation which could be provided, namely dry paper, resulted in considerably more energy losses to the telephone conversations than take place on open-wire circuits in which the conductors are separated at very considerable distances by air.

The use of repeaters in cable circuits made it possible to get high net efficiency over long distances using small conductors, since it was possible to compensate for the relatively large loss by the repeated gains introduced into the circuit by repeaters suitably located about 40 to 50 miles apart. That this might be done, however, required a reduction of manufacturing tolerance limits for cables, loading coils, and apparatus and care in the design, construction, and maintenance of the cable circuits. Also, new loading systems were designed which transmitted a broader band of frequencies than those transmitted by the earlier systems. This was desirable both because of the improved clearness of speech resulting from the broader band of frequencies itself and also because the use of the new loading systems made it possible to provide for better repeater balance within the band transmitted.

While these improvements made possible a very large extension in the distances over which good transmission could be given on small gauge cable circuits, it was found that, with many repeaters, the balance difficulties were still sufficient to justify the development and use for the longer circuits of a different arrangement. This arrangement, which is shown schematically in Fig. 14, consists of using for each telephone circuit two pairs or two transmission channels, each equipped simply with one-way amplifiers and thus arranged to transmit the telephone currents in one direction only. Two such one-way channels, oppositely directed, are connected together at the terminals of the circuit by apparatus similar to that used for associating amplifiers with two sections of line in the ordinary telephone repeater, including apparatus for balancing the line or the equipment to which the circuit is connected when in use. The complete circuit is thus reduced at its terminals to two wires like any other telephone circuit. From the fact that it uses two channels for transmission in opposite directions, it is called a four-wire circuit. These channels may, however, be either side or phantom circuits as in the case of an ordinary repeatered telephone circuit.

With the four-wire circuit, since the two directions of transmission are kept isolated from each other throughout, there is no need for providing balance except at the terminals of the circuit and this makes possible the use of higher repeater gains and, therefore, a higher net efficiency of transmission with such circuits for long distances than would be possible with the other form of circuit (generally called two-wire circuit). Circuits of this four-wire type are now generally used in toll cables for distances more than about 100 to 150 miles.

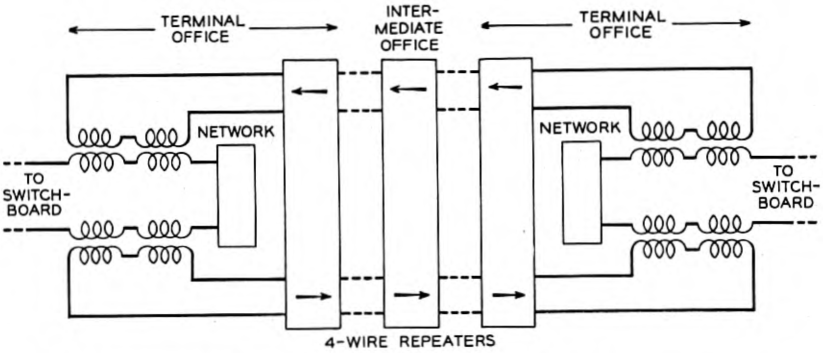


Fig. 14—Schematic of a four-wire circuit using two one-way transmission paths.

Mention was made in the first chapter of this statement of the refinements in manufacture and in installation procedures which were necessary in order to produce suitable interurban toll cables, particularly cables designed for the use of phantom circuits. With the extension of toll cables to great distances equipped at frequent intervals with telephone repeaters, additional refinement in design and in construction was necessary in order to prevent crosstalk between the different circuits in the cable. This includes the physical separation in different parts of the cable of conductors used by four-wire circuits for the opposite directions of transmission. Even with all the refinements which have been worked out, crosstalk remains today one of the major factors to be considered in the engineering of long telephone circuits.

The velocity of propagation of telephone currents over circuits is high so that in all of the early telephone development the length of time required for propagation over the longest circuits used was not sufficient to introduce any new difficulties in the problem of providing good telephone transmission. The velocity of transmission, however, varies with the type of circuit, is lower on loaded circuits than on non-loaded circuits, and in loaded circuits in cable in common use is as low as 10,000 miles a second. With the greater distances for which cable circuits of the four-wire type could be used, it was found that the time of transmission required at a velocity of 10,000 miles a second was great enough to introduce additional difficulties in the provision of satisfactory transmission. The nature of these difficulties and of the means adopted for overcoming them will be discussed a little later. However, it must be mentioned here that to overcome these difficulties, it was necessary, for these longer circuits, to devise new loading systems which provided circuits with a velocity of 20,000 miles a second and at the same time had the advantage of transmitting a broader band of frequencies, although they had the disadvantage that the circuit had higher transmission losses per mile and therefore required greater amounts of amplification. These higher velocity circuits are in general use for all long cable circuits and have been found satisfactory up to the greatest distances spanned by cables in this country at the present time, namely, approximately 2500 miles.

Cables are placed either underground or supported overhead from a steel messenger strand strung on poles. At the present time approximately 47 per cent. is overhead and 53 per cent. underground. For the most part the underground cable is pulled into permanent underground conduit of vitrified clay. Some use has been made, however, of cable buried directly in the ground, the lead sheath being protected either by layers of jute impregnated with asphaltum compounds or by a combination of such layers of jute and wrappings of steel tape. A small use has also been made of a single duct made of compressed fibre for the protection of underground cables.

The conductors used for long telephone circuits are quadded for phantom operation and are largely of 19 A.W.G. although some use has been made of 16 A.W.G. for the shorter circuits because of a possible saving in the numbers of repeaters with the larger gauge in those cases. Many of the cables include a number of special 16-gauge pairs provided specifically for program transmission circuits and equipped with loading and amplifiers designed particularly for that form of service. Figure 15 shows schematically the arrangement of conductors of a standard type of full size cable (outside diameter 2⅝ inches) which is in common use.

With these developments and other auxiliary developments which will be discussed later toll cables have come to have a very important place in the provision of toll telephone service by the Bell System. The percentage of toll wire in cable has increased from 30 per cent. in 1915 to 82 per cent. at the present time. The present toll cable network is indicated in Fig. 16. It will be noted that this network connects together almost all of the major places between the Atlantic Seaboard on the East; Atlanta, Georgia and Dallas, Texas on the South; Western Texas, Kansas City, and Omaha on the West; and Toronto, Montreal, and Bangor on the North. In addition, there are other sections of toll cable connecting important centers as San Francisco–Los Angeles and Miami–Palm Beach. These cable systems provide a storm-proof outlet for telephone circuits to 155 out of a total of 210 cities over 50,000 population in the United States and Canada, and cover the major part of the United States in which open-wire lines are subject to interruption by severe sleet storms. The cable network includes at the present time about 27,000 miles of cable and 12,500,000 miles of conductor.

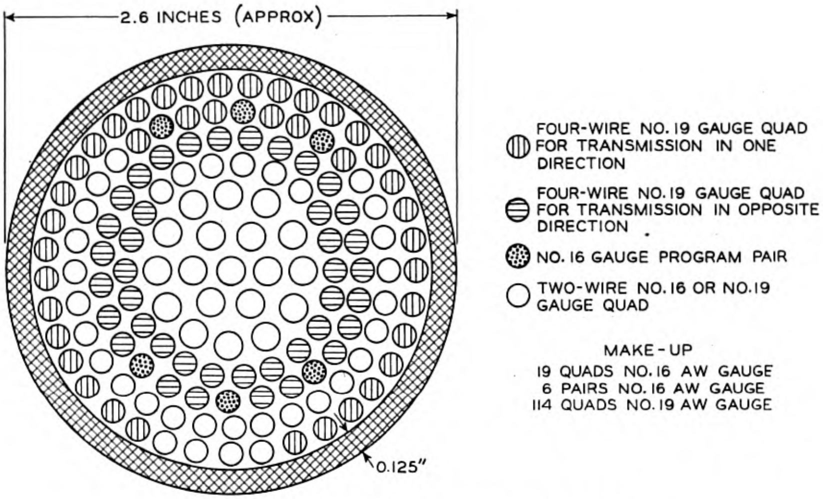


Fig. 15—Cross-section of typical toll cable.

THE TIME FACTOR IN TELEPHONE TRANSMISSION

In the above discussion of toll cable systems it was mentioned that it became desirable for the long circuits in cable to provide a type of circuit having a higher velocity of transmission than that of the loaded cable circuits previously in use. The effects of the length of time required for transmission over long circuits, while particularly noticeable in long cable circuits, are of importance in long open-wire circuits as well. These effects are briefly discussed below.

On non-loaded lines, either in open wire or in cable, the velocity of transmission of telephone currents over the line conductors is high,

Fig. 16—Main toll cable routes—Bell System.

approaching as an upper limit the velocity of propagation of light, namely, 186,000 miles a second. On loaded circuits this velocity is greatly reduced. Loaded toll cable circuits in common use over moderate distances, as already mentioned, have velocities of 10,000 miles a second and still lower velocities were associated with some of the earlier types of loaded toll cable circuit.

The transmission of telephone currents over long circuits is accompanied by reflections of a part of the current at points where the electrical characteristics of the circuit change, particularly at the terminals where it is not practicable to get a close match between the characteristics of the toll circuit and of the various local circuits and terminal equipments to which it must be connected. Considering for the moment only this terminal reflection, speech over the circuit is not only transmitted directly but also a part of the transmission current is reflected back and forth between the terminals producing delayed sounds analogous to the echoes produced when one talks in the face of a distant cliff or building. For example, over a 1000-mile circuit with a velocity of transmission of 10,000 miles a second, the time required for transmission in one direction is .1 of a second and for a round trip of the circuit .2 of a second. On such a circuit the talker may hear in his receiver the echo of his own words .2 of a second after they are spoken and the listener at the other end may hear not only the direct transmission but an echo delayed by .2 of a second. Such effects, if sufficiently great, seriously interfere with the conversation, the amount of interference increasing with the amount of delay.

The reduction in the effect of echoes is partly taken care of by improvements in the design, both increasing the velocity of transmission over the circuit and reducing the amount of reflected current. In addition, special devices known as "echo suppressors" are used to reduce further the effect of echoes. In the echo suppressor a small part of the voice current is amplified and rectified and used to control the circuit in such a way that during the conversation the circuit is operative only in one direction at a time, the interruption of the return path serving to prevent the transmission of echoes. As people speak alternately from the two ends of the circuit, this control is automatically shifted so that the words will be fully transmitted in each case.

While echo suppressors are very successful and are widely used, they have certain limitations and, in spite of their use, echoes remain an important factor to be considered when engineering and laying out long telephone circuits.

Another effect of the time of transmission arises from the fact that, generally speaking, the components of different frequencies making up the voice currents are not all transmitted with the same velocity over the circuit. Often the frequencies in the middle of the range 1,000 to 1,500 cycles arrive first and the highest and lowest frequencies arrive somewhat later. This difference is inappreciable on short circuits but for the longest circuits, if not corrected for by suitable design, may become great enough to be appreciable. Under those conditions a distortion of the speech takes place which interferes with the ease of understanding and, in extreme cases, may seriously impair transmission.

This type of effect can be compensated for by the installation at intervals along the circuit of networks designed to introduce additional delay in the transmission of the frequencies in the middle of the range so that all frequencies will arrive at the distant end more nearly at the same time. Up to the present time, the improved design of circuits used for the very long distances has sufficiently kept down the amount of this distortion so that special compensating arrangements are not necessary to message circuits but they are commonly used in circuits for some of the special services, where transmission requirements are more severe.

Still a third effect of the finite velocity of transmission over telephone circuits is to be found in the time of transmission itself. In the ordinary case, the elapsed time between the speaking of a word at one end of the circuit and its reproduction at the distant end is inappreciable but for very long circuits this requires consideration. Telephone conversations, like face-to-face conversations, involve the repeated interchange of information. Even if one person is doing the talking, he receives frequent acknowledgments from the other that he is followed and understood and, in the case of telephone conversations, those acknowledgments must be vocal in character. If too great a time is required for the transmission of the speech and the return transmission of the acknowledgment or replies, the vocal interchange of ideas is interfered with.

These considerations have led to the preliminary conclusion that the total time of transmission over any telephone circuit should not exceed about ¼ of a second. It would mean that the velocity of transmission 20,000 miles a second now used for long toll cable circuits would not be adequate at some future time for connections between widely separated parts of the earth's surface. Fortunately, the trend of development of very long circuits is for various reasons in the direction of higher velocity circuits, as will be made apparent in the next section, so that it is anticipated that this limitation, except in perhaps a few special cases, will not be difficult to overcome.

MULTI-CHANNEL TELEPHONE SYSTEMS

It was pointed out under "Early Developments" that, for clear transmission, telephone circuits must transmit a band of frequencies, the minimum band used for new telephone circuits being between approximately 250 and 2,750 cycles. However, many telephone lines can be made suitable for transmitting a much broader band of frequencies, namely, frequencies running up into the tens of thousands or, by applying the latest developments, to hundreds of thousands of cycles. This fact naturally raised the question whether some means could not be devised for operating a multiplicity of telephone channels on one circuit using this broader frequency range.

The general idea is as old as telephony itself or older as applied to telegraphy. Alexander Graham Bell's invention of the telephone came, in part at least, through his experimentation in means of providing several telegraph channels over one circuit by using currents of different frequencies. The fundamental principles of multiplex telephony were early thought of and well understood. They involve:

(1) Means for so varying a high-frequency current (called a "carrier") that, with this variation, it represents the sounds to be transmitted over the telephone circuit just as do the voice currents produced by the telephone transmitter in the range 250 to 2,750 cycles. As ordinarily carried out, this involves the control of the amplitude of the carrier current in proportion to the instantaneous values of the voice-frequency telephone currents, this process being known as "modulation."

(2) Correspondingly, means for reproducing the sounds transmitted by suitably operating upon the modulated high-frequency current. This is done by reproducing from this current the ordinary voice current (a process known as "demodulation") and applying this voice current to an ordinary telephone receiver.

(3) Means for joining the modulated carriers of different frequencies so that they can be transmitted over the same telephone wires, and for completely separating them from each other at the receiving end by virtue of their different frequency ranges so that each modulated carrier can be demodulated in a separate receiving circuit and the various conversations carried on simultaneously without interference. This function has been termed selectivity.

While the fundamental ideas as outlined above are old, the physical means by which successful carrier current telephony could be made practicable did not become available until the period 1913 to 1918. In that period, the successful development of the vacuum tube for use in telephone repeaters produced a device which, with different circuit arrangements, could be used satisfactorily for generating carrier currents, modulating them with telephone currents, and for reproducing the telephone currents from the modulated carrier currents. At about the same time, marked advances were made in the development of means for separating into any desired groups a mixture of currents of different frequencies transmitted over the same conductors. These means may be considered in principle an elaboration of the elementary apparatus of this type, called "composite sets," long in use for separating telephone and telegraph currents transmitted over the same circuit by reason of their difference in frequency. The more complete solution of this general problem was made by the development by the Bell System of the "electrical filter."

With these new tools it became possible to develop carrier telephone systems suitable for commercial service. Such systems were first introduced into the plant of the Bell System in 1918. Since that time their use has spread widely, particularly over non-loaded open-wire circuits of the System.

The most important type of carrier telephone system in general use is the Type C. One terminal of such a system is indicated schematically in Fig. 17. With this system three carrier channels, marked *A*, *B*, and *C*, and a voice-frequency channel, marked *V*, are transmitted simultaneously over one pair of wires. The four circuits as they appear at the toll switchboard are alike and are treated indiscriminately by the operator. Coming from the switchboard as indicated at the left of Fig. 17, the three carrier channels first pass through three individual sets of carrier equipment. In each of these sets of carrier equipment, the circuit is separated into transmitting and receiving paths. The transmitting path is passed through a modulator in which the voice currents received from the switchboard act upon a carrier and produce modulated carrier currents, and through an electric filter to the general transmitting circuit indicated on the drawing. The receiving channel is connected to the general receiving circuit through an electric filter and through a demodulator by means of which the received currents are caused to reproduce voice-frequency currents similar to those delivered to the circuit at the other end.

As the next step the three transmitting channels are brought together through a common amplifier and transmitted through a "band" filter to the line filter. Similarly, the three receiving circuits are brought together by a common receiving amplifier with which is associated a "band" filter, which in turn is connected to the line filter. The line filter consists of two parts, one of which permits the carrier currents of Channels *A*, *B*, and *C*, to pass but excludes the voice-frequency currents and through this operation of the line filter the carrier currents are transmitted to the line. The voice-frequency circuit *V* is connected to the line through the other part of the line filter which permits voice-frequency currents to pass but excludes all of the carrier-frequency currents. These currents of different frequencies from four channels are then transmitted together over the line and at the receiving end are separated by apparatus similar to that indicated in this sketch.

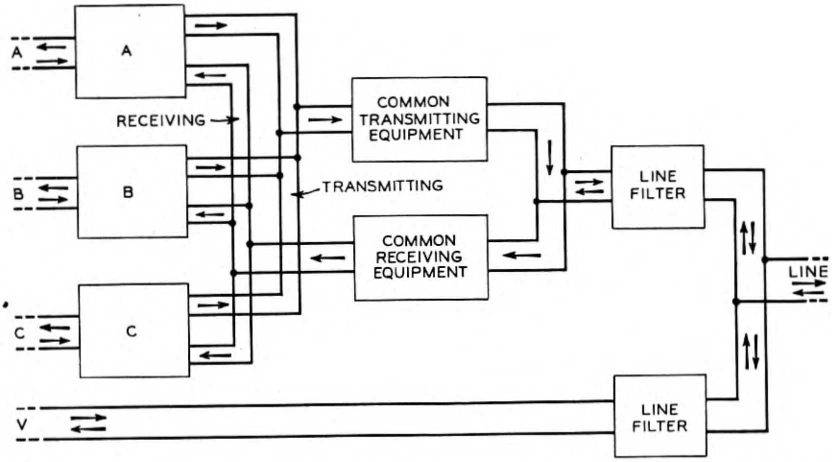


Fig. 17—Schematic arrangement showing the association of a type "C" carrier telephone terminal with the telephone line.

At intermediate points along the circuit, it is necessary to install amplifiers for the carrier-frequency currents as well as for the voice-frequency circuits. At these points, the carrier-frequency currents are separated as a whole from the voice-frequency circuit, a telephone repeater being used for the voice-frequency circuit and a carrier repeater consisting of two amplifiers with electrical filters to separate the two directions of transmission, being used to amplify the three carrier circuits as a group. After amplification, the carrier and voice-frequency currents are again brought together for transmission over another section of line.

It is to be noted that the carrier circuits, like the four-wire cable circuits, use different channels of transmission in the two directions, thus avoiding the difficulties of balance which would otherwise be encountered. In the case of the carrier systems now in general use, however, the two channels are channels of different frequencies operating in opposite directions on the same pair of wires rather than using two separate pairs of wires. As a result the Type C carrier system providing three two-way telephone channels transmits over the line six bands of carrier frequencies, one for each direction for each of the channels. The maximum frequency used by the Type C system is about 30,000 cycles.

In addition to the Type C system just described, there is used in the Bell System a simpler single-circuit carrier system (Type D) providing one carrier circuit in addition to the voice-frequency telephone circuit.

In the case of carrier systems as in the case of telephone repeaters, their application to the telephone plant involved not only the development of the system itself but the development and application of new practices to the telephone plant. This came about from the fact that the plant, heretofore designed primarily for the transmission of ordinary voice frequencies, that is, currents up to about 3,000 cycles per second in frequency, was now called upon to transmit currents up to 30,000 cycles successfully and without interference. In order to do this, it was necessary in the open-wire circuits to use non-loaded pairs and where loading was necessary in short sections of incidental cable in such circuits, to design new loading systems with loading coils of small inductance placed at frequent intervals which would transmit these higher frequency currents. A major problem of adapting the plant to the use of these currents arose from the increasing tendency with higher frequencies for currents flowing in one circuit to induce currents into other circuits in the vicinity. The transposition systems used to prevent crosstalk between voice-frequency telephone circuits on the same pole line were wholly inadequate to prevent crosstalk of the carrier currents and without extensive changes such crosstalk would have been far too great to make possible the satisfactory use of carrier systems. New systems of transpositions involving a large increase in the number of transpositions used in a given section of line were designed for this purpose. Also, it was found that for the largest use of carrier systems it would be necessary to give up the use of phantoms on the circuits involved and also to rearrange the conductors to provide less space between the two wires of the pair and greater amounts of space between the pairs on the same crossarm.

These new construction arrangements have been worked out and applied where the extensive use of carrier is sufficiently important to justify them.

As a result of these various developments, an extensive use of carrier systems has been made in the Bell System plant. This is indicated in Fig. 18, which shows the routes on which carrier systems are used at the present time. The total circuit mileage in service provided by carrier systems is about 400,000 miles, which is over 8 per cent. of the total toll circuit mileage in service.

Up to the present time, the applications of carrier have been confined to open wire, including relatively short sections of incidental cable in the open-wire circuit. Further advances in the art, particularly in the design of very stable amplifiers capable of amplifying simultaneously a large number of carrier channels of different frequencies without mutual interference and improvements in the design of electrical filters to make them less expensive and more effective have opened the way for broader applications of carrier. These broader applications include the prospective use of carrier on non-loaded cable circuits with amplifiers spaced at intervals of twenty miles or less. Systems are now being developed for this service by which it is expected to get 12 one-way channels on a single non-loaded cable pair, and with cables of special construction, such as the coaxial cable, on which experiments are now being made, several hundred one-way transmissions may be obtained on a single unit.

In view of these developments under way, and further prospective improvements in carrier systems applicable to open-wire circuits, it is evident that this form of transmission will have in the future a rapidly growing field of use in the telephone plant.

ASSOCIATED TECHNICAL DEVELOPMENTS

The successful operation in a practical telephone plant of the new types of circuit for transmission over very long distances both in cable and in open wire required, in addition to the main developments briefly outlined above, the developments of a number of associated technical arrangements. Some of the more important of these are briefly outlined in the following paragraphs.

Regulators

In the long telephone circuits made possible by the use of repeaters, having a number of repeaters at different points along the circuit, the net transmission efficiency of the circuit is the result obtained by balancing the amplification of telephone currents in the repeaters

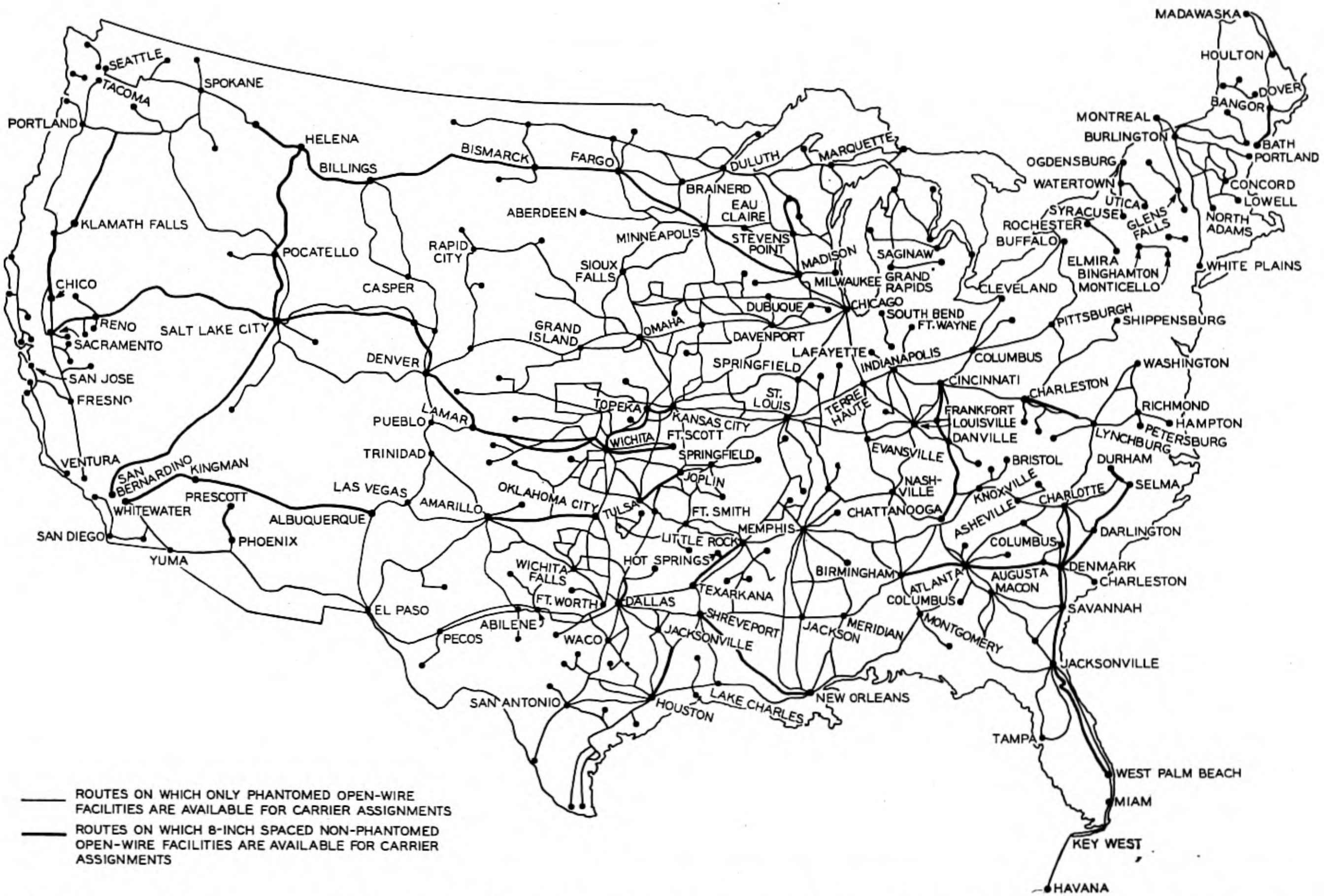


Fig. 18—Routes of the American Telephone and Telegraph Company and Associated Companies in the United States on which carrier telephone facilities are available.

against the attenuation of the telephone current in the various line sections of the circuit. As a result, with increase in length such circuits become increasingly susceptible to the effect of variations in circuit efficiency caused by changes in weather conditions. In the case of toll cable circuits this variation is primarily due to changes in temperature and in a long cable circuit such changes may in a single day make a 10,000 fold difference in the overall efficiency of the cable. In the case of open wire circuits the change is mostly due to rain and is particularly prominent in the highest frequency carrier systems.

In order to offset these variations and provide circuits of approximately constant overall net efficiency these longer circuits are equipped with regulating systems which make it possible to offset the variations in the efficiency of the circuits by either manually or automatically changing the gain of certain of the repeaters.

In the case of the cable circuits the regulation system, known as a "pilot wire regulator," is automatic. It makes use of a direct-current channel over a metallic composite circuit, variations in the resistance of this pilot wire which result from the variations in temperature causing automatic adjustment of the regulating repeaters. A single pilot wire with its associated regulating equipment can be used for controlling all of the circuits in a cable. Sometimes as many as 300 circuits or more in number are regulated with a single pilot wire. In order to get sufficiently accurate regulation and because of practical layout considerations the cable is generally regulated separately in sections of 100 to 150 miles in length.

In the case of a type C carrier system on open wire the regulating system depends upon attenuations of carrier currents transmitted over the same pair as the carrier system. On most of the type "C" systems the regulators give an indication of the net efficiency, which is kept within a prescribed limit by manual adjustment of the repeaters. In some cases apparatus providing this adjustment automatically is in use.

Equalizers

The transmission efficiency of telephone lines is generally different for the different single frequencies comprising the voice-frequency band. This variation is particularly great on some loaded cable circuits where the maximum frequencies transmitted approach the maximum frequencies which the circuit is capable of transmitting. If such variation in efficiency were permitted, resulting in the higher frequencies having much greater losses than the lower frequencies, the normal relative proportion of different frequencies would in some cases be so distorted that the transmitted speech would not be clear or even could not be recognized. In order to prevent such distortion, therefore, it was necessary to develop and apply means for compensating for the variation in the line by variations in the opposite direction. These means are called attenuation equalizers. In the telephone message circuit these attenuation equalizers are generally designed to be an integral part of the telephone repeaters themselves.

Signaling Systems

With the exception of a few special cases all telephone circuits for message telephone service are provided with a means by which signals can be transmitted from one end to the other in order to call to the circuit an operator (or sometimes in the case of dial systems, a machine) or subscriber. In the relatively short circuits used for local telephone service this signal commonly is provided either by the flow of direct current which is used to light a lamp or operate a relay or by the flow of 20-cycle alternating current which is used to ring a bell or operate a relay.

Signals based upon the use of direct current are generally used in cases where it is desired to have the signal continue to indicate the condition of a connection throughout the conversation since the direct current can continue to flow over the circuit simultaneously with the voice current during conversation without interference. The most extensive use of this type of signaling is for the shorter circuits. The method of operation of long toll circuits generally is such that no signal is required over the toll circuit during the conversation period but only before and after the conversation, and for such signals alternating current is generally used.

In the early days the alternating currents used for signals over toll circuits were generally the same as those used for signaling over local circuits, namely, 16 to 20 cycles per second. As the simultaneous use of toll circuits for telephone and telegraph expanded, this was modified because of interference which would occur between the telegraph currents and the 16 or 20-cycle signaling currents. For such cases signaling was accomplished by alternating currents of 135 cycles, sufficiently high to avoid interference with the telegraph systems then in use.

With the further development of long toll circuits having many repeaters at intermediate points and also with the development of carrier telephone systems, the satisfactory transmission of 135-cycle current from one end of the circuit to the other became more difficult. At the same time the advance in the art made possible the development of satisfactory and economical signaling systems using interrupted currents of 1,000-cycle frequency. With such a system the signaling current uses the same transmission path as the voice currents but the system is designed to discriminate between the voice and signaling current. The signaling current is transmitted from end to end over the circuit without the use of intermediate ringers which had been resorted to on the 135-cycle ringing system. This 1,000-cycle system has extended rapidly in its field of use and is now used for the majority of circuits over 100–150 miles in length.

Telegraph System

The early methods by which provision was made for the simultaneous use of telephone circuits for telephone and telegraph service were described in the section on "Early Developments." With the general extension in the telephone plant of the improved types of telephone circuits described above, and with the growth in extent and requirements of the private line telegraph service, it became important to devise new types of telegraph circuits adaptable for use with the new types of telephone circuit and suitable to meet the increased telegraph requirements.

One such new form of telegraph circuit was the metallic telegraph system designed for use on telephone toll cables simultaneously with the use of the same conductors for telephone service. In order to avoid interference between the telephone and telegraph circuits it was necessary to use relatively low voltages and currents on the telegraph circuit. With these low voltages and currents grounded telegraph circuits were impracticable because of outside interference and it was necessary to use metallic circuits in which no use was made of the ground for the transmission path. With the new metallic circuits voltages of 34 volts and currents of 4 milliamperes were used compared with 130 volts and 60 milliamperes in the grounded direct-current telegraph systems.

Another form of telegraph circuit which was developed for use over telephone toll cables is the so-called voice-frequency telegraph system. With this system by carrier current methods the telephone channel is split up into 12 telegraph channels, each of which is suitable for use as an independent telegraph circuit, one telephone circuit thus providing 12 telegraph circuits. In this case, the telephone circuit cannot be used simultaneously for telephone and telegraph circuits. This system is designed to be applied either to a four-wire cable circuit, or to a carrier telephone circuit which, like the four-wire cable circuit, consists of two channels for transmission in the opposite directions. It has large advantages for long circuits because of the fact that no apparatus is required at points intermediate between the terminals, including points where cable and open wire are joined, other than the standard telephone repeaters and associated apparatus already provided with the circuit for telephone purposes.

Still a third type of telegraph system devised to meet the new conditions is that known as the high-frequency carrier telegraph system. This system is designed for application to open wires. It applies to the provision of telegraph circuits the same principles as are applied in the carrier telephone system for the provision of telephone circuits. It uses frequencies above the voice range, roughly in the range from 3,000 to 10,000 cycles, thus permitting the continued use of the conductors for a voice-frequency telephone circuit simultaneously with its use for high-frequency carrier telegraph circuits. With this system 10 two-way telegraph circuits are provided.

Auxiliary Apparatus and Equipment

In addition to the main items described above, developments of other apparatus and equipment auxiliary to the telephone toll circuits were made necessary by the general use of repeaters and carrier systems. Power plants providing current to the filaments and plate circuits of the vacuum tubes used in repeaters and carrier systems had to be provided having much closer voltage regulation than had heretofore been necessary for the earlier types of telephone equipment. New forms of testboards were required and new types of arrangements of distributing frames and of protective apparatus. Plans were developed for the economical arrangement of the new types of equipment in large offices. All of these things while essential for the proper operation of modern toll telephone circuits probably do not need detailed discussion in this statement.

Another type of equipment which had to be developed was that for carrying out the various forms of electrical test necessary to assure the proper operation of these new telephone circuits. The development of this equipment and of the new maintenance methods which made use of this equipment is of sufficient general importance so that it is briefly discussed in the next section of this statement.

DEVELOPMENT OF METHODS OF MEASUREMENT AND MAINTENANCE FOR TOLL CIRCUITS

The history of toll service has been a story of the continuous application of new scientific instrumentalities. The laboratory experiments of one day become the regular service-giving apparatus of ever-growing complexity. Maintaining this complicated equipment at a high state of efficiency has been accomplished through methods of measurements, developed either to make possible the measurement of electrical quantities for which no methods of measurement existed previously or else to make possible measurements in large numbers on a routine basis at little expense which previously were delicate, expensive and confined to the laboratories. It would be out of place to include in this report a general discussion of the development of these methods. Mention will be made, however, of certain items which have particular reference to the new types of toll circuit discussed above.

An important tool in electrical measurements is the Wheatstone bridge devised originally for the accurate measurement of resistances. In dealing with telephone circuits where the performance of circuits and apparatus in the transmission of alternating currents is important, it was necessary to expand the Wheatstone bridge for alternating current use. This involved providing elements for the Wheatstone bridge having not only a known resistance to the flow of direct currents but also a known resistance and reactance to the flow of alternating currents of the frequencies at which measurements were to be made. It was soon found, however, that with frequencies as high as those required in telephone measurements, running up to two or three thousand cycles, the resistance and reactance of the elements of the Wheatstone bridge were not well known and varied depending upon the number of elements connected in the circuit. This variation was due to the effect of incidental capacitances between the elements of the bridge and between them and the ground. In order to overcome these difficulties, G. A. Campbell devised an arrangement of shields by which variation in the effect of these incidental capacitances was prevented and in this way produced bridges for alternating current use which would give accurate results over the range of frequencies required in telephonic measurements.

An interesting example of the application of the shielded impedance bridge to practical telephone measurements is presented by what is called the "capacity unbalance (testing) set." This testing set is designed to measure the very small capacitances between individual wires of a short section of toll cable or more specifically differences between these capacitances for the individual wires of two pairs or of two quads, expressing these differences in such a way that they are directly proportional to the contribution made by the capacitances in the short section of cable to crosstalk between circuits using the pairs or quads thus tested. The purpose of the test is to give information to the splicing forces, which, properly interpreted by them, enables them to splice together pairs and quads in adjacent lengths in such combinations that the crosstalk unbalances in adjacent sections tend to neutralize each other and the crosstalk between all pairs and quads in the cable when completed will be small. The capacitance differences measured in individual lengths are only a few millionths of a microfarad. This measurement, originally possible only under carefully controlled conditions, is, by the use of the capacity unbalance testing set, reduced to a routine part of the work of the construction and cable splicing forces.

Another interesting kind of measurement bearing in a very important way on the maintenance of the efficiency of telephone toll circuits is measurements of transmission efficiency, that is, of the power output of the telephone circuit in proportion to the power input of alternating current at the distant end. In order that such a measurement may represent the efficiency of the circuit for the transmission of telephone currents, it is necessary not only that the frequency of the testing current correspond to one of the important frequencies of telephone currents (1,000 cycles is ordinarily used when only one frequency is necessary) but also that the amount of power transmitted correspond approximately to the average power of telephone currents. For this reason the standard input power for such tests is one milliwatt and the power received at the other end of the telephone circuit is often one-tenth of that or less.

When tests of this sort were first made as a part of the routine work of maintaining telephone toll circuits the only available instrument sufficiently sensitive to measure the received power and practical for use under field conditions was the combination of the telephone receiver and the ear. In making such a measurement power was transmitted alternately over the circuit to be tested and over an artificial circuit whose efficiency was known and adjustable, the adjustment being made until the received sound was equally loud in the two cases. Then with the further development of the art sensitive receiving instruments became available which were substituted for the telephone receiver and the ear, the adjustment then being made of the artificial telphone line until the received power as indicated by the sensitive meter was equal to that received over the circuit under test. The perfection of instruments of sufficient sensitivity for this measurement and yet sufficiently rugged to be practicable for use by the regular telephone maintenance forces constituted a great advance in the development of measuring systems for telephone transmission. The most satisfactory instruments of this type made use of vacuum tubes to provide the necessary sensitiveness.

A still further improvement has been made by development of instruments which within a limited range showed directly by their amplitude of deflection the amount of power loss in the telephone circuit. With this latter development the artificial circuit is entirely dispensed with, the standard amount of alternating current power applied to the circuit at one end and the meter connected to the other end. These great advances in the technique of measuring instruments provided an ease of measurement almost comparable to the ease of the measurements commonly made in power transmission systems where the large amounts of power available made the development of satisfactory instruments very much less difficult. Now a still further advance in these methods of measurement has been made by devising arrangements such that the deflection of the instrument is indicated in an enlarged scale on an illuminated screen. This makes it unnecessary to transport the instrument to the terminal of the circuit and makes it possible in a repeater office, by making connections in one part of the room so that the circuit is connected to the receiving instrument, for the maintenance man to read the deflection of the meter at a distance thus further cutting down the time required for tests of this nature.

Other types of tests on telephone toll circuits for which special measuring apparatus and measuring methods have been devised include measurements of the crosstalk between circuits, measurements of the noise currents induced in circuits by other electrical circuits, such as electric power circuits, measurements of the uniformity of electrical impedance from the standpoint of suitability for operation with repeaters, measurements of the amplification of telephone repeaters and measurements of the thermionic activity of the vacuum tubes.

While the above discussion refers to instruments for the measurement of alternating currents in what is called the voice-frequency range, that is, up to about 3,000 cycles per second, the introduction of carrier telephone and telegraph systems made necessary the development of similar measuring instruments for the higher frequency currents used in carrier, namely, up to about 30,000 cycles per second. With the expected use in the future of currents up to frequencies of 100,000 or 1,000,000 cycles or more the range of field measuring apparatus will, of course, have to be greatly increased.

The use of these special types of apparatus for making necessary electrical measurements has required a large amount of instruction of the maintenance forces. Also, it was necessary to devise systems of test and adjustment using these measuring methods by means of which the transmission performance of toll circuits of the new types can best be maintained at the desired standards. This involves a determination of the kind of tests and the limits of adjustment necessary for the different types of apparatus included in these circuits, the frequency of tests and the desirable range of performance results for the maintenance of a high quality of service over these circuits, with the least practicable expense for their maintenance. Maintenance routines of this sort are developed from time to time with each new type of circuit and amended to accord with modifications in the details of the circuits or to take advantage of the results of field experience.

Special Services

With a nation-wide network of poles, wires and circuits available for telephone message purposes, and with its accumulated knowledge concerning technical communication problems the Bell System, as the demand has arisen, has naturally been in a position to analyze the technical requirements of the special communication services and to provide suitable facilities for them. The earliest demand for intercity circuits for special services were for private telephone circuits between telephones in different cities and for private line telegraph circuits. Since that time developments in the communication art, such as radio broadcasting and the transmission of pictures over wires, have created additional demands.

The toll wire plant of the Bell System can be used either interchangeably or simultaneously for telephone message service and many of the special services. In addition, the telephone message service and practically all the special services make common use of many other parts of the toll plant, such as poles, conduits, buildings and power plants.

Some of the special services which make use of telephone circuits or of circuits similar to telephone circuits involve special requirements for satisfactory transmission. This is best illustrated by the transmission of programs for radio broadcast stations, a service which is given on a nation-wide basis over the toll plant of the Bell System. The principal reason for the wide difference in technical requirements of program transmission circuits and of telephone message circuits is that, unlike the message circuits, program transmission circuits are required to transmit music as well as speech. The satisfactory reception of transmitted music requires the transmission of a broader band of frequencies than is necessary for speech alone. The national program transmission networks of the country at the present time, consistent with the requirements of radio broadcast art, transmit a band of frequencies of from about 50 to about 5,000 cycles compared with a band of frequencies of 250 to 2,750 cycles commonly transmitted by message circuits, and means by which a broader band of frequencies can be transmitted over program transmission circuits have been developed. Another important requirement of program transmission circuits is that they shall be able to handle a wide range of input power. Generally speaking, the power may be varied over a range of 10,000 to 1, without the overloading of the amplifiers or other apparatus on the circuit at the highest levels or interference with the program by extraneous noises at the lowest levels.

Because of these and other special requirements a large part of the telephone plant devoted to program transmission is designed specifically for that service. In the toll cables special 16-gauge pairs have been placed and these pairs are equipped with loading and with amplifiers designed to produce satisfactory transmission circuits. The equalization for variations in attenuation, the regulating arrangements to assure constant efficiency, and the compensators for the difference in the velocity of transmission of currents of different frequencies present special problems.

On open-wire lines the conductors used are generally of the same type as those provided for telephone message circuits. On the other hand, it is necessary to give up the use of direct current telegraph and generally necessary to give up the use of phantoms on circuits used for program transmission. Also, in some cases the number of carrier channels which can be superposed upon the conductors is reduced. The amplifiers and other equipment used in connection with these conductors for program transmission are of special design.

Not only is the plant for program transmission of special design but even to a greater extent the operating features are special to this type of service. For many conditions continuous monitoring is necessary during the transmission of the program. Special switching arrangements are required to make possible rapid changes in the connection of program transmission networks at the moment of a change in program.

At the present time there are about 60,000 miles of program transmission circuit maintained for full-time and recurring program service, of which about 40,000 miles are in daily service in the Bell System on full-time networks. The extent of the network devoted regularly to this purpose is indicated in Fig. 19.

Fig. 19—Routes of the American Telephone and Telegraph Company and Associated Companies in the United States used for radio program transmission.

Telephotography

In 1925 the Bell System inaugurated between a limited number of points a service for the transmission of photographs by wire. Such a system involved the use of telephone circuits, the band of frequencies required for successful transmission being approximately 800–1,800 cycles. This service was discontinued in 1933 because of lack of commercial demand.

At the present time the Bell System is providing to one of the press associations special circuits for their use in transmitting photographs with apparatus owned by them. The type of apparatus used for this circuit is a Bell System development, and represents a marked advance over the earlier apparatus, transmitting pictures at a higher speed and requiring a band of frequencies of approximately 1,200–2,600 cycles. Within the band of frequencies used for the picture transmission a very high degree of equalization of attenuation and velocity of transmission is required. This involves the use of apparatus designed specifically for this service which is associated with regular telephone repeaters. It also requires special attention on the part of the operating forces.

Other Special Services

The Bell System gives an extensive private line telephone service. The requirements for circuits for this service are similar to those for telephone message service and do not require any special discussion.

Also, the toll plant of the Bell System is from time to time used in a limited way for other special services. The private line telegraph service and teletypewriter exchange service are not discussed here, being outside the scope of this statement.

TOLL OPERATING METHODS

Operating Method Defined

By "toll operating method" is meant the process by which a toll call is received, recorded, completed and timed. This process is referred to as "handling the call." It relates, for the most part, to the routine and procedure of handling the call, although it must conform to the type of equipment provided, the trunking method involved and the arrangement of the plant. During the development of the telephone business many different toll operating methods have been used, but in the following only the five are described which at various times have come into general use and by which the vast majority of all toll calls have been handled. Such questions as the following are involved in the toll operating method:

How shall the customer's order be received and recorded?

How shall the operator reach the called place?

What combination of plant and method will result in the best service at least cost?

Interrelation of Method and Equipment Design

The operating method and the design of the equipment must be considered together. In many cases the design of the equipment must be changed to permit the use of an improved operating method. In other cases redesign of the equipment is not essential to the improvement of an operating method but in nearly all cases some change in equipment design or arrangement is desirable to permit the best service and the most economical operation of the method. In the normal evolution of the business, improvements in methods and equipment design follow along concurrently. It is not unusual that the greatest amount of work in connection with the improvement of a method has to do with the study and design or redesign of equipment rather than with the study of the operating method alone.

Rearrangement of Plant Brought About by Changes in Method

Various types of switchboard equipment are designed to serve specialized functions in the toll operating room. These various types of equipment must be arranged so that the toll calls can be handled most speedily and economically. Most of the equipment used by operators is provided to make possible the interconnection of a telephone with any other telephone within the exchange or toll network. In addition, however, certain auxiliary equipment is provided which facilitates such interconnection. At information desks no connection is made between telephones but this equipment is provided to make available to operators and subscribers the telephone numbers required in completing connections. In the long distance office the route desk is provided to perform a similar function in connection with the routing of calls. The various operating methods are designed to use these auxiliary equipments to best advantage and the various items of equipment must, therefore, be arranged in such a manner as to meet different operating conditions as methods are changed. Occasionally an improvement in method makes it possible to eliminate one of these auxiliary equipments. An example of this will be shown below in connection with the combined line and recording method. The manner in which various types of equipment are arranged in the operating room, their proximity to each other, their relative locations on different floors of the building, the arrangement of the trunks that tie them together, the arrangement of the ticket distributing apparatus, all have important effects upon the service rendered by and the efficiency of the operating method. Changes in method, therefore, frequently call for rearrangement of equipment.

Trunking Methods Distinguished from Operating Methods

As soon as the telephone business developed to the point where it became necessary to connect together two telephones not served by the same central office, the arrangements for interconnection between the two offices became an important consideration. Offices are connected together by trunks or toll lines and there must be arrangements for operators to get into communication with each other promptly. In general this is accomplished by signals transmitted over the circuit which later is used for conversation, but sometimes a separate circuit, known as a call-circuit, is used. The manner in which trunks are arranged and used is known as trunking method, as distinguished from operating method which has to do with the manner in which calls are handled. Much of the trunking methods experience gained in handling local traffic has been applied to the handling of toll calls. The more important trunking methods are call-circuits, straightforward, ringdown and dialing. Any of these trunking methods may be used with the various toll operating methods.

Description of Trunking Methods

Call-Circuit Trunking Method

Under this method a call-circuit was provided between the two offices. The terminating end was connected to an operator's receiver and at the originating end, any one of a number of operators could connect her telephone set to this circuit merely by depressing a key. Let us assume, for example, that a call from New York to Philadelphia is being handled by this trunking method. The customer in New York has given the Philadelphia number to the New York operator. The latter depresses a key which connects her telephone set to the call-circuit which at Philadelphia is connected to the receiver of an operator who handles only inward connections from New York. The New York operator listens for a moment, to determine that no one else is speaking on the call circuit, and then passes the Philadelphia number over the circuit. Let us also assume that there are 50 toll circuits between New York and Philadelphia, numbered 1 to 50. At the moment that the New York operator passes the number to the Philadelphia operator, some of these circuits are in use. By glancing at her switchboard the Philadelphia operator determines that circuit No.

13, for example, is not in use. In response to the number passed by the New York operator, she says "one-three." This notifies the New York operator that she is going to connect the required telephone number at Philadelphia to circuit No. 13. The New York operator connects her calling party to this circuit and conversation begins as soon as the Philadelphia subscriber answers his telephone. As on any local call the removal or hanging up of the receiver at the called telephone is indicated to the New York operator by appropriate signal lights.

Straightforward Trunking Method

As improvements in equipment and operating methods were made, the call-circuit trunking method gradually was replaced by the straightforward trunking method. Let us assume that a call is being handled by the straightforward method from office A to office B. The calling party gives the called number to the operator in office A who then makes connection to a trunk to office B. The trunk is connected to apparatus at office B in such a way that when the operator at A makes connection to it she is connected automatically to the receiver of an operator at B and a momentary audible tone indicates to her that the operator at B is ready to receive the call. Upon hearing the tone the operator at A passes the called number to the operator at B who then connects the trunk to the called telephone line. It will be noted that the selection of the trunk or circuit between the calling and the called offices is made by the originating operator under the straightforward trunking method, whereas under the call-circuit trunking method the selection of the trunk is made by the operator at the terminating office.

Ringdown Trunking Method

The ringdown trunking method was the first to come into use and is still used where it is uneconomical to provide the equipment necessary to straightforward or dial operation. Under this method the operator at office A signals the operator at office B by making connection to a trunk or circuit between A and B and by depressing a key which operates a signal associated with the circuit at office B. The operator answers this signal by connecting her telephone set to the circuit and announcing the name of her office. The operator at A then passes the number of the called telephone to the operator at B who makes connection to the called number.

Dial Trunking Method

Under some conditions it is feasible to arrange for the originating toll operator to dial the called number without the assistance of an inward operator at the called place. By this trunking method the calling party reaches the operator and gives her his call in the usual way. She then makes connection to a trunk or circuit to the called place and upon receipt of the proper automatic signal, indicating that the apparatus at the terminating office is ready to receive the call, she dials the called number. Under this method, as with the call-circuit and straightforward trunking methods, switchboard lamp signals indicate to the originating operator whether the receiver at the called telephone is on or off its hook.

Description of Toll Operating Methods

General Characteristics of Toll Calls and Operating Methods

The percentage of toll calls handled by the various toll operating methods has varied from year to year, as shown in Fig. 20, until at present about 99 per cent are handled by the A-Board Toll and Combined Line and Recording methods. A large percentage of toll calls involve short distances and are of a simple type that may readily be handled at local switchboards. The remaining toll calls are handled

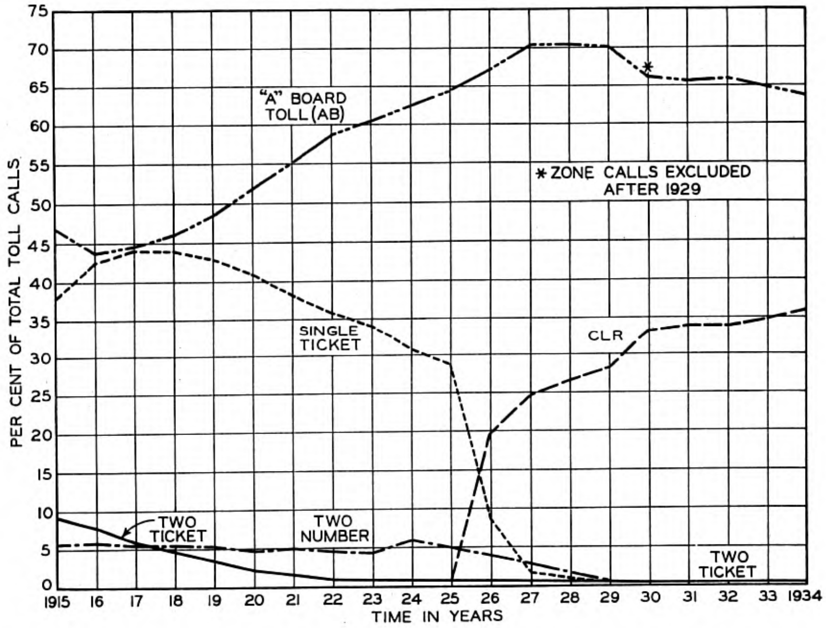


Fig. 20—Distribution of toll calls by operating methods at Bell operated offices in the United States.

at separate long distance offices where equipment especially designed for the handling of long distance calls is provided. In addition to the switchboard positions at which the operators work who handle the long distance calls, there are certain auxiliary positions where operators supply information to other operators with regard to routes, rates and charges. Whether the toll call is handled at the local office or at the long distance office the operator who handles the call and deals with the customers must have access to the toll lines and means of communication with the auxiliary operators. Under any toll operating method the operator who handles the call must make a record from which the customer is billed. This is done on a small ticket which also serves other supervisory purposes. There must be timing devices by which the operator may time the length of conversation and facilities for sending the ticket to file or to other operators if additional or special work is to be done in connection with it.

A-Board Toll Operating Method

On the toll calls handled at local A boards, the subscriber reaches his local operator (by dialing the code "0" in dial areas) and gives his call to her. If she does not know the route to the called place from memory, she obtains it either from a bulletin at her position or by inquiry of the route operator. She reaches the called place by whatever trunking method is in use over the route in question. Most such calls today are completed by the straightforward or dialing methods over direct trunks. If direct circuits to the called place are not provided and the straightforward method is used, the operator selects a trunk to an intermediate or tandem office and upon receipt of proper signal passes the proper order to the tandem or intermediate operator who connects the trunk on which the order was received to a trunk to the called office. Upon receipt of the order at the called office, the terminating operator makes connection to the called line. If the dialing method is involved, the originating operator dials the called number over tandem trunks to the called place. When the called telephone answers, the operator enters the connect time on the ticket. When both parties hang up the receivers this action operates signals before the operator which indicate to her that the customers have finished talking. When these signals appear, the operator enters the disconnect time on the ticket above the time previously shown and the duration of the connection then may be obtained simply by subtracting the connect time from the disconnect time. If the calling party requests the charge for the call, the operator makes this subtraction, obtains the rate to the called place either from her bulletin or from the rate operator, computes the charge and advises the customer.

Two-Number Toll Operating Method

For transmission reasons it was found desirable in large metropolitan areas to provide a separate trunk plant and a separate toll switchboard for handling calls between widely separated central offices. This separate office became known as the "two-number" office and the traffic was handled by the "two-number" method. This method was used for a number of years before the present tandem systems came into service.

Under the two-number operating method the subscriber gave the called number to his local operator as on a local call. The local operator, over a trunk to the two-number board, passed the called number and then the calling number to the two-number operator. The two-number operator then obtained connection to the calling number over another trunk which afforded better transmission than that of the first trunk, and disconnected from the trunk over which the call was received. This disconnection caused a signal to light before the local operator who originally received the call, whereupon the local operator took down the connection she had made between the calling party and the two-number operator. The two-number operator then proceeded to establish connection with the called telephone over a trunk of proper transmission design by whatever trunking method was in use. At the time the two-number toll operating method was in greatest use, the usual trunking method was call-circuit although much of this business was handled by the ringdown method. Tickets were written, connections timed, and routes and rates were obtained in much the same manner that they are obtained with the A board toll operating method. The two-number method acquired its name through the fact that the local operator passed two numbers on each call to the so-called two-number operator.

Two-Ticket Toll Operating Method

For that portion of the toll business on which the customer reaches and gives his call to the long distance operator, three important toll operating methods have been used. One of the important early toll operating methods involved the writing of a ticket by the operators at both ends of the connection and became known as the "two-ticket" method.

In each long distance office where the two-ticket operating method was in use, there was provided a recording board at which long distance calls were recorded by a special group of recording operators; there was an arrangement for sending the tickets either by mechanical device or by messenger from the recording board to other positions as required. There was a directory desk where the directory operator wrote on the ticket the telephone number of the called person. Usually associated with the directory desk was an arrangement for filing completed tickets such that should any customer wish to inquire the charge on his call after it had been filed, it might be located quickly. There was a route and rate desk to which the ticket was then sent and where the operator recorded upon it the route and the rate to the called place. There was an outward or line board where operators established connection between the calling and called telephones. There was a special board known as an inward board where operators established connections to local offices for operators at distant offices. There was a through board where operators connected toll circuits together, end to end, on calls coming from a distant city and going to another city via this office. Each pair of line positions was equipped with a device for timing calls, the calculagraph.

With two-ticket operation, a customer wishing to place a long distance call reached his local operator and asked her to connect him with long distance. The local operator complied with this request by making connection to a trunk to long distance which appeared for answering before a special group of operators trained only to record the customer's order. The recording operator answered the signal on this trunk by saying "Long Distance." The customer told the recording operator whom he wished to reach and where he might be found. He was then told by the recorder that the operator would call him and he hung up his receiver. After recording the information supplied by the customer on an "outward" ticket form, the ticket was sent to other operators for further handling. If the customer had not supplied the number of the called telephone, the ticket was sent to a directory operator who looked up in the directory of the called place the telephone number of the called person. Each toll office did not then, nor does it now, have direct circuits to all other toll offices. It was necessary, therefore, in many cases, to determine the route to the called place. After the telephone number had been supplied to the ticket by the directory operator, the ticket next went to the routing operator who indicated on the ticket the route to the called place. The ticket was then sent to the particular line operator who handled calls to the desired place. The line operator obtained connection with the calling subscriber's telephone and to a circuit to, or in the direction of, the called place. Having reached the inward operator at the called place, she passed the details of the call to her. The inward operator recorded them on an "inward" ticket form and proceeded to obtain connection with the called telephone or party or to find out where or when the called person might be reached. Having reached the called station or party she notified the originating operator who then rang the calling party. When both the calling and called parties answered their telephones, the operator inserted the ticket in the calculagraph and stamped the time. When the calling party hung up his receiver, the originating operator received a disconnect signal on his line, stamped the time on the ticket by means of the calculagraph and took down the connection. The ticket was then sent to the ticket filing desk where it was filed in the numerical order of the calling number. The inward operator also took down the connection upon receipt of a signal indicating that the called party had hung up his receiver.

Single-Ticket Operating Method

Before the single-ticket method came into use operating methods and practices, as well as accounting methods, varied from place to place. This made it necessary for a considerable part of the operating work on toll calls to be done by the operator at the called place. The first step in passing from the two-ticket to the single-ticket method was to eliminate the ticket at the inward end, and to place the responsibility for all work in connection with handling the call, except the purely mechanical operation of making physical connection to the called telephone, upon the outward operator at the calling place. The elimination of this work made possible also the elimination of a large amount of equipment at the terminating place, avoided the duplication of operator time at both ends of the circuit and saved circuit time. It required standardization throughout the System in equipment, local and toll practices, and auditing methods.

Under the single-ticket method the customer reached long distance just as he did with the two-ticket method and the preliminary work of finding the called number and the route for the call remained unchanged. When the ticket reached the line operator, however, she took up a circuit to the called place and merely passed an order to the inward operator for connection to the called number. When the called telephone answered, the originating operator announced the call, arranged for the called party to come to the telephone and connected the calling party to the circuit when the person at the called station was ready to talk. The connection was timed and the ticket filed in the same way as under the two-ticket method.

Combined Line and Recording (CLR) Method

Experience with the single-ticket operating method had suggested the possibility of having the line operator receive and record the call as well as perform the work of reaching the called telephone or party and of establishing the connection. Improvements in toll plant contributed to the feasibility of this type of operation. Such a plan would eliminate the need for a separate recording board but would increase the number of outward line positions required. It also would bring in new problems of training and supervision. With the proposed method it appeared that the speed of service on long distance calls might be considerably improved by virtue of the fact that it would no longer be necessary to send tickets from one position to another within the office. Furthermore, with this method it would be unnecessary for the operator to dismiss the customer after he had given her his call and to recall him when ready with the connection. Instead the customer could remain at the telephone while the line operator attempted to complete his call.

Under the CLR method of operating, now in use, the customer dials or asks for long distance in the usual way. The signal at the long distance board appears before the line operator who answers with the words "Long Distance." The line operator records the call in the usual way except that when the customer gives the name of the called place and the number of the called telephone she takes up a circuit to the called place and records the information on the ticket while waiting for the inward operator at the called place to answer. After passing the called number to the inward operator and while waiting for the called telephone to answer, she asks the calling party for his telephone number. Conversation is timed and the ticket disposed of in the usual way.

Under the single-ticket method calls to or via a given city are always handled by the same group of operators. Under the CLR method any line operator may handle a call to any place in the toll system. If the call is not completed on the first attempt, the ticket is sent to the so-called point-to-point positions where calls to a given city are assigned to positions designated to handle calls only to that city. This assures prompt and careful handling of those calls which have encountered delay and the handling of such calls does not interfere with the handling of work on new calls at the CLR position.

It may be of interest to follow the handling of a call by the CLR method. Figure 21 shows schematically the route of a long distance call through the telephone plant, and the functions performed by the various operators along the route while handling the call by the CLR method. Let us assume that the call in question is a station-to-station paid call from an individual line dial telephone in New York to an individual line telephone in Chicago. The New York subscriber removes the receiver from its hook, listens for dial tone and dials a code for the long distance operator (in New York "211"). A signal appears before the line operator at the long distance switchboard and the customer hears the ringing signal. The line operator plugs into the trunk on which the customer's signal has appeared and indicates her readiness to receive the call by saying "Long Distance." The customer gives his order by saying "Chicago, Harrison 1234." The long distance operator plugs into a Chicago circuit with the other end of the cord pair used in answering the subscriber and rings. While the customer was speaking and while performing these operations and waiting for the Chicago inward operator to answer, she has recorded the abbreviation for Chicago and the Chicago telephone number on a toll ticket. The Chicago inward operator answers by saying "Chicago." The New York operator responds with "Harrison 1234" and while waiting for the Chicago inward operator to obtain connection to this number, she asks the New York subscriber for his telephone number. The subscriber at Harrison 1234 answers and conversation begins. After recording the New York number on the toll ticket, the

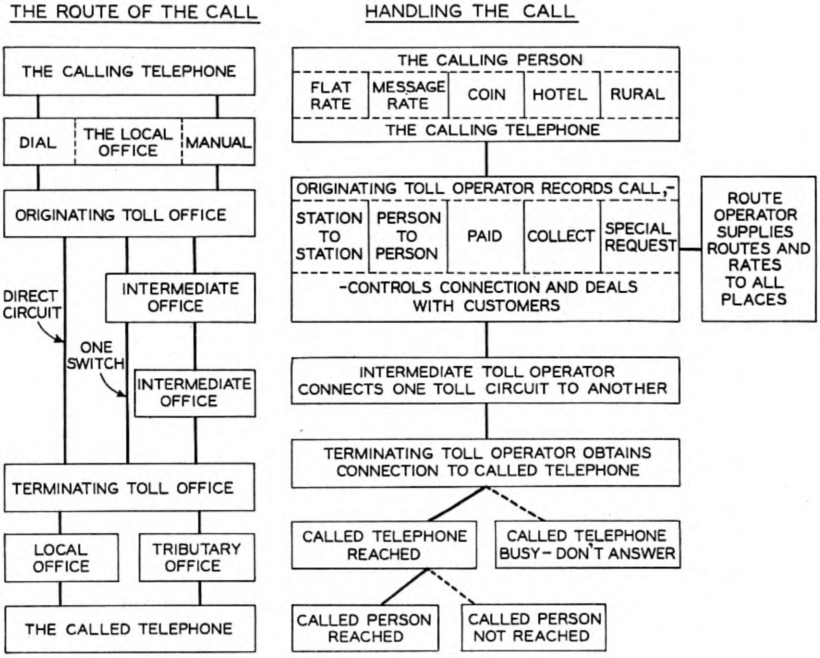


Fig. 21—The long distance call.

New York operator inserts the ticket in the calculagraph in readiness to stamp the start of conversation. When she hears the party at Chicago speak to the New York party, she cuts out of the connection, stamps the start of conversation on the ticket and places the ticket in a clip associated with the pair of cords on which the conversation is taking place. When the parties have finished speaking, the New York party hangs up his receiver which lights a signal associated with this pair of cords, whereupon the operator inserts the ticket in the calculagraph and stamps the finish of conversation. She then takes down the connection and sends the ticket to file. When the Chicago party hangs up his receiver, the inward operator at Chicago receives a disconnect signal and likewise takes down the connection.

The above describes the steps in the handling of the simplest type of long distance call. There are many variations from this. The process varies with the type of telephone at which the call originates and at which it terminates. Person-to-person calls involve reaching particular persons and introduce additional variations in handling. Calls may be placed either paid or collect and the routine is different in each case. Direct circuits are not provided to all places and intermediate operators are involved in handling switched calls. The called telephone sometimes is busy or does not answer or the called person may not be available and additional attempts must be made to complete the call. All of these conditions call for variations in the process of handling the call, yet the operating method and the operating rules or practices which describe it must cover all of these situations.

Evolution of Toll Operating Methods

It may be seen from the above that toll operating methods have grown and developed along with the business to meet the changing requirements. As each new method came into use the quality and usefulness of the toll service has steadily improved and the way has been cleared for a better operating job and improved supervision. High grade operating and supervision broaden the possibilities in methods betterment work and may well be the controlling factors in the success of improved plans. The operating method is influenced by features of plant design such as transmission requirements and improvements in switchboard equipment. Conversely, the design and arrangement of plant is influenced by changes in operating method made to improve the quality of the service. Through the toll system the telephone service of the country as a whole is tied together as one great network and the coordination and standardization of the plant and methods make possible universal service.

GENERAL TOLL SWITCHING PLAN

The technical developments which are outlined in the preceding sections of this account made possible continued improvement in the range and quality of telephone conversations over long distances and economies in the costs of providing long distance circuits. As a result, long distance telephone service grew rapidly, both in volume and in extent, and by 1915 service was established between the Atlantic and the Pacific Coasts. The application of technical developments continued, increasing the transmission efficiency not only of the very long telephone circuits which technical developments have recently made possible but also of shorter toll circuits of all lengths.

Although the opening of the transcontinental line showed the possibility of establishing direct telephone service between any two points in the country, a great deal more had to be done in order to closely realize the Bell System ideal of universal service, that is, good service between any two points in the country. While a large proportion of the toll board messages (at present 80 per cent) is handled by direct circuits between the two terminal points, there is naturally a very large number of combinations of cities and towns in the country between which the telephone business is too light to justify direct circuits—in fact, these constitute a large percentage of all the combinations of places in the country. For these conditions, when a telephone connection is required, it must be established by switching together two or more telephone circuits. Some cases might require switching together a considerable number of telephone circuits, this sometimes involving difficulty and delay in establishing the connection. Also, while the telephone circuits may be so designed that, individually or in combinations of two, they provide very satisfactory transmission, in some of these cases requiring a number of switches, the combination of circuits might result in unsatisfactory transmission.

In order that universal service for the nation might practically be realized, it was necessary to provide an underlying plan for the routing of telephone calls between any two places such that the maximum number of switches necessary for building up the connection would be as low as practicable. This must apply to connections between any two points in an operating area, or other natural subdivision of the country, and also to the country as a whole. Furthermore, the plan should provide for a transmission design of toll circuits such that transmission conditions will be satisfactory on individual circuits when used for direct traffic between their terminals, and also for any combination of circuits which may be connected together in establishing a connection between any two points. It is the purpose of the General Toll Switching Plan to provide a general design of the toll plant which meets these requirements and which, therefore, when fully effective, provides for satisfactory service between any two points in the continental United States. The Plan also covers that part of Canada served by the Bell Telephone Company of Canada. For most of the messages, where volume of business and other conditions justify, the telephone service is of course better than the minimum contemplated by the Plan as, for example, by the provision of direct circuits.

In addition, trends in the construction of toll circuits were such that there was a growing need for an underlying plan for routing toll circuits in such a way as to provide for the most economical plant design. Large numbers of additional toll circuits were required and the types of new telephone plant were such as to trend increasingly toward the concentration of large numbers of telephone circuits on a single route. This is illustrated best by the telephone cable, making possible the installation of many hundreds of circuits along the same route and in a smaller way by the application of carrier telephone systems to open-wire lines, doubling or trebling the number of circuits which could be carried by each such line. Satisfactory operation over connections built up by switching together several toll circuits (multi-switch connections as they are called) requires the insertion of transmission gain at the switching points. Developments in methods of providing such transmission gain by the proper manipulation of repeaters were of such nature that increasing economies could be realized by concentrating through switching as far as possible at a small number of points. Also, this concentration could result in operating economies. A General Toll Switching Plan lends itself naturally to concentrations of circuits on important routes, and in the development of the plan, account was taken of this trend. It therefore forms a background for realizing in future plant extensions the maximum economies from these concentrations of route and of through switching.

These considerations led to the development in 1928 and 1929 of a General Toll Switching Plan. The general features of this Plan may be understood by referring to Figs. 22 and 23. Figure 22 shows how the Plan applies within a given operating area such as an operating unit of an Associate Company. Within such an area there were selected a few important switching points and these were designated as "primary outlets." Each toll center in the area is directly connected to at least one primary outlet and each primary outlet is directly connected to every other primary outlet in the area. There-

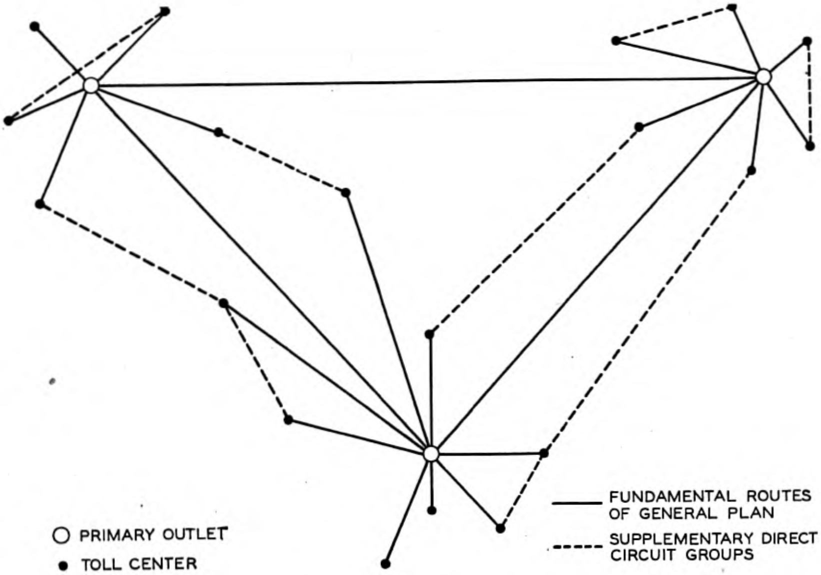


Fig. 22—Application of the toll switching plan to an operating area.

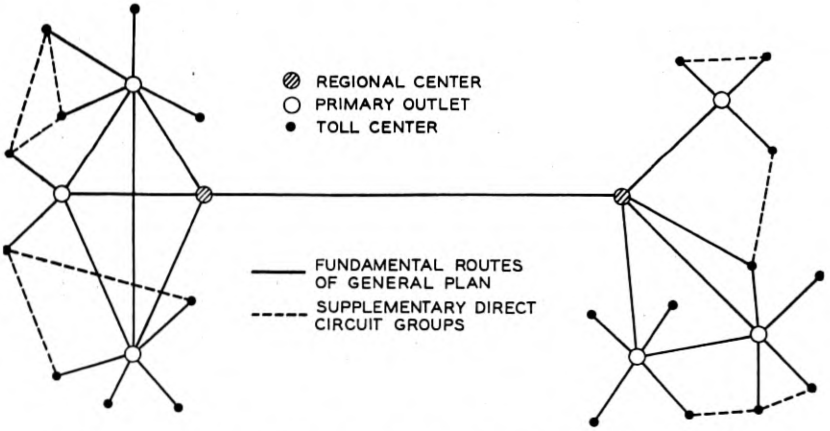


Fig. 23—Application of the toll switching plan to the country as a whole.

fore, any two toll centers in the area can be connected together with a maximum of two intermediate switches. The primary outlets for each area were selected after a careful study of present switching and operating conditions. Due weight also was given to the probable future trends. The number and location of primary outlets selected for each operating area were designed to give maximum economy considering both present and future conditions. This naturally resulted in many cases in the selection of the larger cities of a given operating area although in some cases other points were chosen as primary outlets due to their advantageous location, for example, at the point of intersection of a number of important toll routes. The routings provided by the Plan are supplemented by direct routes or other routings where the volume of traffic or other conditions made this desirable. These other routings, however, are designed to provide service conditions at least as good as those provided by the General Toll Switching Plan.

Figure 23 shows the application of the General Toll Switching Plan to the country as a whole. In order to tie together with a minimum number of switches the interconnected groups of primary outlets, each one of these primary outlets has direct connection to at least one very important switching point designated as a "regional center," and each regional center has direct connection to every other regional center in the country. This means that any two primary outlets in the country are connected together with a maximum of two intermediate switches. The numbers of switches between telephone points of different classifications are shown by Fig. 24. It will be noted that in the limiting case of toll centers in different regional areas and not connected directly to any regional center, the maximum number of intermediate switches is four.

	Same Regional Area				Another Regional Area			
To— From	Regional Center	Primary Outlet	Toll Center Directly Connected to Regional Center	Toll Center Directly Connected to Primary Outlet	Regional Center	Primary Outlet	Toll Center Directly Connected to Regional Center	Toll Center Directly Connected to Primary Outlet
REGIONAL CENTER.....	0	0	0	1	0	1	1	2
PRIMARY OUTLET.......	0	1	1	2	1	2	2	3
TOLL CENTER (directly connected to Regional Center).............	0	1	1	2	1	2	2	3
TOLL CENTER (directly connected to Primary Outlet).............	1	2	2	3	2	3	3	4

Fig. 24—Numbers of switches between telephone points of different classifications.

The present location of regional centers and primary outlets in the General Toll Switching Plan is shown in Fig. 25. There are, as will

Fig. 25—Locations of primary outlets and regional centers.

be noted, eight regional centers in the United States, and 143 primary outlets including three in the eastern part of Canada.

While a regional center has direct circuits to all of the primary outlets tributary to it, it also has direct circuits to many other primary outlets. This is illustrated by Fig. 26 showing for the case of the Chicago regional center the direct circuits to a large number of primary outlets throughout the country. In addition, Chicago has, of course, direct circuits to many toll centers which are not primary outlets where the volume of traffic is sufficient to justify such direct circuits. The same is true also of other regional centers and of primary outlets.

In order that the transmission between any two points in the country over a circuit routed in accordance with the General Toll Switching Plan should be satisfactory, standards were established for each class of toll circuit, that is, for toll circuits between toll centers and primary outlets, between primary outlets and regional centers, etc. These standards provide satisfactory overall transmission for connections between any two points in an operating area, with an economical division of the total transmission loss between the different toll circuits entering into the connection. Generally speaking, these same circuits form parts also of very long connections, switching at primary outlets or regional centers to long circuits running to other parts of the country. In order that satisfactory transmission may be given under these conditions, it is necessary that severe requirements be applied to the very long circuits with the result that they must be designed and maintained with great care and coordination throughout their entire length. It is also necessary that transmission gain be inserted at points where circuits are connected together, and therefore that the characteristics of the shorter circuits be such that they do not limit the possibilities of inserting such transmission gains. The application of these various complex requirements for toll circuits, in order that they may form satisfactory links in any connection, short or long, in the nation-wide toll telephone network, is greatly facilitated by the systematic character of the General Toll Switching Plan, and by the recommendations as to minimum performance standards which that plan contains.

Until recently, the method generally used for inserting transmission gain on through connections of toll circuits was by means of repeaters associated with the cord circuits at the intermediate switching points. About the time that the Toll Switching Plan was established, there was made available an improved method by which the gain of repeaters permanently inserted in the toll line is automatically adjusted at the switching point when the toll circuits are connected together. These

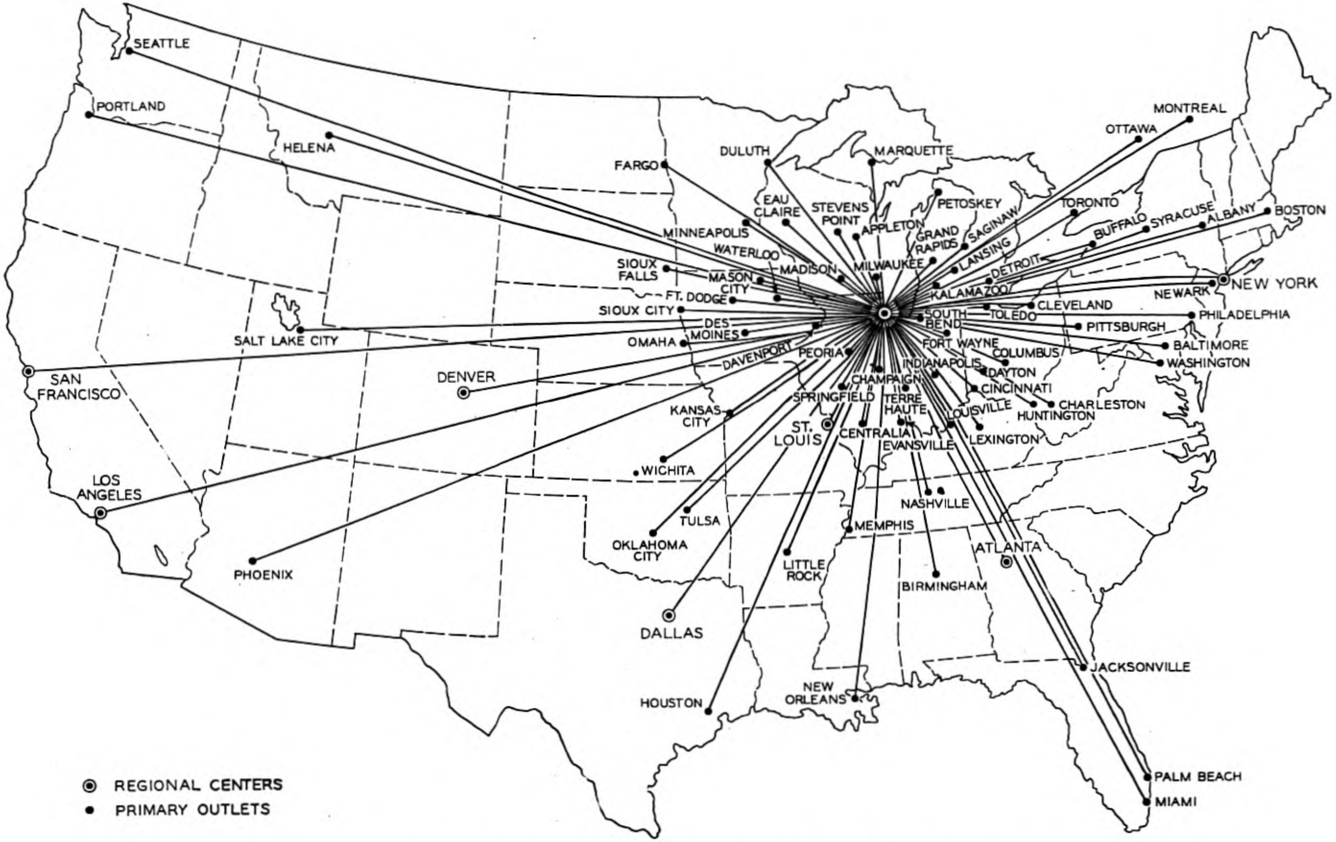


Fig. 26—Direct circuits from Chicago to primary outlets and regional centers.

improved arrangements were scheduled for application as circumstances warranted to the regional centers and primary outlets. At the present time they have been applied to all of the regional centers and about half of the primary outlets and about 95 per cent of the switched connections requiring gain at the switching centers make use entirely of this improved method.

As the Bell System is a living and growing organism, the General Toll Switching Plan is continuously under review and frequently revised in detail. For example, while there are now four primary outlets in the territory of the New England Telephone and Telegraph Company, it seems probable that future developments in concentration of circuits on cable routes will result in reducing these in number.

The transmission requirements applied to the different classifications of circuit for best results vary with the availability of further technical developments. For example, in the future the improved high-speed circuits made possible by the application of carrier to cables will result in modifications of the General Toll Switching Plan, resulting in improvements of transmission over all switched connections and in economies in circuit design through liberalizing the transmission requirements for certain routes, particularly the circuits between toll centers and primary outlets.

The General Toll Switching Plan is an important instrument in systematizing plans for the design of plant extensions, for the application of technical and operating improvements, and for realizing in fact the ideal of universal service between any two telephones in the country.

THE JOINT OCCUPANCY OF PLANT

The Bell System organizations involved directly in the giving of telephone service include regional companies (known as the Associate Companies), operating in various areas throughout the United States, who are responsible for the exchange service and for toll service within their areas,* and the American Telephone and Telegraph Company, responsible for the long distance toll service between points in the areas of different regional companies.

As a result, it is a common situation to have inter-area toll plant of one company terminating in towns and cities where the exchange plant is owned and operated by another company, and sometimes extending for considerable distances along the same general routes as the intra-area toll plant of that company. In a great many cases

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* There are a few companies in which certain interstate items of traffic within the company area are handled by the American Telephone and Telegraph Company.

there are economic and service advantages in the consolidated construction of plant used by the two companies involved and, for such situations, this is the common practice. This involves the joint use of land, buildings, right of way, pole lines, conduits, etc.

The economic advantages of such joint use of plant are obvious. For example, one duct run with a sufficient number of ducts for both companies can be built more cheaply than two separate duct runs, and the same is true of pole lines. When toll cable is installed, it is an economy, when practicable, to place within one sheath sufficient circuits to take care of the requirements of both companies. The same is true for other parts of the telephone plant. Furthermore, there are advantages in having the toll switchboard in a building used for exchange service and often in having inter-area and intra-area toll circuits terminate at the same switchboards and use the same groups of trunk to the local exchange plant.

Other things being equal, there is an advantage in each company owning the plant required for its service, and this is the basis generally followed. This leads to a large extent to the joint ownership of jointly used plant, particularly of outside plant. This includes joint conduit runs, joint pole lines, and jointly owned toll cables.

In some cases, rather than joint ownership of jointly used plant, there are advantages in a single ownership by one of the companies, generally the company having the largest requirements, which leases some of the plant to the other company. This applies, for example, to land and buildings where, because of the greater ease and simplicity of transactions of various sorts, a single ownership is preferable. This is also often true where the requirements of one company are small or where, as a result of growth, the division of ownership of jointly occupied plant no longer corresponds exactly to the relative needs of the two companies for the use of the plant. It applies also to the temporary use by one company of spare plant owned by another which will later be required for the owner's use.

Rental Arrangements

To meet the varying conditions, two general bases of rental are in use: (1) the "reserved plant" basis, and (2) the "spare plant" basis.

On the reserved plant basis, rentals cover plant designed and constructed by the owning company for joint use with the renting company or for the sole use of the renting company under a specific plan mutually agreed upon, usually in advance of construction. Existing plant may also be put on a reserved basis by specific agreement. The plant reserved for the lessee provides not only for its present needs, but usually for growth as well. A good example of this type of arrangement is a jointly occupied building which is designed to meet the present and expected future requirements of both companies and in which certain designated space is reserved for the lessee company.

The spare plant basis applies to plant which, in general, the owning company has provided for its own use in anticipation of its own future requirements, or to plant which is spare because of fluctuating load demands and can be temporarily placed at the disposal of the renting company. Such plant may be released by the lessee at any time or may be taken back by the lessor company at any time upon reasonable notice to the other company.

Illustrations of both these bases of rental where the American Telephone and Telegraph Company and an Associate Company are involved are given below.

(*a*) *Buildings*

In providing building space, it is the general practice for one company to own the building used jointly by both companies. This arrangement is advantageous, particularly in the larger cities, since it permits one company to deal with taxing authorities, zoning commissions, public works authorities, and the public generally. Where space for a local central office is required, it is the general practice for the Associate Company to own the building. The American Telephone Company's ownership in buildings is accordingly largely confined to intermediate repeater stations. The owning company generally furnishes space to the other company on a reserved plant basis.

(*b*) *Equipment*

In the case of toll equipment, one of several arrangements is followed, depending in part upon local conditions, such as local operating or maintenance conditions, and in part upon the relative amount of equipment required by the two companies involved. In some cases where one company requires a relatively large part of the total equipment used, that company owns all equipment and furnishes equipment for the other company's needs on a reserved rental basis. Thus, on some of the long through routes where the American Telephone and Telegraph Company uses the majority of the equipment in the intermediate repeater stations, it owns all equipment and rents such portion as required to meet the other company's needs on a reserved rental basis. In many other cases where both the American Telephone and Telegraph Company and the Associate Company have considerable toll equipment requirements and these can best be provided in joint installation, each company will own the equipment provided for its use. If there is any sudden peak in the equipment requirements of one company, the other company will usually temporarily furnish spare equipment from its own reservation on a rental basis to aid in meeting the peak demands.

(*c*) *Outside Plant*

Where both companies' use is substantial, arrangements are usually made for the joint ownership of the common items of plant. In underground conduit, the ownership is usually divided on the basis of number of ducts required by each company, except that if one company's requirements are less than one-half of one duct (occupied by a jointly owned cable), it is customary for that company to rent duct space from the other company. Open-wire pole lines are generally jointly owned where each company has a requirement of one crossarm or more, the cost of the pole line being divided in proportion to the numbers of crossarms required by each company. In cases where the requirements of one company are minor, it may lease space from the other company on an attachment rental basis, using a reciprocal rental rate for the use of the supporting structure which reflects the average carrying charges on both line and right of way. In the case of toll cables, the ownership of certain wires in the cable is generally held by each company, the cost of the cable being divided in proportion to the copper cross-section of the wires owned by each of the companies.

In the open-wire plant, each pair or phantom group is generally owned by one company and located in the crossarm space reserved on the pole line for that company.

Emergency situations arise from time to time in which service may be restored most quickly by a temporary use of spare facilities of the other company or by a temporary pooling of the circuits of both companies which remain in service and applying them most equitably to the service demands of both companies. The work of restoring service in such cases is handled without the execution of any formal agreements between the companies involved, and such adjustments as are necessary are worked out later.

Joint Maintenance Arrangements

The joint maintenance arrangements are based on the principle of providing the most economical procedure in each case. This results, generally speaking, in the maintenance by employees of one company of all jointly occupied outside plant on a single route. It is obviously economical, for example, to have such an arrangement for the maintenance of pole lines, conduit, and cables which are jointly owned by the two companies.

In the case of central office equipment, it is generally desirable in large cities where a large amount of equipment is owned by each company to have separate maintenance staffs, particularly for the service maintenance work performed by the toll test room forces. At smaller points, a single maintenance force is generally provided by the company having the greater amount of work.

The division of maintenance costs between the two companies is based upon the same principles of equitable allocation as applied to the division of ownership and to rental charges. For example, the cost of maintaining toll cables is divided between the companies in proportion to their ownership interest in the cable. Another example is the cost of pole replacement, which is one of the large items of pole line costs. Replacements are made upon the basis of periodic inspections of the pole line, the first inspection being made about ten years after the new line is built and subsequent inspections approximately every four years. These inspections determine the poles which are in such deteriorated condition as to require replacement. Where the replacements consist of substituting the same size of pole for the existing pole, the charges are borne by the companies concerned on the basis of their assignments on the old pole.

General

The above indicates briefly the types of arrangements for the usual case. No attempt has been made, however, to indicate all of the variations in these arrangements applying to the extensive plant of the Bell System covering the entire country and sometimes requiring modifications of these arrangements or some other special provisions. However, the general principle outlined above is followed, namely, that of providing the most economical overall result with an equitable division of costs and responsibility between the companies involved in each case.

STANDARDIZATION

The electrical design of telephone toll circuits is necessarily complicated, as the overall electrical characteristics on which the efficiency of the circuits depends are the result of the composite effect of many different electrical phenomena. Also, the overall characteristics of a toll circuit are the composite resultant of the characteristics of a large number of individual pieces of apparatus and sections of circuit. The construction of the plant at such times and in such quantities as to produce most economic results involves many considerations. In many cases, as for example, in the construction of pole lines and of toll cables, it is necessary for greatest economy to provide plant to meet the estimated requirements for a considerable period ahead. Furthermore, the maintenance of this plant at a higher degree of efficiency and its operation to connect together quickly and accurately any two of the fourteen million telephones in the Bell System involve a good deal of complication in routines and procedures. In view of these considerations, the telephone toll plant and service offer very good examples of the advantages of standardization in plant and in operating methods.

The complexity of the toll plant and the number of types of apparatus and material which would be required would be greatly multiplied if it were not for the high degree of standardization in the Bell System telephone plant. In fact, it is not an exaggeration to say that the telephone toll service of today could not be given had not effective steps been taken from the beginning looking to this high degree of standardization and simplification.

Plant Design

It is evident that if each toll circuit were designed individually to meet exactly the requirements for that circuit as regards efficiency for good transmission and other requirements, the result would be, in general, that each small group of toll circuits between two points would differ in electrical design from every other group of toll circuits between any other two points. This would result in many thousands of different kinds of toll facilities, each designed for a specific use only, and would result in endless confusion and lack of practicability. However, the standardization of the apparatus and materials forming the toll telephone plant has been carried on since the beginning of toll service and has resulted in a simplification of practice and the general use of the same types of apparatus and material throughout the country. For example, there has been a high degree of standardization of the sizes of copper wire used for open-wire telephone conductors. A very large percentage of the wire used in the plant for this purpose is made up of three sizes, respectively, 104, 128, and 168 mils in diameter. In toll cables, practically all conductors are made up entirely of two gauges, 16 and 19 B & S gauge. With few exceptions, repeaters for telephone message circuits are of either one of two basic types, one for two-wire circuits and one for four-wire circuits, with such modifications in balancing arrangements, signaling arrangements, etc., as are necessary to adapt them to the different types of circuit. Carrier systems are one of two general types, a three-channel system for long distances and a single-channel system for shorter distances, although additional types of system for other types of circuit condition are now under development. In the design of any given circuit, choice is made from this limited number of types of facilities, selecting the one which will give not less than the required transmission efficiency in the given case with maximum economy and other advantages. This procedure results in great advantages in simplicity of plant design and in the flexibility with which sections of toll circuit can be transferred from one use to another as occasion requires.

Construction, Maintenance, and Operation

The advantages of standardization apply to the operating field as well as to the engineering design. Standard construction practices are based upon the use of standard types of construction material all over the country. This standardization of materials makes it possible for the purchasing organization to buy large quantities of a relatively small number of types of material with a resulting saving in cost. Also, the standard construction practices facilitate the training of men and the transfer of men from one part of the System to another with shifting needs.

Similar advantages result from the standardization of maintenance practices. The Bell System maintenance practices make use of the maintenance experiences of the operating companies and of general investigations of the relative advantages of different practices and methods. These practices are generally used throughout the country with advantages from the standpoints both of economy and of service. Men at widely separated points and sometimes employed by different companies can cooperate closely in the maintenance of telephone circuits which have been or may be connected together in the toll service. Also, at times of emergency, men and materials from various parts of the country, wherever available, may be concentrated on the emergency job, and the men, applying standard methods to standard materials with which they are familiar, can work most effectively in the quick restoration of service.

It is perhaps in considering traffic operation practices that the advantages and, indeed, the necessity of standardization in relation to operation is most evident. The toll operators must constantly deal with other operators in distant cities, and it is obviously essential that the operating practices should be alike in order to avoid extreme difficulties and reaction on the speed and quality of service. The standard Bell System operating practices provide in detail the standard procedures to be followed by operators in handling the various types of toll call and, in general, specify also the phraseology to be used by operators with a view to insuring maximum accuracy, clearness, and convenience to subscribers.

General

While, as pointed out in the above paragraphs, standardization in the Bell System is a means of obtaining economy and efficiency, it is more than that. It is essential to the best service and the most rapid progress. The conditions bearing on the telephone toll plant and toll service are constantly changing through growth, shifting demands, the development of new needs of customers for telephone service. Also, the best means and methods available for giving service are constantly developing as a result of the experience of the various operating companies and through the development of new instrumentalities and operating methods by the headquarters forces of the Bell System. These types of apparatus and of communication systems, and methods and practices for construction, maintenance or operation represent the outcome of careful consideration of the best way to meet a type of situation. Through the headquarters organization their availability is made known at once to the operating telephone companies of the Bell System throughout the country with information regarding their desirable field of use. This greatly facilitates their adoption and application by these Companies.

In some cases, such new standards present means for doing something which could not be done before. In many cases, such new standards replace existing standards due to advances in the art, improvements in methods or technique, or changes in operating requirements. Standardization in the Bell System, therefore, involves a continuous procession of new standards to meet new conditions or to meet old conditions better than was heretofore possible, and the subsequent dropping of old standards. Such standardization is based not only upon the present needs of the telephone system, but also upon the best picture which can be formed of future trends. It is essential to the rapid and satisfactory development of telephone toll service.

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Microchemical and Special Methods of Analysis in Communication Research

By BEVERLY L. CLARKE and H. W. HERMANCE

Analysis was beginning to take its place as an important branch of chemistry when, in 1828, Wöhler synthesized urea and the Age of Synthetic Organic Chemistry was born, destined to overshadow analysis for nearly a century. When interest in synthesis began to diminish, in the late 1800's, physical chemistry arose to intrigue the chemical mind. The analyst, thus neglected, had to work with apparatus, techniques and viewpoints evolved for other chemical purposes. In 1910 the Austrian Pregl found it necessary to analyze a sample too small for the then available technique to handle. His solution was the invention of a new kind of analysis—microanalysis, the essential features of which are: reduction of apparatus size and of scale of operations to a point commensurate with sample size; development of entirely new techniques, apparatus and chemical reactions specially suited to analysis; and inculcation in the mind of the analyst of the attitude that analytical problems are, in greater or less degree, research problems, and are to be approached as such, with a mind entirely unrestricted by chemical classicism. This article discusses the applications made by the Bell Telephone Laboratories of microanalytical and related special techniques to communication research and engineering.

THE beginnings of chemistry are lost in antiquity. The basic entities of the early natural philosophers, earth, air, fire and water, gradually gave way to the more numerous and fundamental entities, the elements. In the Middle Ages the alchemists concentrated their talents on an unsuccessful attempt to change base metals into gold. Although these men were, with several notable exceptions, charlatans and fakers, they did focus attention on matter and its objective properties. As early as the 5th century, B.C., Thales of Miletus proposed an atomic theory; but it was John Dalton who twenty-three centuries later formulated the modern Atomic Theory which is the foundation-stone of chemistry.

In the intellectual gropings of man, atoms and molecules, in due course of time, became concepts that explained many phenomena. During all these years there has been a search for the single entity of which all matter was made. Prout's hypothesis of the early 19th century named hydrogen as this single elemental substance. By the end of the 19th century and the beginning of the 20th the one element became charges of electricity, positive and negative. Today they are the electron and the positron. Out of all the earlier concepts slowly arose the basic idea of chemistry, that the substantial and ponderable part of the world, matter, composed of solids, liquids and gases, is susceptible to controlled transformation.

The devising of tests by which various kinds of matter could be recognized was one of the early accomplishments of the chemist. Many such tests were used by the ancients. It was left for Robert Boyle (17th century), famous for his Gas Law, to conceive identification tests as an important branch of chemistry. Boyle was the first to use the expression "chemical analysis." Lavoisier, of French Revolution era, is credited with having brought about a chemical revolution, one result of which was "quantitative analysis"—methods for determining quantitatively the composition of materials. The Swede Berzelius, working early in the 19th century, analyzed with prodigious industry hundreds of compounds, thus laying the foundation for the quantitative data of chemistry. In the middle 1800's the Belgian chemist Stas repeated and extended Berzelius' work, developing methods and techniques of much greater accuracy.

With the impetus given to it by Stas' work analytical chemistry might have been expected to hold the center of the chemical stage during the 19th century. But in 1828 the German Wöhler synthesized the substance urea from laboratory chemicals. Urea belonged to the vast class of compounds produced by vital processes, and chemists accepted the dogma that these *organic* compounds could not be otherwise produced. Wöhler's synthesis disproved that dogma, and the great Age of Synthetic Organic Chemistry began, destined to occupy chemists' minds for about a century.

Since little attention had been given to analytical chemistry during these years, it became the step-child of the science, useful but not particularly creative. The natural result was that it became a stagnant, static science. It had no special apparatus of its own, but had to be content with the instrumentalities designed for other purposes. Similarly, no one had made any special search for chemical reactions particularly adapted to analysis. Interest in synthesis had also begun to wane. Then physical chemistry burst forth to open up new vistas for the science.

This continued, essentially, until 1910. In the University of Graz, Austria-Hungary, the biochemist Pregl labored for years on a research. Finally he reached a crucial stage of the work. Before him were a few small resultant crystals, whose composition it was necessary to know before further progress was possible. His analyst told him that the sample was far too small to analyze. So Pregl faced a clean-cut dilemma: either he must start all over again on his research, work for years more on a larger scale, in order to prepare a larger sample, or some way must be discovered to analyze the small sample in hand. Pregl chose the latter alternative, and in so doing initiated an era of development in chemical analysis that has not even yet reached its zenith, namely microchemistry.

Pregl worked in organic chemistry. Simultaneously another Austrian, Emich, approached inorganic analysis from the new point of view. In this country Chamot, at Cornell, concentrated on chemical microscopy. These three, Pregl, Emich, and Chamot, are properly credited with the invention of what has come to be called microanalysis; but their many students and co-workers, as well as scores of independent investigators, did and are doing much brilliant work in the shaping of the science to the practical needs of industry and research.

The basic idea of microanalysis is the reduction in size of analytical apparatus to suit small samples. This has shown the necessity of devising many entirely new methods for carrying out common laboratory operations. Many new chemical reactions have been discovered, on specific search, that have special usefulness in analysis.

The Microanalytical Laboratory at Bell Telephone Laboratories has been established for about seven years. The peculiar nature of many problems arising in communication research and engineering has made necessary the development of many new techniques and types of apparatus. It can be said, in fact, that this laboratory employs a special kind of microanalysis, constituting, for the most part, an original contribution to the science of analysis.

Analysis consists in transforming an unknown material into one or more recognizable substances. These products may then be suitably separated and purified and their quantities measured. Thus weighing, measurement of volume, solution, filtration, washing, evaporation, drying, ignition, distillation, etc., are familiar operations in analysis.

The techniques and apparatus formerly used for these operations, while suitable for the other chemical purposes for which they were designed, were in general ill-adapted to analysis. Apparatus was designed for general utility and manual convenience; that is, to fit the worker's hand rather than the sample. A chemist of the last century would not have thought of using a 1000 cc. beaker to contain 50 cc. of liquid; he would have selected a 100 cc. vessel. But if an analyst had only 0.1 cc. of sample he could find on the shelf no vessel of commensurate size.

Suppose, for example, it is desired to determine traces of heavy metals such as copper and nickel, in a certain plant ash. Because of the disproportionality between the quantities of the elements sought and the size of the apparatus, the errors introduced are large when ordinary methods are employed. Mechanical losses incurred in the many manipulations and transfers of material, over-dilution with resulting incomplete precipitation, contamination both by dust and by substances dissolved from the glass are almost unavoidable. Since the heavy metals represent only a few hundredths of a per cent of the ash, it is obvious that a large sample, perhaps twenty-five grams, is required, if an ordinary balance sensitive to 0.1 mg. is used. It would therefore be necessary to start with a kilogram or more of the fresh plant to obtain results which are sufficiently precise.

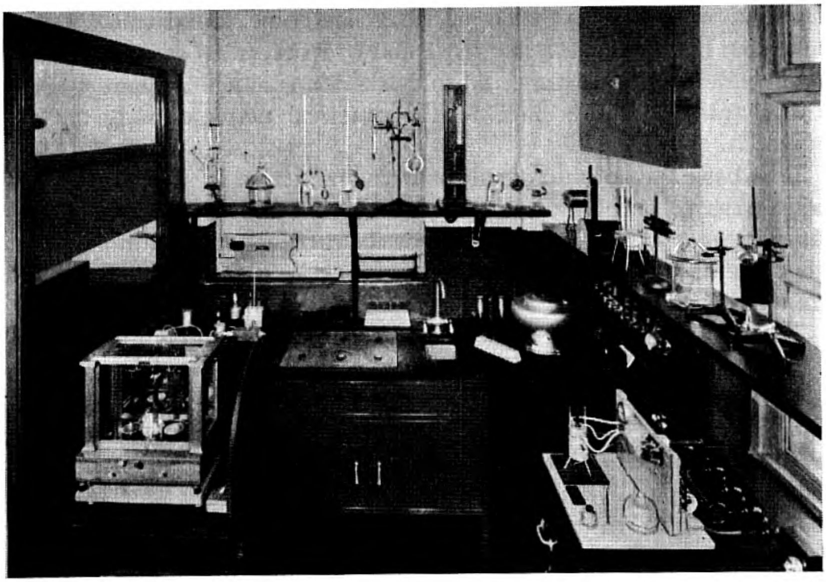

Fig. 1—A corner of the microanalytical laboratory.

Other disadvantages of the usual scale of operations are great time consumption, explosion hazards, and costliness of chemicals and apparatus. On a greatly reduced scale, these difficulties frequently tend to vanish. For example, the precipitation of the sulphides of heavy metals is ordinarily avoided wherever possible in quantitative analysis. This is because they are slimy and difficult to filter as ordinarily precipitated with hydrogen sulphide. To filter and completely wash a gram of lead sulphide might be a matter of several hours and there is great danger that the precipitate will occlude other constituents of the solution. The long exposure on the filter increases the danger of oxidizing the precipitate. On the other hand, a few milligrams of lead sulphide can be precipitated in a sealed tube by a process which produces hydrogen sulphide up to a pressure of ten atmospheres, yet at very little risk of explosion. The resulting precipitate is granular, can be filtered in one or two minutes and its tendency to occlude other metals is much smaller.

Until recently, the most important industrial applications of analysis were the evaluation of raw and finished products and the control of manufacturing processes, neither of which often demanded special technique. With the growing technical trend in commercial production, however, the analyst is being called upon to provide new services. Industrial research must be guided by frequent analyses, both to determine the nature of newly formed products and to gain knowledge of the mechanisms of particular processes. The great diversity of materials, natural and synthetic, and the intricate and often delicate mechanisms embodied in devices of modern manufacture, have enormously enlarged the problem of tracing the causes of failure both in the finished product and in the processes entering into its production. Trouble often arises from obscure defects in materials, the nature of which must be discovered by analytical studies. Impurities, minute foreign inclusions, corrosion and tarnish films, chemical changes occurring with aging or produced as an inherent result of the particular combination of materials used, may contribute.

To make effective use of chemical analysis either as an industrial research tool or as a means of diagnosing manufacturing and maintenance difficulties, the necessity of improving the technique is beginning to be recognized here as in other fields. Great flexibility is needed to fit the operations to highly specific problems. Ability to handle and observe small quantities is frequently necessary because of the minuteness of the phenomena in question. Rapidity is often essential because of the possibility of tying up production, pending solution of the difficulty.

Realization of conventional limitations has stimulated the search for new methods of approach by which the refinement and extension of analytical technique might be accomplished to fulfill the special needs of both science and industry. An outstanding result has been the development in the analyst of a new mental attitude. He seeks to attain his goal first by reducing the scale of operations to a degree consistent with the small quantities of material frequently handled;

second, by augmenting his ability to make observations through the use of adequate instruments; and third, by employing specific and highly sensitive reactions as well as conversion products of high molecular weight.

Micromethods serve the obvious purpose of analyzing minute amounts of material, thereby providing information otherwise unobtainable. Actual experience at Bell Laboratories, however, has shown that the reduction in magnitude of operations frequently permits analyses to be carried out with greater rapidity and more certain results even when the quantity of sample available is not a consideration. The construction of apparatus, when more intricate set-ups are necessary, is far easier and more economical on a small scale and the breakage is less. Reactions run their courses more quickly and are more easily controlled. Reagents may be used whose costliness would be prohibitive on a larger scale. These advantages, added to the capacity to make minute observations, provide a technique of great flexibility, a fact repeatedly demonstrated by successful applications to problems arising in the design, manufacture and maintenance of telephone equipment.

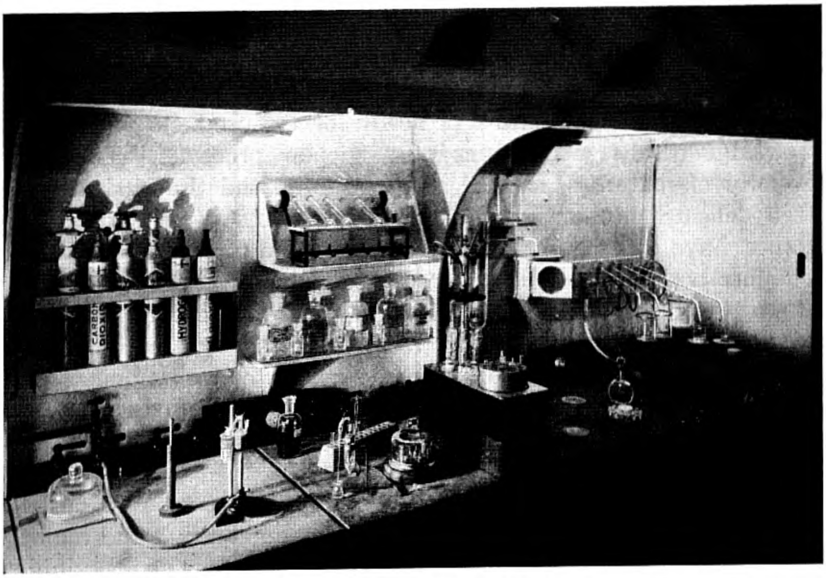
Fig. 2—General view of hood in the microanalytical laboratory, giving some idea of the relative size of glassware and other equipment used.

In microqualitative examinations, an effort is usually made to bring the unknown material into solution in a volume not exceeding a few tenths of a cubic centimeter. Identification reactions are then carried out in single small drops of the solution. To accomplish this, a number of procedures are available. One which is very generally applicable, yielding information of a particularly specific and positive character, is that of carrying out the reaction directly under the microscope. By this means, quantities of elements ranging between a thousandth and a few hundredths of a milligram may be detected. The drop to be examined is placed on a glass slide, the reagent introduced from a capillary pipette and the progress of the transformation watched under magnifications of between fifty and three hundred diameters.

In addition to revealing the presence of minute amounts of reaction products separating from the solution, the use of the microscope facilitates study of the individual particles composing such precipitates. A number of properties are thereby brought into analytical significance which might not otherwise be observed or utilized. In ordinary practice, the analyst is guided in his conclusions as to the presence of an element simply by the bulk formation of a precipitate, specific recognition of which is based only on characteristics readily apparent to the unaided eye, such as color and gross structure. Under the microscope, however, the crystal structure and similar distinctive morphological features, color, transparency, index of refraction, behavior toward polarized light, characteristics of growth and other specific properties may all be studied and employed to give greater certainty to the identification. Further, it is frequently possible to identify the individual components of a mixed precipitate, thereby obviating the necessity of separation. Thus, the double salt potassium mercuric thiocyanate gives insoluble compounds with a large number of the bivalent metals. To apply this reagent to a solution containing several metals would result in the formation of a precipitate which to the unaided eye would yield very little specific information. Under the microscope, the experienced analyst, in a single observation, can often tell from the known habits of the crystals produced by various combinations of metals, the nature of the mixture.

Recognition of substances is not always confined to the precipitation of insoluble reaction products, but soluble salts, when the solution is carefully evaporated, sometimes possess sufficiently distinctive morphology to permit direct identification. In this way minute amounts of sodium chloride have been detected in dust deposits collected near the sea-coast. In the identification of traces of organic material, valuable information is frequently obtained from microscopic studies of the crystalline deposits produced when the substance is sublimed directly on the slide. Crystallographic constants and other optical properties as well as the melting point and solubility may be readily determined on the sublimate even though only a fraction of a milligram is available.

Another advantage to be gained by reactions carried out under the microscope is that of performing tests *in situ*. In practice, it is sometimes difficult to isolate physically the particles of material to be studied. For example, it may be desired to learn something of the nature of a tiny inclusion embedded in a metal or a thin film of corrosion product present on its surface. Here again, the microscope is of great service, both in guiding the physical manipulations necessary to restrict the action of the reagents to a localized area and in observing the actual identification reaction (usually chosen to yield an intensely colored product or bubbles of gas, rather than a precipitate).

When, instead of the commonly used qualitative reagents, compounds are employed which are capable of more specific and sensitive reactions and which yield intensely colored products rather than precipitates, such products may be instantly recognized, even in a single drop of solution. Within recent years, many organic compounds have been developed for this purpose. The use of these, and of a number of inorganic compounds giving highly characteristic color reactions, constitute the basis for a new technique combining rapidity, simplicity, and certainty of identification without the use of the microscope. The drop to be examined is placed on a white background such as a porcelain plate. A drop of the reagent is added and the color change, which may involve a sequence of changing shades, is observed. In cases where turbidity is also significant, a black porcelain plate is used. Because of the highly specific nature of these reagents, it is often unnecessary to resort to a preliminary group separation. Because of its simplicity, the technique is particularly useful for field investigations.

A modification of the drop analysis procedure described above consists in bringing the drop under examination together with the reagent onto loose-textured paper such as filter paper. The colored product which forms is adsorbed on the fibers of the paper at the center of the drop, while the solution spreads out due to capillarity. The capillary action of the paper fibers is sometimes utilized to devise rapid separations, thus enabling the analyst to detect two or more elements simultaneously. In a typical case, a solution contains copper and nickel. A drop of this solution, acidified with acetic acid, is brought onto the paper which is impregnated with hydrorubeanic acid. The bluish-black copper compound is insoluble and therefore forms first, near the center of the drop. The nickel compound, being more soluble, does not form until the solution has spread out to a considerable extent and most of the acid has evaporated, when it is visible as a violet zone near the periphery of the drop.

Papers which have been impregnated with specific reagents and preserved in the dry condition are extremely useful both in the laboratory and the field. In the analysis of gaseous substances or materials readily volatilized, these dry test papers have been very satisfactory. Arsine, stibine, hydrogen sulphide, sulphur dioxide, hydrocyanic acid and other objectionable gases present in minute quantities in the atmosphere, may be detected and their approximate concentrations determined by passing a stream of the air through the fibers of a suitable test paper.

In order to obtain solutions to which identification tests may be applied, some preparatory chemical treatment is necessary. The initial solution and concentration of the sample, its recovery from inert material as well as its separation into convenient analytical groups require laboratory operations capable of dealing with a few drops of liquid and often with a fraction of a milligram of solid. A variety of types of apparatus and special processes have been developed to facilitate these operations. In a few cases, reduction in size has alone sufficed; more often such reduction, with retention of the original form of the apparatus, results unsatisfactorily and new principles must therefore be followed in the microdesign.

For example, it is obvious that the usual folded paper cone cannot be satisfactorily reduced in size to permit the removal and recovery of suspended matter from a few drops of liquid. Microfiltration may be accomplished in a number of ways but the most convenient is to draw the liquid into a capillary pipette provided with a retaining well which holds a very small pellet of the filtering medium. In this way a single drop may be filtered and completely washed in a few seconds, the residue being concentrated in the tiny filter plug from which it may readily be redissolved in a trace of acid. Practically all of the common analytical operations have been reduced to a microscale and may be carried out with rapidity and precision in equipment of appropriate design.

It may be of interest to note here a few of the more ingenious devices and processes that have been developed to aid qualitative microanalysis. The electrolytic cell of H. Brenneis provides for the precisely controlled electrolysis of a drop of solution, at the same time permitting continuous observation of the electrode surfaces under the microscope. By its use, 0.001 mgm. of copper may readily be recognized and as little as 0.0001 mgm. of zinc has been observed on a previously coppered cathode. The electrodes are formed by encasing closely spaced platinum wires in glass which is subsequently cut and polished through a perpendicular plane, thereby exposing cross-sectional areas of the wires. The drop to be electrolyzed is placed on the polished glass surface and the portion covering the platinum areas observed under the microscope.

A process rarely used in ordinary analysis but of great service in microwork is that of sublimation. A few thousandths of a milligram of a volatile crystalline solid may be separated in this way from a large bulk of inert material in a condition that permits immediate treatment with reagents. In order to apply this process to dusts, corrosion products and other frequently-encountered materials, an improved microsublimation chamber has been designed by this Laboratory. The apparatus is so arranged that both temperature and pressure can be regulated. The vapor condenses on a water-cooled microscope cover-glass and the recovery is practically quantitative. As little as 0.002 mgm. of mercuric iodide was found to give a deposit of definitely recognizable crystals.

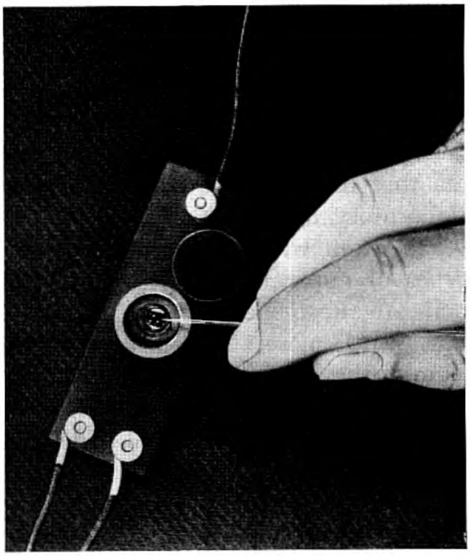

Fig. 3—The electrolysis cell shown here, when used under the microscope, permits one to observe the deposition of metals from tiny drops of solutions. Less than a thousandth of a milligram of copper or zinc may be detected by its use.

A phenomenon that has long been familiar, yet not applied to analysis until its value in microwork was recently demonstrated, is the production of "schleiren" or refraction lines when two fluids of differing optical density are added together without mixing. One liquid is contained in a flat optical cell of a few tenths cc. capacity. The other is slowly introduced below the surface of the first liquid from a capillary orifice. The refraction effects set up are observed through a horizontally mounted microscope under controlled illumination. When one of the liquids is known, such observations are the basis for both specific gravity and refractive index determinations. So sensitive is the method that a difference of 0.0001 in the refractive indices of the two liquids is still detectable. It therefore affords an excellent test for purity. If, for instance, two fractions of a distilled liquid are added together with the production of "schleiren," it may be assumed that the original liquid was not a pure substance.

Glass capillary tubes have shown great versatility in microwork. When the quantity of material operated upon is exceptionally small, as, let us say, in the case of a foreign deposit on relay contact points, their use affords distinct advantages. Almost every operation can be executed through appropriate adaptations of capillary technique. Thus reactions may be carried out under pressure in sealed capillaries when the volume of liquid is only a few thousandths cc. and the whole process watched under the microscope. Distillation and sublimation are processes to which capillaries are especially suited. Suspensions may be centrifuged or filtered in capillaries. In the latter case capillary attraction is the force that draws the liquid through the filtering medium.

The possibilities of capillaries may be illustrated by a practical example. Tiny discolorations were found on the surface of a polished silver sheet used in photocell manufacture. Mercury contamination was suspected and an analytical confirmation was desired. The procedure was as follows: A 1-mm. capillary tube was drawn out to form a pipette having a very fine tip. With this a very small drop of nitric acid was transferred to one of the discolored areas under the microscope, and allowed to act for a few seconds, after which it was removed, transferred to a capsule and the excess acid evaporated. The residue was re-dissolved in a small drop of water and drawn up into a second capillary tube containing a few mm. of No. 32 copper wire. Both ends were sealed and the tube heated in boiling water for a few minutes, after which one end was opened and the liquid withdrawn by means of a finer capillary. The open end was then drawn out to a very fine tube of microscopic bore. The closed end was heated by a microflame, gently at first to drive out moisture, then strongly until the glass had completely fused about the copper wire. Heating in this manner was continued almost to the constricted portion. When the capillary, after cooling, was examined under the microscope minute globules of condensed mercury were plainly visible. In this process, the mercury is displaced from solution by the copper and

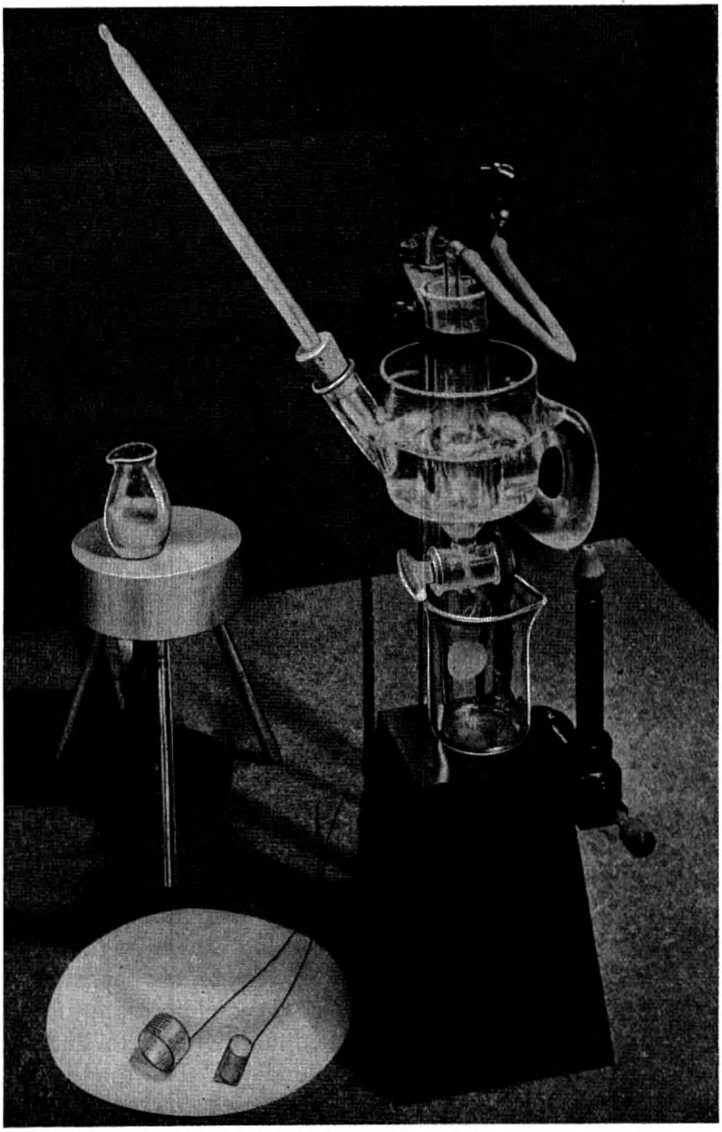

Fig. 4—With this electrolytic cell as little as a milligram of various heavy metals may be precisely determined.

deposits on the wire from which it is subsequently distilled. As little as 0.001 mgm. can be readily detected in this way.

A considerable part of the microanalyst's task is the physical isolation and recovery of the material on which his analytical operations are to be performed. His problems very often require examinations of minute particles or aggregates of foreign substances which have become attached to or embedded in the surface of a material. He may also be required to isolate and study the structural units which compose a given formation. For example, a deposit occurs on the surface of a metal as a result of corrosion. This deposit is not of a homogeneous nature but is built up in successive layers, each of which differs in composition. To obtain a satisfactory picture of the mechanism of the production of the deposit it is necessary to know the composition of each separate layer.

The mechanical manipulations necessary to obtain sample material frequently tax the analyst's ingenuity more than the analysis itself. The work is usually carried out under the low powers of a microscope, preferably of the binocular type. Much of the technique of the biologist has been appropriated by the microanalyst in this phase of his work. Various types of dissecting tools find ready application here. The dental engine with its various attachments, such as drills, burrs, carborundum wheels, has been found extremely useful for drilling out inclusions in metals and for the removal of hard surface films. The micromanipulator, an instrument originally designed by biologists to perform intracellular operations, has recently been employed in microchemical work with very satisfactory results. This instrument furnishes the means of regulating with great precision the movement of needles, capillary pipettes, electrodes, electrically heated platinum wires, etc., under relatively high magnifications. It offers great promise where particles of exceptionally small dimensions are to be studied.

A number of methods have been developed and used by the Laboratories' Microchemical Group for the collection and study of central office dusts. A device which deserves particular mention is the impinger, an adaptation of which has been employed to remove dusts from the extremely localized area represented by a single relay contact point. The device is so constructed that the particles, after being picked up by suction, are projected at high velocity against a microscope slide, the surface of which is coated with an adhesive medium. The slide is removed from the apparatus and the dust subjected to physical and chemical treatment to determine its nature.

In quantitative microanalysis, the analyst is faced with the added problem of weighing a few milligrams of material with the same precision as might be obtained with samples of the usual size. The Nernst quartz fiber balance, capable of weighing to a few ten-thousandths of a milligram, has proved very useful in certain types of work, where the total load does not exceed a few tenths of a gram. Its application to chemical analysis, however, is quite limited because of the difficulty of reducing the load to this extent. The quantitative extension of

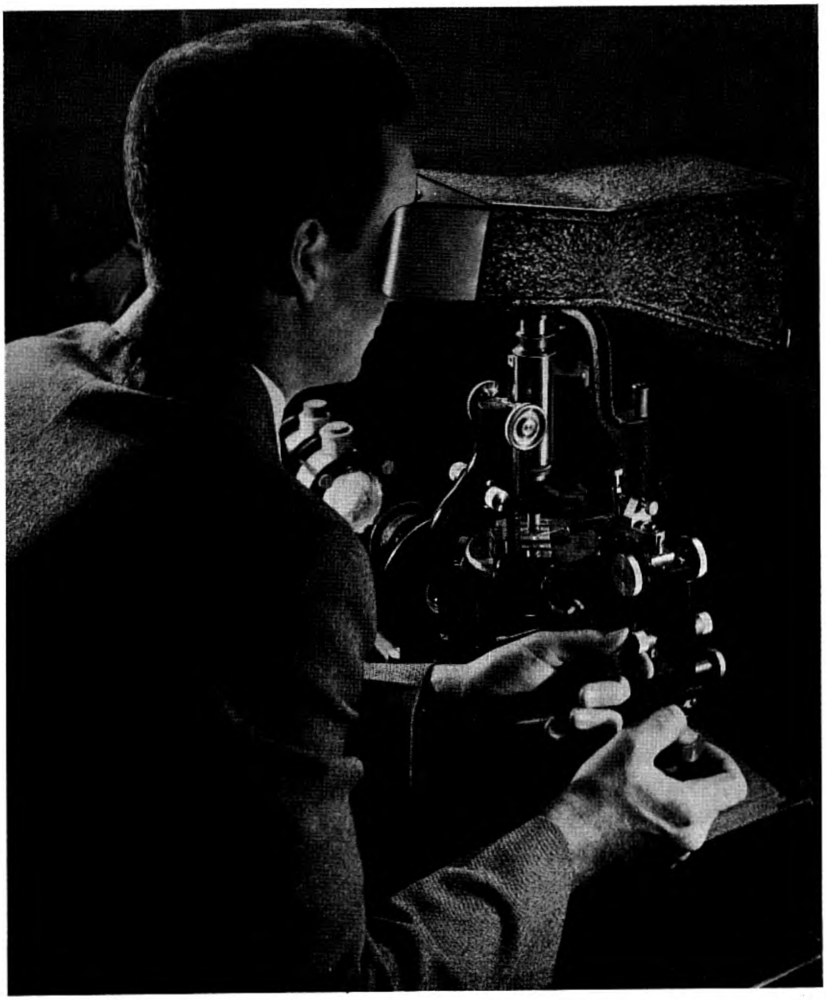

Fig. 5—The micromanipulator finds use when it is necessary to operate on unusually small particles or within areas bounded by the microscopic field.

microtechnique consequently made little progress until a beam balance was produced by W. Kuhlmann of Hamburg, which was capable of weighing to a thousandth of a milligram with no appreciable change in sensitivity with loads up to 20 grams.

With the perfection of this essential instrument quantitative microtechnique developed rapidly, and because of the economy of time and material it is in many cases actually displacing older methods operating on the usual scale. This is particularly true in organic analysis where the methods are ordinarily tedious and expensive. Pregl, who received the Nobel prize in 1923, worked out rapid, precise micromethods for the determination of carbon, hydrogen, nitrogen and various organic radicles, which require only a few milligrams of sample. As an example of the great practical value of such methods may be cited an instance mentioned by Cornwell[1] in which a complex organic compound was synthesized with a yield of about a gram of product. The labor and material involved brought its cost to about $5,000. An analysis was required as a check on the composition, and by the usual methods this would have required 0.2 gram of sample at a cost of $1,000. The analysis was actually made by the micromethod on 2 milligrams of sample, cost $10.

Most of the general equipment originally devised to facilitate micro-operations in qualitative analysis is also applicable to quantitative work. Considerable additional equipment is required, however, for the recovery, conditioning and quantitative measurement of the final transformation products of the analytical process. Precipitates are collected and weighed either by centrifuging in suitably shaped vessels or on suction filters which are essentially miniature reproductions of those used in ordinary work. An innovation in filtration practice consists in the use of an inverted filter which is weighed together with the microbeaker in which the final precipitation takes place. The clear liquid and washings are simply drawn off through the filter. This obviates the necessity of completely transferring the precipitate to the filter, thereby avoiding losses that are otherwise almost certain. Duralumin blocks of various designs have been found excellent for drying and conditioning precipitates. The high heat capacity afforded by the large mass of metal insures a very constant temperature. Various types of micromuffle and combustion furnaces have been devised. Their small size greatly reduces construction costs and permits a more generous use of quartz or platinum linings.

For the measurement of liquids, microburettes are available which can be read to 0.001 cc. When the quantities are too small for

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[1] Cornwell, R. T., *J. Chem. Education*, *5*, 1099–1108 (1928).

measurement by micromodifications of the conventional gravimetric and volumetric methods, the microscope sometimes may be ingeniously applied to quantitative determinations. Colorimetric and turbidimetric measurements may thus be made on a few thousandths of a cubic centimeter of solution contained in a capillary tube. The relative quantities of two or more components of a mixture may frequently be approximated from area determinations made on the individual particles in the microscope field. Instead of weighing the mercury recovered by capillary distillation, the condensed globules may be united by centrifuging and the mass of the resulting single globule estimated from diameter measurements under the microscope. Similarly the analysis of a minute amount of gas may be carried out by measuring the shrinkage in diameter of a single microscopic bubble as the absorption reagents in which it is immersed are changed.

A striking example of a quantitative determination so contrived that the final measurement is performed microscopically is the micromolecular-weight method of Barger. Two solutions, one known and the other containing the unknown, are placed in a capillary with a small air bubble separating them. The ends of the capillary are sealed and the lengths of the two liquid columns measured on a micrometer scale. After several hours the measurement is again made, and repeated at intervals until the column lengths become constant. When this occurs, the vapor pressure of the two solutions will be identical and since vapor pressure is a function of the molar concentration, the latter may also be assumed to be the same in each solution. Knowing the original weight concentrations and the molecular weight of one of the substances, that of the other may be calculated from the change in the volumes of the two solutions necessary to bring about equilibrium.

The application of quantitative microtechnique to engineering and research problems at Bell Telephone Laboratories has required a considerable amount of development work directed toward the improvement of apparatus and the creation of new types of technique. Thus, in order to carry out micrometallurgical analyses, several forms of electrolysis cells were developed which permit the determination of metals such as copper, zinc, nickel, lead, cadmium, tin and others. With these cells, using five milligram samples, the same accuracy is attained as in ordinary analysis on half a gram. One of these cells, designed for the analysis of extremely dilute solutions, permits the qualitative detection of one part of copper, zinc, or lead in 100,000,000 parts of water and is particularly useful in isolating minute quantities of heavy metal impurities in such metals as aluminum or nickel, or in examining waters after use in corrosion experiments.

In order to reduce the errors of weighing in microgravimetric analysis, it is obviously desirable to obtain transformation products having the greatest possible mass. To facilitate manipulation, it is also desirable to deal only with products of a coarse crystalline nature

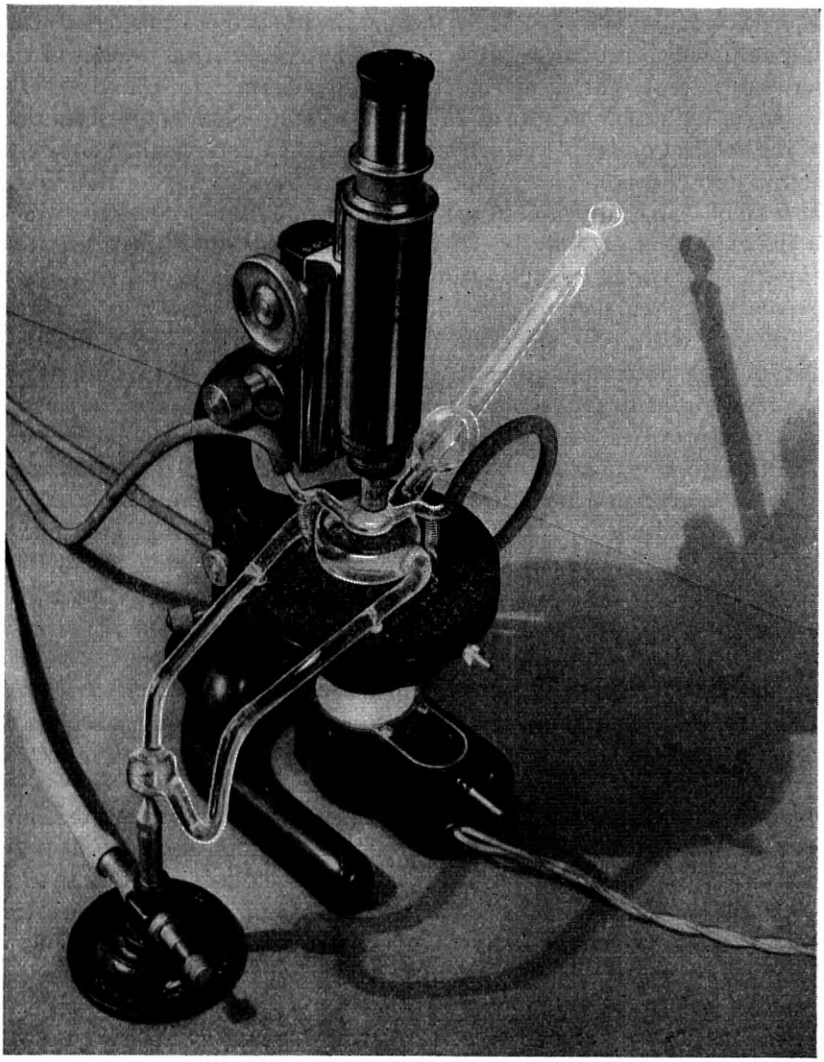

Fig. 6—The glass hot stage assembly shown here provides for the determination of melting points or the sublimation of volatile substances under the microscope.

which may be readily centrifuged, filtered and washed, and which exhibit a minimum tendency to adhere to the wall of the containing vessel. The simple insoluble salts, oxides or hydroxides usually obtained in the older, classical methods, rarely meet these requirements satisfactorily and recently much attention has been given the search for more suitable quantitative precipitants. The result has been an increased use in microwork of organic, complex and double salts of high molecular weight. Thus sodium is no longer weighed as the sulphate, which provides only a threefold increase in the weight of the sodium present, but rather as crystalline sodium zinc uranyl acetate having a molecular weight of 1591 or a weight equal to 69 times that of the sodium present. Silver may be collected and weighed as silver-copper propylenediamine iodide of molecular weight 939. Aluminum, instead of being precipitated as gelatinous aluminum hydroxide, which is difficult to filter, may be separated and weighed as the crystalline oxy-quinolate with an eighteen-fold increase in weight.

Another possibility of chemically amplifying weight consists of employing a train of reactions the final weighable product of which has a high molecular weight. Although it may not contain the element originally sought, this product is still stoichiometrically related to it and provides the basis for quantitative estimation.

Although Pregl, Emich and Chamot are considered the founders of modern microchemistry, there were a number of earlier isolated instances of such methods being used. The earliest attempt to organize qualitative microchemical methods systematically was made by Boricky in 1877 who applied the technique to petrographic studies and wrote a treatise entitled "Elements of a New Microchemical Analysis of Minerals and Stones." In 1885, Haushofer in his book "Mikroskopische Reaktionen" provided a rather complete description of reactions carried out under the microscope, his work covering most of the common elements. It remained for Professor H. Behrens of Delft, Holland, and H. Schoorl to expand the technique to a point where minute quantities of substances could actually be separated and manipulated to permit the application of common analytical operations. In the biological field, H. Molisch developed the technique of applying microreactions directly to plant tissues and in this way was able to identify many intracellular substances. His book "Mikrochemie der Pflanze," and that of Mayerhofer, "Mikrochemie der Arzneimittel und Gifte," are well known.

In Europe, particularly in Germany and Austria, awakening interest in the application of microchemical methods to industrial problems is evidenced by the appearance of a large number of articles on the subject in current journals. Until very recently, however, American chemists did not appear to have fully realized the technical possibilities and advantages of micromethods. The installation of a completely equipped microchemical laboratory at Bell Telephone Laboratories about seven years ago, constituted, the authors believe, a pioneer step in the direct application of microtechnique in its broadest sense to engineering problems. Since that time, a number of industries and industrial institutions have made similar installations with favorable reports as to their usefulness.

In order to convey a more concrete idea of the types of problems in which the microchemical approach has been particularly helpful at Bell Laboratories, this paper will be concluded with a few actual examples.

The equipment used in the telephone plant and associated industries contains numerous small functional parts, concerning which analytical information is frequently needed. Such information may be desired in connection with laboratory studies required in the design of the apparatus or it may be needed because of unsatisfactory performance in service, traceable to some irregularity in the particular part. Obviously such results as might be obtained by compositing the large number of parts necessary for an ordinary analysis would be inadequate. Both the peculiarities of the individual case and the variations in quality and composition will be obscured unless the analytical study be made to include only particular specimens. Thus single relay contact points, weighing between five and ten milligrams, have been quantitatively analyzed to check the composition of the alloy when excessive deterioration was noticed. The gold plating, amounting to a few tenths of a milligram, has been precisely determined on small areas of handset transmitter parts for the purpose of observing the uniformity of the coating.

In studying the various phenomena occurring in vacuum tubes and photocells the Microchemical Laboratory has frequently been requested to identify and occasionally to analyze quantitatively various metallic films and surface deposits in which the total material has ranged from a few thousandths to one or two milligrams. The distribution of caesium on the various surfaces of the photocell was quantitatively studied by microanalysis, the greatest quantity of caesium present in any one determination being about 1.5 mg. Single filament wires weighing from eight to thirty milligrams have been analyzed, the thoria determined in the case of tungsten filaments, while nickel wires were examined for copper, iron, silicon and manganese.

Micromethods have been utilized in studying variations in composition between very thin layers of a material. In a typical case, sheets of an iron-cobalt magnetic alloy were observed to undergo a change in properties after rolling to diaphragm thickness. It was suspected that the surface had lost iron through oxidation and subsequent mechanical removal. By using pure silica abrasive, a layer of metal was removed from the surface corresponding to a thickness of about 0.005 millimeter. The metal was then extracted from the abrasive by acid treatment and the iron-cobalt ratio determined microchemically. A similar technique has been applied to tinned copper wire, to determine the quantity of copper dissolved by tin during the tinning process and the extent of its migration to the surface of the coating. It has also been used to study the alloy layer formed between the zinc coating and the iron base in sherardizing and galvanizing processes. Micromethods applied to thin films have been used in the study of the copper-oxygen ratio variation in copper oxide rectifier discs.

The inclusion of foreign particles in the surfaces of metals and other materials occasionally occurs as a result of faulty conditions of manufacture. Determination of their nature and source is naturally necessary before remedial measures can be taken. Since the particles are small, frequently even of microscopic dimensions, microchemical methods in such cases are the only ones practicable. Thus small hard particles were observed in an experimental lead cable alloy which were at first thought to consist of segregated impurities. Microanalysis showed these particles to be composed of iron and nickel, indicating that they had probably been accidentally introduced into the surface during the extrusion process. Paper removed from a condenser that had failed on test was found to contain microscopic particles of iron, iron rust, brass and carbonaceous aggregates which had also been accidentally incorporated during manufacture.

The isolation, detection and determination of traces of impurities or substances otherwise associated with large quantities of a given material have benefited through the application of microtechnique. Methods have been worked out for determining sulphur and phosphorus in steel and for silver in lead in which these impurities are all present in quantities less than 0.001 per cent. Acetic acid has been isolated from the corrosion products occurring when lead cable is exposed in creosoted wood ducts. The quantity actually present is usually very small, amounting to between 0.01 per cent and 0.001 per cent of the weight of the corrosion product.

Electrolytic corrosion in the windings of relays and other similar types of apparatus may occur as the result of minute quantities of salts present in the insulating materials or acquired from the manufacturing environment. These salts furnish electrolytes when the humidity is relatively high, dissolving the copper at certain poorly insulated points in the winding until the wire is eventually severed. In tracing the sources of this type of corrosion, microtechnique has afforded the only satisfactory method of attack.

Recently studies have been made to learn the effects of the dusts found in the telephone central office on the functioning of machine switching equipment. In these studies, microchemical methods have figured largely in the identification of the individual dust particles as well as in the quantitative determination of the major type of components.

Switchboards and Signaling Facilities of the Teletypewriter Exchange System *

By A. D. KNOWLTON, G. A. LOCKE and F. J. SINGER

The development of a nationwide teletypewriter exchange system in the United States required the design of switchboards and signaling facilities adapted to this special service. The two types of switchboard now in use are described in this paper, and the operation of the circuits by means of which connections between the various subscribers are established and supervised by the operators is explained.

A NATIONWIDE teletypewriter service giving direct connection between subscribers for the exchange of written messages by means of the teletypewriter in a manner similar to the service offered by the telephone system for the exchange of spoken messages was offered to the public as a new aid to business by the Bell System on November 21, 1931. This service, known as the teletypewriter exchange (*TWX*) service, introduced a switching technique which, although familiar in the telephone art, involved many new technical problems when applied to the telegraph art.

Records show that during the nineteenth century some telegraph exchanges were established at which connections could be made on a message basis for to and fro telegraph communications between subscribers. These earlier exchanges had a commercial appeal although the various forms of subscriber instruments then used were slow and required considerable skill for operation. Later, when the telephone was introduced, these exchanges gradually disappeared because the public naturally preferred the more convenient instrument. With the introduction of the modern teletypewriter the telegraph exchange idea was again revived because the teletypewriter, being very similar to an ordinary typewriter and permitting an accurate written record of a to and fro communication, has, from a subscriber standpoint, overcome the objectional features of the early telegraph instruments.

The private line telegraph and teletypewriter service furnished by the Bell System has formed a very important background for the new teletypewriter exchange service. The older service, which provides relatively permanent networks interconnecting various stations in a predetermined manner for a predetermined time, has been available to the public since about 1890. During the earlier period it was used

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chiefly by the press and brokers and was operated on a Morse telegraph basis, generally using composite or simplex line facilities. Later, with the introduction of the modern teletypewriter, the carrier telegraph, and other improvements, together with the growth of American business and the demand for rapid and accurate written communications, this private line business expanded rapidly and service was furnished not only to the press and brokers but also to other financial institutions, manufacturers, government bureaus, police departments, and a wide variety of retailers and distributors of goods. This business has become nationwide. Many of these private line systems are provided with switching facilities for use by the customer in each system, although the supervisory arrangements are rather elementary.

In addition to the private line telegraph service and the arrangements which had been developed and applied to that service, the many developments in the telephone field formed an important contribution to the teletypewriter exchange service. It is obvious that in providing *TWX* service, which is a point-to-point service with connections set up and taken down on the subscriber's order, use can be made of many traffic and service practices used in the telephone service. Furthermore, certain telephone apparatus such as switching relays, cords, plugs, etc., can be employed to advantage.

With this background, when it was decided to furnish a nationwide teletypewriter exchange service to the public, Bell System engineers had the problem of determining what general plan of design to adopt. There were two alternatives: (1) to provide a service using the telephone plant and existing telephone switchboards, or (2) to provide separate switchboards for use with the telegraph plant. The important advantages of the first plan are:

(*a*) The switchboards and signaling arrangements designed for and in use in the telephone plant could be employed.

(*b*) The same operating groups handling the telephone service would handle this service. Inasmuch as telephone service is on a 24-hour basis throughout the country, the *TWX* service could be furnished on the same basis with a relatively low operating cost.

The disadvantages of the first plan are:

(*a*) Because the teletypewriter operates on a d-c. basis it would be necessary to provide an oscillator and associated apparatus at the station to generate an audio-frequency alternating current for modulation by the signals sent by the teletypewriter, and a rectifier to convert the a-c. pulses received from the distant station to d-c. pulses for operation of the receiving mechanism of the station teletypewriter. Furthermore, it would be necessary to furnish a telephone instrument at the station to permit the subscriber to communicate with the operator unless a teletypewriter or other type of recording instrument were provided at each operating position.

(*b*) Relatively expensive telephone lines known as inter-toll trunks would be required between central offices. If the cheaper telegraph channels were used as inter-toll trunks it would be necessary to provide frequency converters at each terminal to translate the frequency band required on the subscriber loop to a band suitable for application to the telegraph inter-toll trunks. If the telegraph channels were used between switchboards it would also be necessary to provide the operators with teletypewriters or other means of communication because the telegraph channels do not permit oral communication.

(*c*) A number of miscellaneous engineering and plant problems other than those listed in (*a*) and (*b*) would be introduced if standard telephone facilities were used to interconnect the stations in the teletypewriter exchange network.

After due consideration of all these factors it was decided to utilize the telegraph plant and to design and provide the necessary teletypewriter switchboards and inter-office signaling arrangements. By following this plan it has been possible to establish service on a nationwide basis using switchboards at the larger switching centers and employing modified telegraph private wire testboards at the smaller centers.

This paper describes the signaling and switching arrangements used in the present system, and particularly the two principal types of switchboards that are in use. The discussion is limited to the most important signaling and switching arrangements, as the transmission features are described in another paper.[1] A description is included of the principal factors entering into the design of the more important circuits used in these switchboards: the subscriber lines, inter-toll trunks, and cords. The subscriber line treatment is divided into three broad classes: local subscribers having either attended-only or unattended service; distant subscribers served over telegraph toll line facilities; and distant subscribers served over telephone facilities. Particular attention is given to the fundamental problem of providing supervisory signals over the telegraph lines used as inter-toll trunks in the inter-office connections.

TELETYPEWRITER SWITCHBOARDS

To reach subscribers in all parts of the country there has been established a network of teletypewriter switching points interconnected by telegraph lines. At each of the larger switching points a teletypewriter switchboard is provided, the principal switchboards being the No. 1 Teletypewriter Switchboard having a capacity of 3,600 subscriber lines, and the No. 3*A* Teletypewriter Switchboard having a capacity of 1,200 subscriber lines. The former, a general view of which is shown in Fig. 1, is used in large cities such as New York and Chicago, while the latter, a general view of which is shown in Fig. 6, is used in smaller cities such as Pittsburgh and Kansas City.

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[1] "A Transmission System for Teletypewriter Exchange Service," R. E. Pierce and E. W. Bemis, this issue of the *Bell System Technical Journal*, and *Electrical Engineering*, v. 55, September 1936, pp. 961–70.

Fundamentally, a manual switchboard consists of two parts: the terminations for subscribers lines and inter-toll trunks, and the switching facilities used by the operators in interconnecting the lines and trunks. The line and trunk terminations are in the form of multiple jacks and lamps located in the jack field and are accessible to all operators. The switching facilities, or cords, together with the means for communication to subscribers or other operators, are individual to each operator and are, in general, located at the keyshelf. Although the design of the switching equipment and the multiple are to some extent dependent upon each other, the principal factors influencing the design are, for the purpose of discussion, considered independently.

Fig. 1—No. 1 Teletypewriter Switchboard at New York, N. Y.

No. 1 Teletypewriter Switchboard Position Equipment

The No. 1 Teletypewriter Switchboard position consists essentially of a teletypewriter for the operator's use in sending and receiving the instructions for establishing the connections, together with a number of cords for making the various interconnections between the line terminations. The number of these cords necessary for the efficient functioning of an operator is the most important factor governing the width of the position, a primary consideration in the design of a switchboard.

The number of cords per operator is dependent on the average time required to set up and disconnect each call (known as the average work time per call) and the average communication time per call. Whereas the former can be forecast quite accurately by the operating characteristics of the circuits, the latter is dependent on the commercial application of the service. To insure the provision of an adequate number of cords it was necessary to allow for the longest average communication time which could be reasonably anticipated. The analysis of the average work time per call together with the forecast communication time resulted in the requirement being set up for a maximum of 18 cords per operator.

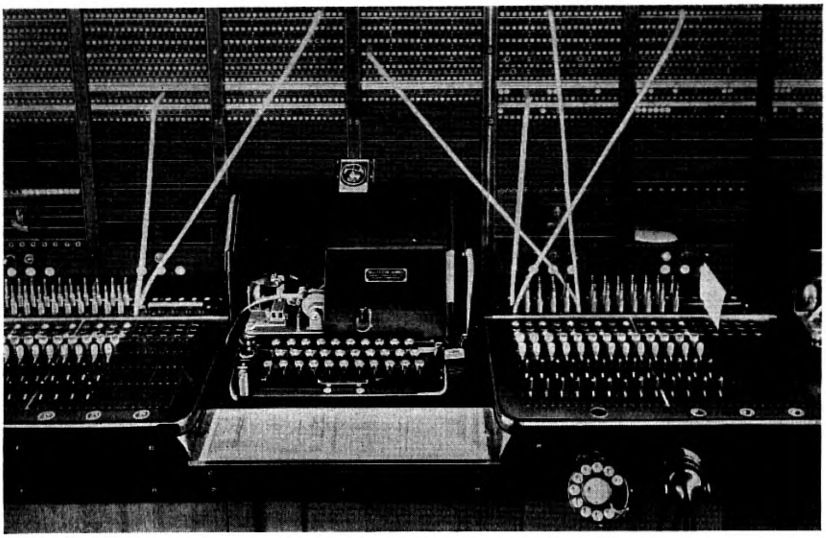

Fig. 2—Keyshelf arrangement of No. 1 Teletypewriter Switchboard.

With the requirement for the position equipment established at 18 cords (and one teletypewriter for communication purposes), the width of the position was determined to be approximately 34 inches, or the width of four panels of the jack field, each panel being 8½ inches in width. The division into an even multiple of panels is for constructional purposes, to separate the switchboard into sections for manufacturing. It was, however, necessary to adopt a new type of keyshelf construction, shown in Fig. 2, to provide for the operator's teletypewriter.

Because of its large size, the teletypewriter was located as low as possible to minimize blocking the jack field. This required the provision of a teletypewriter shelf the lower edge of which was at the same height as the lower edge of the adjacent keyshelves. The depth of the teletypewriter made it necessary to recess it in the jack field. This recess was obtained by cutting off one stile strip and adding a longitudinal detail the entire width of the section to support the lower end of the cut stile strip. The teletypewriter shelf was placed on rollers to permit its sliding out easily for maintenance accessibility.

The teletypewriter, being the operating center of the position, has nine cords on each side to locate all 18 cords within easy reach of the operator. Because of this arrangement it was not possible to make the position boundaries coincide with the section boundaries as this would require two keyshelves of nine cords each per section with the consequent waste of equipment space for the supports between adjacent keyshelves. This loss of space was reduced by providing one 18-cord keyshelf per 2-position section and associating one half of the cords with the teletypewriter to the left and the other half with the teletypewriter to the right. This caused an overlap of the position and section boundaries so that the nine cords on the left end of each section form a part of the right position of the adjacent section to the left.

No. 1 Switchboard Multiple Equipment

The primary objective in the design of multiple equipment is the provision of line terminations in a form that will make each line readily accessible to every operator, taking into consideration the physical limitations imposed by the operator's reach. Previous experience in the design of telephone switchboards has determined that, for a subscriber switchboard, satisfactory operating conditions may be obtained in respect to the horizontal reach of the operator by the multipling of the line terminations on an 8-panel basis (using the standard 8½ inch panel) giving a distance of 68 inches from one appearance of a line to the next. The maximum reach in each horizontal direction will then be half of this distance, or 34 inches. This was, however, reduced to a 6-panel multiple giving a maximum reach of 25½ inches to insure operating efficiency.

In determining the maximum vertical reach for the operator, the standard practice was followed of limiting this reach to 30 inches for line terminations which are to be answered, and to 34 inches for lines to which calls are to be completed. The line terminations to be answered by the operator are kept lower than the lines for completing purposes because the operator's attention must be attracted to the line by the illumination of the line lamp. The line capacity of the switchboard is limited by the number of line terminations that can be provided within the above dimensions.

The lower line of Fig. 3 shows the inter-toll trunk and subscriber line capacities obtainable within the permissible reach limits on a 6-panel multiple basis where the complete subscriber multiple is equipped with answering lamps. The capacity shown is based on various ratios of subscriber lines to inter-toll trunks. Because of the essentially toll character of the teletypewriter exchange service, it was anticipated that there would be a high ratio of inter-toll trunks to subscriber lines and comparatively little local traffic. The traffic studies indicated that the average ratio would be in the order of seven or eight subscriber lines to one trunk. It may be seen from Fig. 3 that, with this ratio, a capacity of only 2,200 subscriber lines is obtainable with the entire multiple equipped with answering lamps.

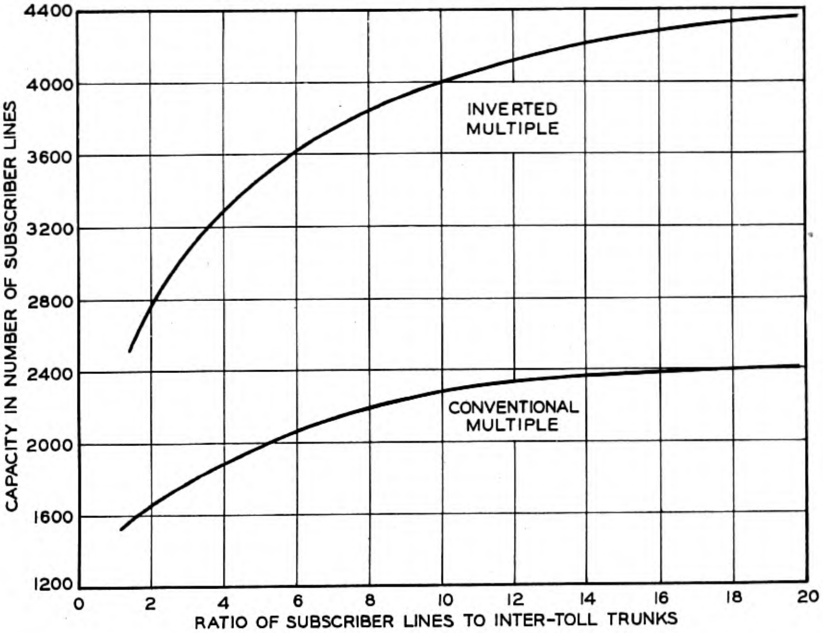

Fig. 3—Curves showing variation of subscriber line capacity for No. 1 Teletypewriter Switchboard. *A*—Inverted multiple. *B*—Conventional multiple.

By providing answering lamps for only the first half of the subscriber lines and installing the second half without answering lamps in the upper portion, the total space for a given number of lines can be reduced and advantage taken of the additional space afforded by the 34-inch vertical reach permissible for calling multiple. This arrangement, known as the inverted multiple, provides answering facilities for the second half of the subscriber lines in a second line-up of switchboard in which they are equipped with answering lamps. The first half of the lines also are multipled in this line-up but on a calling-only basis; that is, without lamps. With this arrangement, calls originated by the first half of the subscribers are answered in the first line of switchboard, and those originated by the second half are answered in the second line. Any operator may complete a connection to any line as there is a full multiple of jacks in both boards. In the second line-up the two halves of the multiple are inverted as to location in order to place the lines with answering lamps within easy reach. The upper line of Fig. 3 shows the capacities obtainable with this arrangement. It may be seen that, with a ratio of 7.5 subscriber lines to one inter-toll trunk, a subscriber line capacity of approximately 3,800 is possible. It was necessary, however, to reduce this to 3,600 lines in order to obtain a division in a multiple of 600 lines to simplify the numbering of the jacks. With this arrangement 300 lines are provided in each panel without answering lamps and 300 lines with answering lamps.

This multiple arrangement is illustrated in Fig. 4, which shows schematically the cabling for the first half of the subscriber multiple (lines 0 to 1,799). It may be noted that a third line of switchboard, the inward and through board, is provided. Experience has shown that the most efficient operation is obtained if the inward and through traffic is segregated when the switchboard grows to 30 or more positions. As the subscriber multiple is used here for calling purposes only, the answering lamps may be omitted from the entire subscriber multiple, thus making additional space available for increased inter-toll trunk capacity as discussed in the following. The subscriber lines are cabled from the main distributing frame (*MDF*) to the relay equipment and from there to the *TWX* intermediate distributing frame. Here cross connections are provided to permit the assignment of any subscriber line relay equipment to any multiple jack for flexibility in assigning numbers. The distributing frame terminal strip also serves as a doubling-up point for the cable to the switchboards.

A somewhat similar arrangement used for the inter-toll trunk multiple is shown schematically in Fig. 5. The standard telegraph line facilities and terminating repeaters designed for private line service are used for the *TWX* trunks. Connections to these trunks are made at the test board distributing frame and the trunks are cabled to the *TWX* distributing frame. Here arrangements are provided for inserting a single-line repeater, which is necessary for converting the positive and negative 130-volt signals to positive and negative 48-volt signals for transmission through the switchboard. The trunk is then carried to the teletypewriter test board where a termination is provided for the purpose of testing the equipment. From the test board the trunk is cabled through the relay equipment to the distributing frame, where it is cross-connected to the switchboard multiple, the multiple for all three lines of switchboard being doubled up at the distributing frame terminal strips. Ordinarily, with the inverted subscriber multiple arrangement, there will be a capacity for 480 inter-toll trunks equipped with answering lamps in the first two lines of switchboard. However, opportunity is provided for increasing this capacity by the provision of the separate inward and through switchboard. As described above, the lamps in this inward board may be omitted from

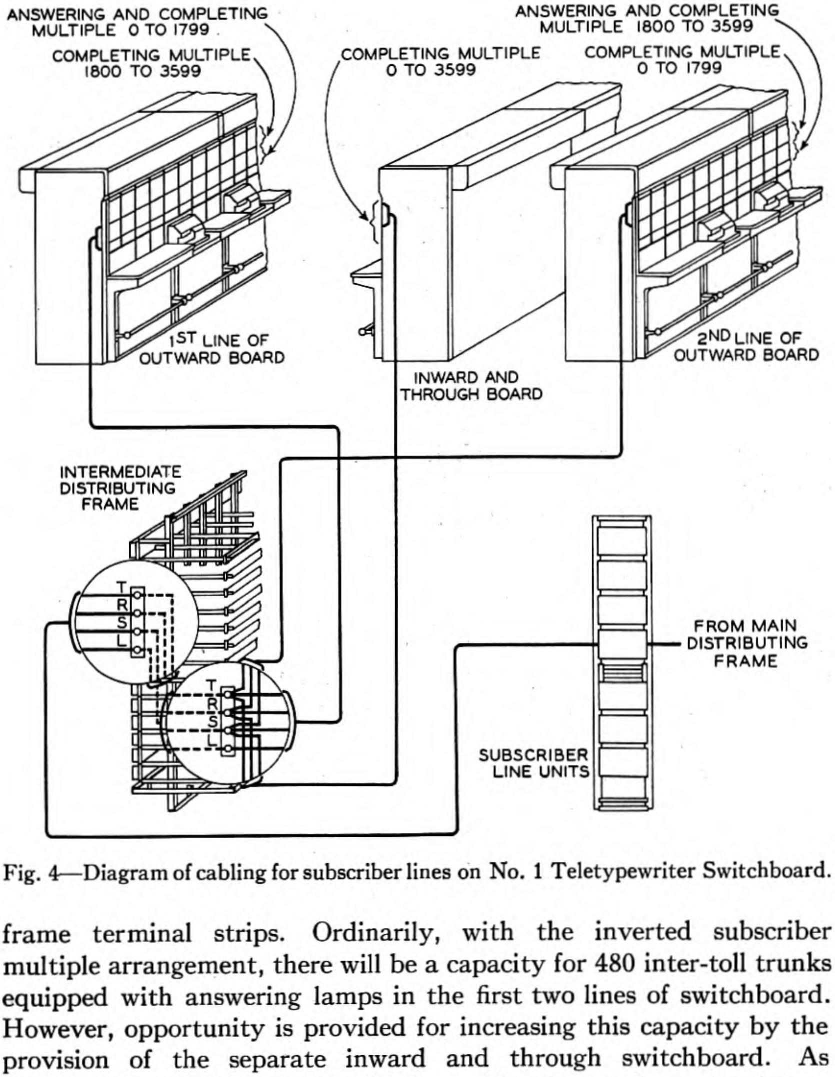

Fig. 4—Diagram of cabling for subscriber lines on No. 1 Teletypewriter Switchboard.

the subscribers' multiple. This arrangement provides sufficient space for the installation of 840 trunks equipped with answering lamps. As all trunks are answered at the separate inward switchboard, the answering lamps may be removed from the trunk multiple in the two outward switchboards, thereby releasing sufficient space for the full 840 trunks without the answering lamps.

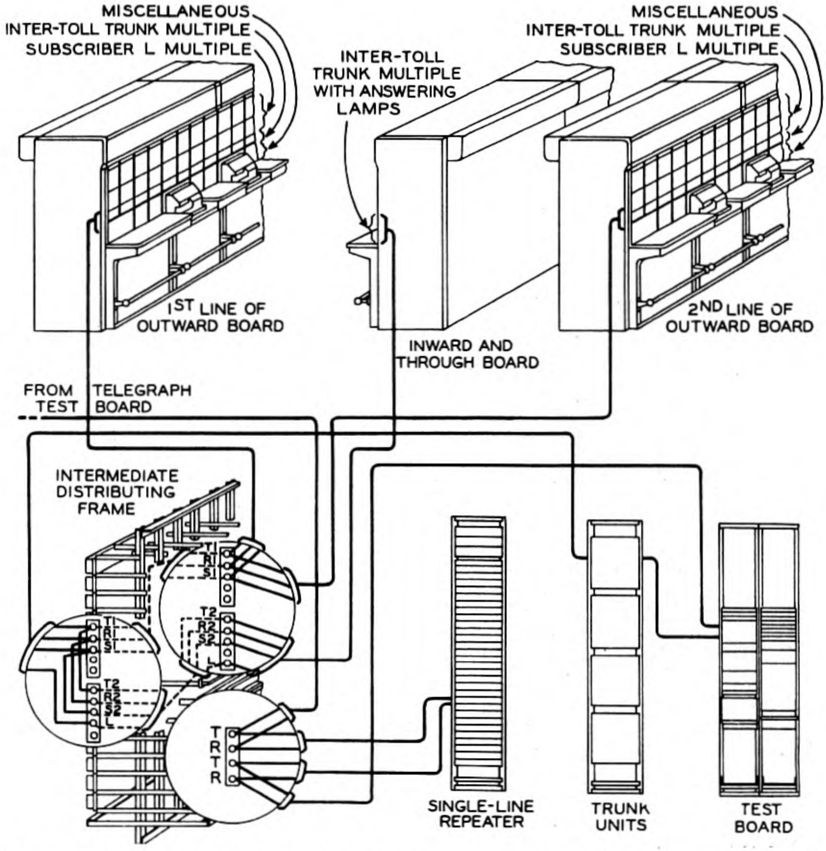

Fig. 5—Diagram of cabling for inter-toll trunks on No. 1 Teletypewriter Switchboard.

No. 3A Teletypewriter Switchboard

The design of a switchboard for the medium sized *TWX* switching points was not undertaken until the system had been in operation for about two years, temporary switching facilities having been used at these points in the meantime. Actual operating experience and traffic data were then available upon which to base the design of the switchboard, a general view of which is shown in Fig. 6.

Efficient design requires that the width of a position be kept as small as possible to avoid the excessive cost of a long switchboard multiple. Because the smaller capacity required for this switchboard did not make the vertical reach an important factor, a key-shelf arrangement different from that used for the No. 1 switchboard was adopted.

Instead of placing the teletypewriter and cords on the same level as in the No. 1 switchboard, the cords are placed above the teletypewriter. This was accomplished by the use of a sloping key-shelf permitting the cords to pass by the teletypewriter in the manner shown by the cross-sectional view in Fig. 7. With the object of keeping the vertical height of the keyshelf as small as possible, the cords are located in a single horizontal row instead of in the conventional double row. With this arrangement, the answering cord is the left cord of a pair and the calling cord is the right cord. Differentiation is obtained by using colored plug shells, black for the answering cord and red for the calling cord.

Fig. 6—No. 3A Teletypewriter Switchboard at Pittsburgh, Pa.

An additional feature resulting from this relation of the keyshelf to the teletypewriter is an arrangement whereby the position may be adjusted to include various numbers of cords. This flexibility is obtained by the location of the teletypewriter on a table separate from the switchboard, connections being made by a flexible plug-ended cord. This permits the location of the teletypewriter in front of any group of cords. A position jack is provided in each section which affords facilities for operators spaced on minimum centers of 20½ inches, each operator having access to a maximum of 10 cords. This represents the closest centers which can be obtained with sufficient physical room for operating. Although the switchboards are usually engineered on the more ample operating centers of about 25⅝ inches, the design permits the reduction of these centers to the 20½ inch dimension in the event that more operators are required for unexpected increases in traffic. If traffic conditions change or the inward and through traffic is segregated, thus necessitating positions equipped with more

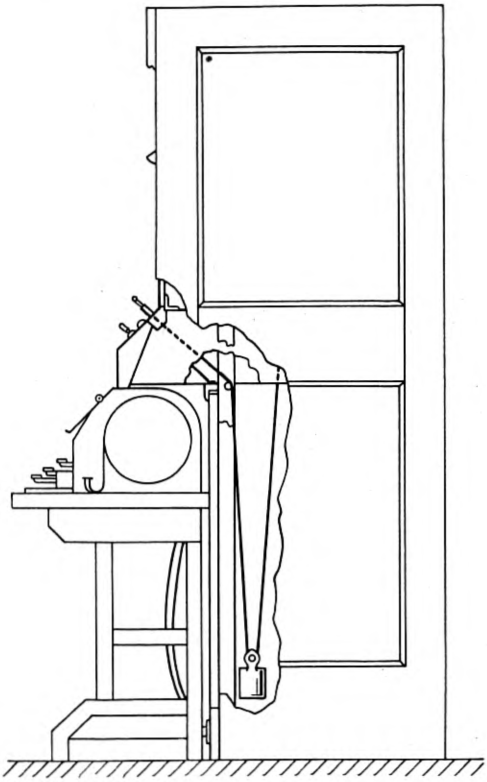

Fig. 7—Sectional view of No. 3A Teletypewriter Switchboard.

cords, the width of the position can be increased to include the number of cords required.

The switchboard is divided into sections, each having two panels and each arranged for a position circuit. The section is an arbitrary division of the switchboard for constructional purposes and has no bearing on the position boundaries. All keys and cords in a section are terminated on terminal strips in the rear. The cord relay equipment is furnished in units of 10 circuits, each unit being equipped with terminal strips so located that, when a unit is placed in the rear of a section, the terminal strips come directly under the section terminal strips. Distributing rings above the two rows of terminal strips provide facilities which permit any relay equipment to be cross-connected to any keyshelf cord equipment.

The engineering of this switchboard is thus reduced to a very simple process. The number of cords required per operator is determined by the anticipated traffic data. From this information the width of each position is determined. The sum of the positions required to handle the peak load represents the total length of the switchboard and determines the total number of sections required. Cord units are then provided in the rear of the switchboard. The cords required for each position are then cross-connected to relay circuits on the cord units which are in turn cross-connected to the nearest position circuit. Teletypewriters are moved in front of the various groups of cords and plugged into the jacks for their position circuits. Should conditions require a different assignment of cords, they may be recross-connected to meet the new requirements and the teletypewriters moved to new positions.

No. 3A Teletypewriter Multiple Equipment

For convenience, the operator's vertical reach for lines with answering lamps has been defined as 30 inches above the standard type of keyshelf. From the lower edge of the keyself, which prevents the operator from rising to reach farther, the permissible reach is 35 inches. Deducting the space required for the teletypewriter and keyshelf equipment, there remains $14\frac{1}{2}$ inches available for multiple below the 35 inch reach limit. About $2\frac{5}{8}$ inches of this space is required for unattended line terminations and miscellaneous multiple, leaving a space of $11\frac{7}{8}$ inches for the subscriber line multiple.

This space provides for the capacities shown in Fig. 8, which are in terms of ratios of subscribers lines to inter-toll trunks. This curve is based on the use of a 6-panel multiple which, with the $10\frac{1}{4}$ inch panel required for the type 49 jack used, results in a horizontal reach of

30¾ inches. It may be seen that, with a ratio of 7.5 subscriber lines to one trunk, a capacity of about 1,300 lines is obtainable. Because the ratio of trunks to subscriber lines is somewhat greater on small switchboards than on the larger boards, due to the relative inefficiency of smaller trunk groups, the multiple is designed on the basis of 1,200 subscriber lines and 240 inter-toll trunks which gives a ratio of five subscriber lines to one trunk.

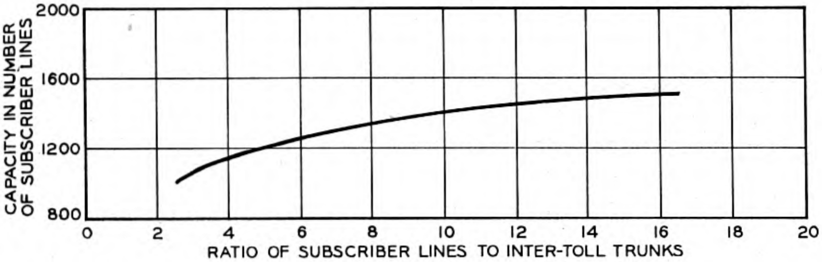

Fig. 8—Curve showing variation of subscriber line capacity for No. 3A Teletypewriter Switchboard.

Circuit Functions

The foregoing paragraphs have given a picture of the physical arrangement of the more important switchboards, and an idea of the number of subscriber lines and inter-toll trunks that can be accommodated by each. Some idea must also be given of the circuit methods by means of which connections are established between the various subscribers and supervised by the operators.

Subscriber Station and Station Circuit

The basic instrument by means of which the subscriber sends and receives his message is the teletypewriter. It is not proposed to give here a description of the teletypewriter as this is discussed in other papers. Other equipment, however, is required in addition to the teletypewriter to provide for the necessary signaling facilities for the exchange service.

A typical installation in a subscriber's office is shown in Fig. 9. The arrangement shown provides for the No. 15 (page) teletypewriter, used predominantly in the *TWX* service, mounted on a table which has been designed to provide adequate mounting facilities for the signaling equipment. This table is arranged with a removable panel known as a control panel, which is mounted in an opening in the top of the table to the right of the teletypewriter to make the key levers readily accessible to the attendant. The control panel equipment may be varied to meet the different service requirements. Space is available on a shelf on the inside for a rectifier or an apparatus box where this additional equipment is necessary.

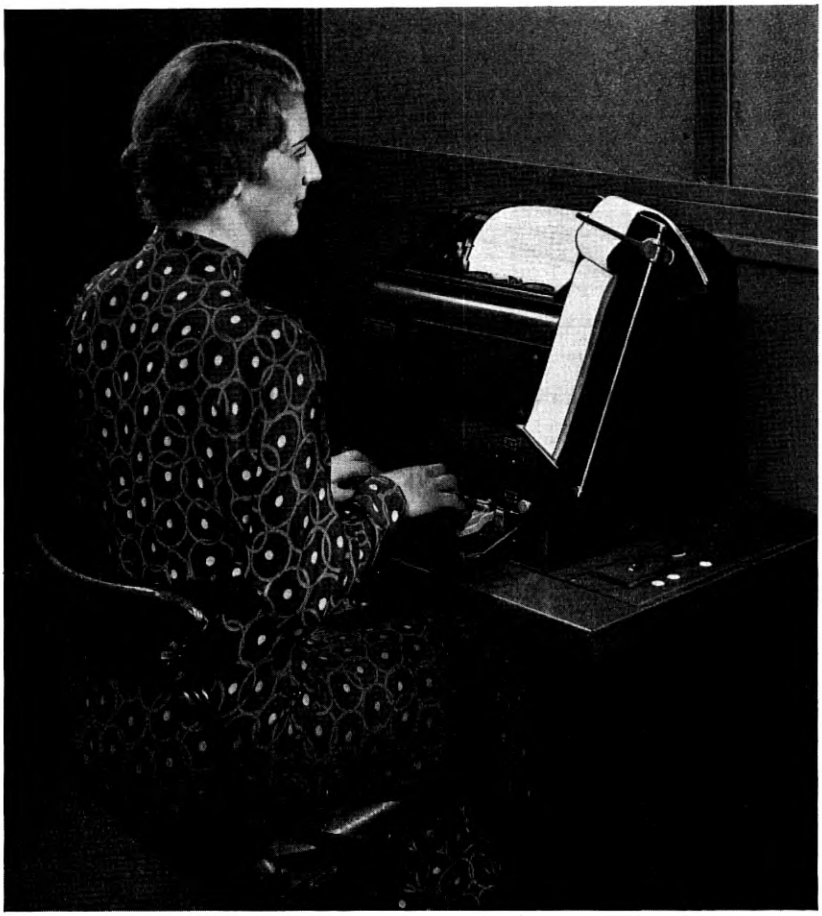

Fig. 9—Typical teletypewriter subscriber equipment for attended service.

A typical circuit arrangement for a station connected to a *TWX* switchboard is shown in Fig. 10. The station is equipped with a switch which, when operated, applies power to the motor of the teletypewriter, and also closes the loop so that a relay in the central office is energized. This relay lights the answering lamps associated with the subscriber's multiple in the face of the switchboard. An operator answers by plugging the answering plug of a cord circuit into the jack. This action by the operator connects the station line to the cord circuit, and in addition energizes another winding of the relay previously energized when the subscriber called. This relay, being differentially wound, is then released and the answering lamps are extinguished.

In addition to calling the central office the subscriber must be able to recall the operator in case new services are required during the progress of the communication. This is accomplished by the subscriber simply turning the power switch off and then on again, which causes certain relays in the cord circuit to operate and the cord lamp to flash intermittently, indicating to the operator that her services are required. The subscriber must also be able to indicate to the operator when a disconnection has been made. This is accomplished by the subscriber turning off the power switch, causing the motor of the teletypewriter to stop and a lamp in the cord circuit to light.

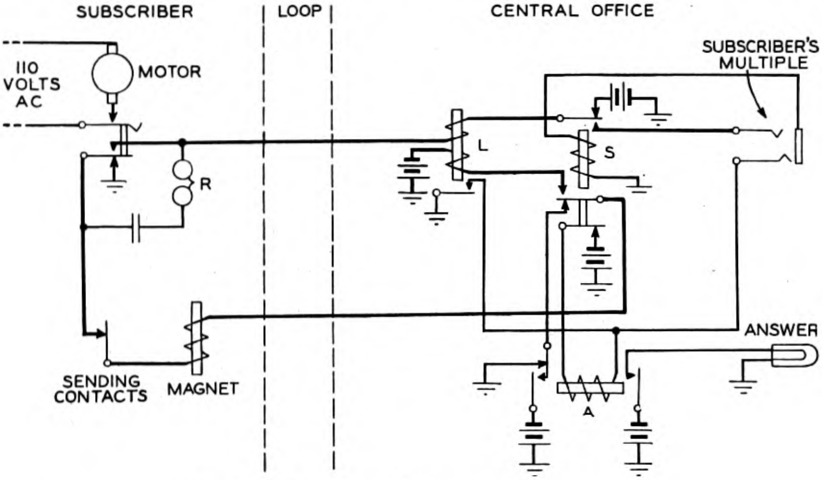

Fig. 10—Fundamental teletypewriter circuit.

The operator must also be able to signal the subscriber that a call is being completed to him. To provide this signal the station is equipped with a standard telephone type ringer which is energized, when the station is in the idle condition, by 20-cycle alternating current which flows over one side of the loop when the operator depresses a ringing key in the cord.

The teletypewriter lends itself admirably to the function of leaving messages on the subscriber's machine when no one is in attendance. When such service, known as unattended service, is desired, the station is similar to that already described, but additional equipment is provided for starting the motor from the switchboard. An attempt is made to complete the call on an attended basis as outlined above and, if the called subscriber does not answer, the operator asks the calling subscriber if he wishes to leave his message. If he does, she presses a key in the cord circuit, which starts the motor at the absent subscriber's teletypewriter. The operator then instructs the calling subscriber to proceed with the communication.

Long Subscriber Lines

The subscriber stations just discussed are connected to the central office by two wires, known as a loop, the maximum distance between station and switchboard for loop connections being approximately 38 miles. A network is placed in the loops where the mileage makes its use necessary to improve the transmission efficiency.

It is necessary in some instances to connect subscribers situated at greater distances from the switchboard, perhaps as much as 200 or 250 miles. Two methods are available for accomplishing this: the d-c. method using telegraph facilities, and the carrier method using telephone facilities.

With the d-c. method a standard telegraph repeater is used at the central office, and a simplified repeater is placed on the subscriber's premises. These repeaters, with suitable signaling apparatus, provide a high grade of transmission and also the same type of supervisory signals as would obtain on the shorter loop connection.

The carrier method is used to a limited extent in the few instances where telegraph facilities are not available. In this method both the central office and the station are equipped with carrier apparatus and the regular telephone facilities are used. When the subscriber operates the power switch of the station, an answering lamp is lighted before the operator of the local telephone switchboard. The local operator, knowing by the multiple marking that this is a teletypewriter station, immediately connects through to the *TWX* switchboard over the regular toll telephone facilities. When the *TWX* switchboard is reached the call is handled in the same manner as a regular d-c. telegraph connection. All the signaling facilities available for the other subscriber stations are also available here. Completion to the subscriber is also made by the *TWX* operator over the regular toll telephone facilities, and the local telephone operator at the switchboard to which the subscriber is connected rings the subscriber.

Inter-toll Trunk Supervision

To provide inter-toll trunk supervision in the *TWX* network, it was necessary to select different types of signals than those occurring during the normal transmission period of the teletypewriter; that is, the code and "break" signals.

Three types of supervisory signals are required to be sent over the inter-toll trunk. These are (1) the call signal, (2) the recall signal, and (3) the disconnect signal. There is a fundamental difference, however, between the call signal and the others in that it is applied to the trunk only when the stations are not connected. When the stations are connected the apparatus for receiving the call is removed from the trunk. The calling signal can therefore be any type of signal with the limitation that it must be such that it will not be produced by ordinary interruptions of the line, or line "hits."

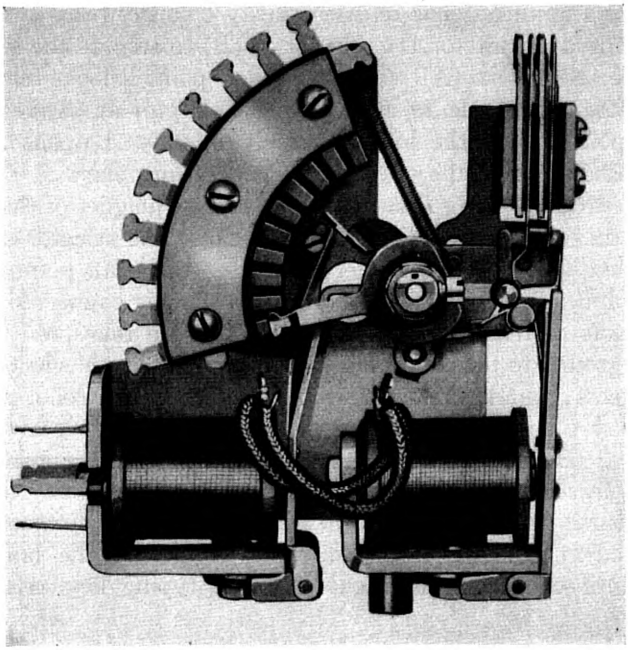

Fig. 11—Selector used for timing supervisory signals.

The three types of supervisory signals chosen are therefore:

1. The call signal, produced by sending a spacing signal of 2 seconds.
2. The recall signal, produced by sending a spacing signal of 7 seconds.
3. The disconnect signal, produced by sending a spacing signal of 10 seconds.

To permit sending these signals, use is made of a mechanism that will measure the length of the signal. The basic apparatus used to measure this time is the selector shown in Fig. 11. By the use of this selector in conjunction with a ground interrupted 60 times per minute, it is possible to obtain a means of measuring a line "open" within a sufficient degree of accuracy.

A typical method of sending and receiving the timed spacing signals or "opens" is shown in Fig. 12. The method of sending is shown at (A), and the method of receiving at (B). To send a recall signal, the operator at (A) presses the toll signal key momentarily leaving the cord up, the sleeve relay therefore remaining operated. The closure of the toll signal key operates relay *A*. Relay *A* operated opens the loop circuit at both ends of the trunk, releasing relays *B* and *C*. Relay *B* released closes a circuit which causes the selector to step at the rate of 60 steps a minute. The release of relay *C* causes relay *D* to release and provide a circuit for the selector at (B) to step at the same rate. When the selector at (A) reaches the first point it locks relay *A* and both selectors continue to step until the selector at (A) reaches the seventh point, when the locking circuit of relay *A* opens and that relay releases, closing the circuit and reoperating relays *B*, *C*, and *D*. The reoperation of relay *B* energizes the release magnet of the selector through the off normal contacts which cause the selector at (A) to release. At (B), when the selector reaches the sixth point, relay *K* operates and, when relay *C* reoperates, ground is connected through the contacts of relays *K*, *L*, and *M* to operate relay *N*. Relay *N* connects ground to the cord lamp, lighting it. Relay *N* when operated also connects ground to relay *M* which locks under control of contact *P*. When relay *C* reoperates ground is also connected to relay *D* which reoperates. Battery is then connected to the release magnet and the selector releases. After a time relay *K*, which is slow to release, also releases causing relay *N* to release. The release of *N* connects ground interrupted at the rate of 60 times per minute to the lamp which flashes until contact *P* is opened by the typing key, releasing relay *M*.

To send a disconnect signal, the same operations take place at (A) except that, immediately after the cord key is operated, the cord is pulled down, releasing the sleeve relay, and causing the selector at both ends to continue to the tenth point. At (B) when the selector reaches the tenth point relay *L* operates and, when relay *C* reoperates, ground is applied to operate relays *M* and *N* which hold a steady ground on the cord lamp until the cord is pulled down.

These signals appear at all offices in a built-up connection. The frequency of the machines supplying the 60 interruptions per minute is accurate to within plus or minus five per cent, and the multiple connections on the receiving selector bank take up any inequalities that may exist in the speed of the machines in two different offices.

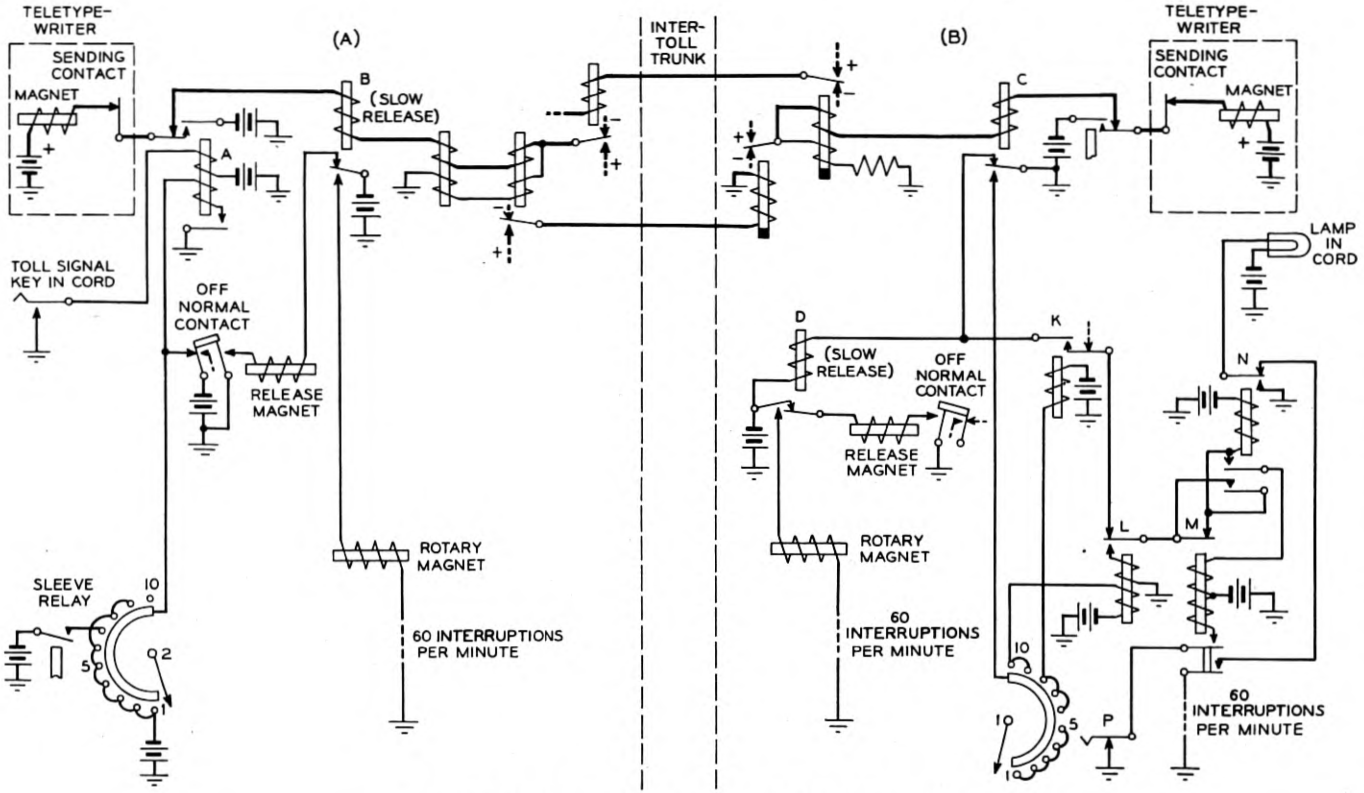

Fig. 12—Fundamental inter-toll trunk signaling circuit.

That section of the receiving selector between terminals 1 to 5 inclusive is used for the call signal which is actuated manually by the originating operator.

Cord Circuits

In order to provide each operator with sufficient traffic for operating efficiency, especially in the smaller offices and during light load periods, the cord circuits in the *TWX* switchboards are made universal, that is, adapted to handling all types of calls. This universal feature is obtained by equipping them with a simple type of repeater. By means of this repeater it is possible to provide for the maximum length of station loop and at the same time establish the following connections:

1. Subscriber line to subscriber line, known as a local to local connection.
2. Inter-toll trunk to subscriber line, or *vice versa*, known as a toll to local connection, or local to toll connection.
3. Inter-toll trunk to inter-toll trunk, known as a through connection.

In a local-to-local connection the two loops could not be connected together directly unless the repeater were provided in the cord circuit for two reasons: first, each loop may be maximum in length so that the two loops in tandem would result in the operating current being halved; and second, each loop is normally terminated on the negative side of the telegraph battery. Because it is essential, in *TWX* service, to make interconnections without requiring adjustments, all loops are padded or "built out" to the same value as the resistance of a maximum loop and each side of the cord circuit repeater is arranged to operate with each loop.

With the provision of the repeater in the cord circuit to permit interconnecting two subscriber lines, the same cord may be used for toll-to-local and toll-to-toll connections because the loop circuits of the inter-toll trunk repeaters are all terminated on the negative side of the telegraph battery and the loop resistance of each is built out to equal that of the longest station loop.

A very simplified form of the essential elements of a *TWX* cord circuit is shown in Fig. 13. The cord circuit basically consists of a repeater of the type before mentioned, a key known as the typing key, by means of which the operator may cut her teletypewriter in and out of the circuit for monitoring purposes, and facilities for receiving the recall and disconnect signals both from the subscriber lines and the inter-toll trunks.

The method of receiving these recall and disconnect signals was explained in the section on inter-toll trunk supervision, and the method used to receive those from the subscriber was pointed out in the subscriber circuit description. Many other items are included in the cord circuit by means of which the operator may expedite the setting up and removing of connections. Among these items is the busy test. When an operator is about to complete a call to a station it is necessary that she know that the station is free to receive the call. To ascertain this a means is provided so that she may make a tip busy test on the sleeve of the jack associated with that subscriber line and, if the station is busy, a position light will be lit. If no light is received the operator will plug into the jack and complete the connection.

Multiple appearances of the jacks and lamps associated with subscriber lines and inter-toll trunks are provided so that a number of operators may be available to answer a call from a station or an inter-toll trunk. If more than one operator answers it is necessary that they be aware of that fact, and that the first operator shall take and complete the call. A circuit is provided to indicate this.

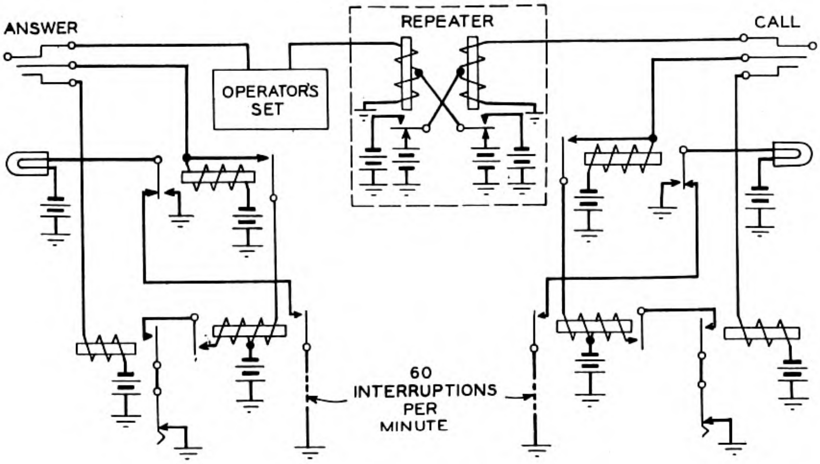

Fig. 13—Typical cord circuit.

Facilities are provided to split the cord, that is, to enable the operator to communicate in one direction without the communication being recorded in the other direction. Ringing is accomplished in a manner similar to that used in telephone practice, the No. 1 switchboard using manual start machine ringing and the smaller No. 3*A* switchboard using manual ringing. While the cord is connected to one line and the operator is attempting to complete the connection to another line, the first line is held closed in order not to mar transmission.

Conference Connections

The teletypewriter exchange system provides a means whereby practically unlimited numbers of stations can be connected in conference connections. Figure 14 shows a typical conference connection. Each link in the conference circuit is provided with a simple repeater, each of which is equipped for breaking. In this manner to and fro communication by the half-duplex method operation can be attained. The conference repeater circuits are made up in groups of five or ten, each of which is equipped with a multiple appearance so that all operators have access to the repeaters.

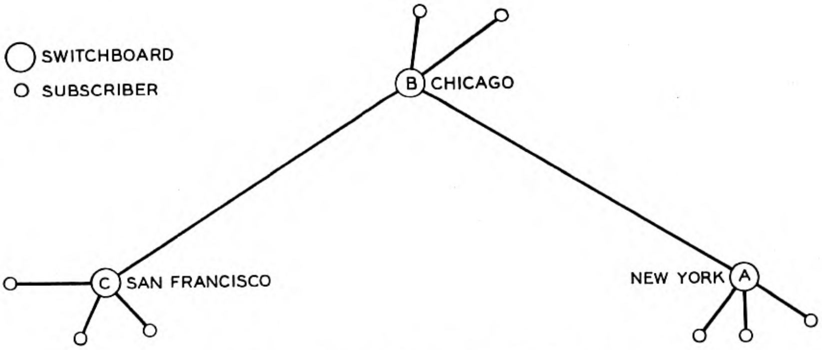

Fig. 14—Typical conference connection.

Regenerative Repeaters

It is necessary in some long circuits to improve transmission by inserting a regenerative repeater in the circuit. To make this possible and easily performed by any operator, regenerative repeaters are provided with a complete jack multiple appearing before all operators. Both ends of the repeater are available in this multiple and the repeater may be inserted where the transmission equivalent of the circuit involved makes it necessary.

TYPICAL BUILT-UP CONNECTION

In order to provide *TWX* service on a nationwide basis, certain of the connections require one or more intermediate switchboards so that one or more through operators may be involved. As an illustration of this Fig. 15 shows a connection established between a calling station in New York and a called station in San Francisco with a through switch at Chicago, a method used when all direct trunks are busy. This figure shows the manner in which the *TWX* equipment has been arranged to operate in conjunction with the telegraph line facilities. The station loop is a pair of wires such as those used for telephone service. Each inter-toll trunk consists of one or more sections of the same standard types of carrier, metallic, or grounded telegraph line systems that are employed in private line telegraph service. The signaling and supervisory apparatus is all contained in the *TWX* switchboard equipments.

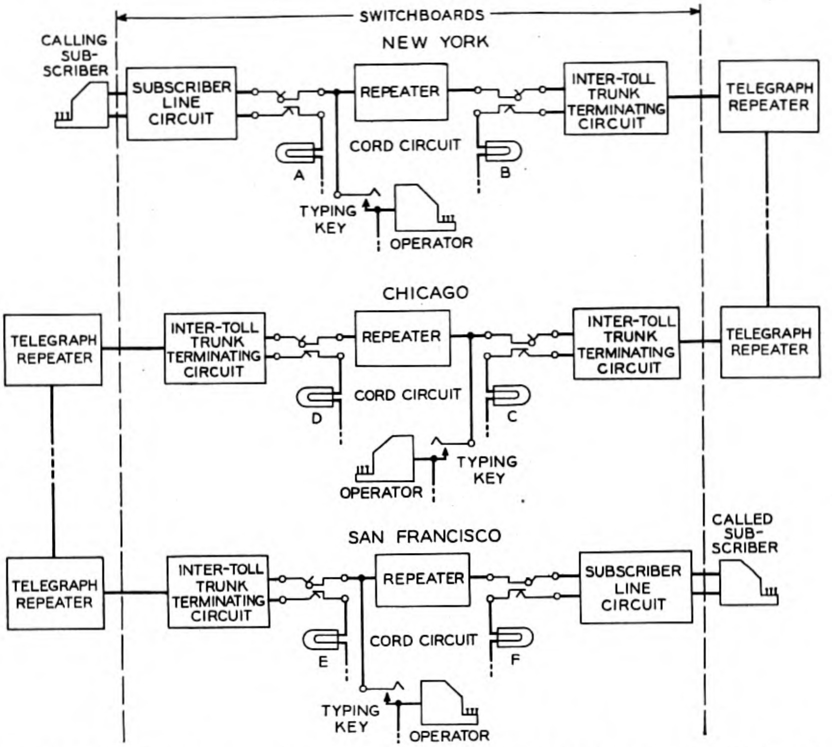

Fig. 15—A built-up connection such as would be used if all direct New York-San Francisco trunks were busy.

In the example illustrated the New York operator, being the outward operator, supervises the call and times the ticket. The following traffic table shows the important steps taken in setting up and taking down this connection:

1. *The New York subscriber calls:* Subscriber closes loop and starts teletypewriter by operating switch. Subscriber line lamps light in the New York switchboard.
2. *A New York operator answers with the cord typing key (similar in function to the talking key in the telephone cord circuit) operated:* The line lamps are extinguished. The operator and subscriber communicate.

3. *The New York operator connects to an idle trunk in the New York-Chicago multiple:* Plugs the completing end of the cord into the trunk jack and operates the cord ringing key for 2 seconds. The trunk multiple lamps at Chicago light.

4. *A Chicago operator answers:* Plugs the answering end of a cord into the trunk jack with the cord typing key operated. The trunk lamps are extinguished. The Chicago operator communicates with the New York operator.

5. *The Chicago operator completes to an idle trunk in the Chicago-San Francisco multiple:* Plugs the completing end of the cord into an idle trunk jack and operates the cord ringing key for 2 seconds. Releases typing key. The trunk multiple lamps at San Francisco light.

6. *A San Francisco operator answers:* Plugs the answering end of a cord into an idle trunk jack with the cord typing key operated. The trunk lamps are extinguished. The San Francisco operator communicates with the New York operator.

7. *The San Francisco operator completes the connection to the called subscriber line:* After making a tip busy test with completing cord to insure that the called station is idle the San Francisco operator plugs into the jack and operates the ringing key in that cord. The ringer in the San Francisco station is operated.

8. *The called subscriber answers:* The answer is received on the operators' teletypewriters at the San Francisco and New York switchboards and at the New York subscriber station. The San Francisco and New York operators release the cord typing keys leaving the communication between the subscribers. The New York operator starts timing the ticket.

9. *The calling and called subscribers disconnect:* Lamps *A* and *F* light. The New York operator completes the timing of the ticket.

10. *The outward (New York) operator sends the disconnect signal:* Operates cord key momentarily and pulls down both cords. After 10 seconds lamps *C*, *D*, and *E* light.

11. *The inward (San Francisco) and through (Chicago) operators disconnect:* Upon noting the disconnect lamp signals both operators pull down both cords.

If during the progress of the call the subscriber desires to regain the attention of the operator, a recall signal is sent. The procedure in this case is as follows:

12. *The calling (or called) subscriber recalls:* Operates power switch at the station. Cord lamp *A* (or *F*) flashes.

13. *The operator answers the recall:* Operates cord typing key connecting her teletypewriter to the circuit. The flashing cord lamp is extinguished.

14. *The outward (New York) operator recalls the inward and through operator at Chicago:* Operates recall key in cord. After 7 seconds lamps *B*, *C*, *D*, and *E* flash. The outward operator releases the typing key momentarily to extinguish the lamp.

15. *The inward and through (San Francisco and Chicago) operators challenge:* Operate cord typing keys which extinguish the flashing lamps, and then challenge by typing.

CONCLUSION

This paper has outlined the technique of teletypewriter switchboard operation as it stands today. Although the designs as here outlined have given satisfactory service within due limits of economy, the expansion of the system and experience in its operation will undoubtedly lead to changes in the design of both the equipment and circuits and to changes in the methods of operation to increase the efficiency and improve the quality of the service.

A Transmission System for Teletypewriter Exchange Service *

By R. E. PIERCE and E. W. BEMIS

A nationwide transmission system has been established in the United States for teletypewriter exchange service by means of which 2-way communication between teletypewriter subscribers can be established in a time comparable to that required for long distance telephone service. A brief description of the principle of operation of teletypewriters is included in this paper as an introduction to the discussion of the transmission requirements and the plan of the present system.

TO MEET the growing needs of business organizations, particularly those operating on a nationwide basis with branches at widely separated locations, there has developed in the United States an extensive use of private line telegraph service. This trend has been accelerated by the perfection of the teletypewriter, which makes it possible for regular office employees to transmit and receive communications without a large amount of special training. Some of these private line teletypewriter networks have been provided with switching facilities to permit the customer to set up connections between his various offices or groups of offices as desired. As these arrangements were perfected and as the public gained experience with the teletypewriter method of communication, a demand developed for a teletypewriter service in which all connections would be set up on a switched basis similar to that provided for spoken conversation by the telephone system. To meet this demand teletypewriter exchange service or as it is usually called, *TWX* service, was inaugurated by the Bell System in November 1931.

Briefly described, teletypewriter exchange service makes available to subscribers a complete communication system for the written word, consisting of:

(*a*) Teletypewriters for sending and receiving, installed on the customers' premises with a connection to a nearby switching center.
(*b*) Transmission channels interconnecting all of the switching centers.
(*c*) Teletypewriter switchboards for connecting the subscribers' stations and loops to each other or to the inter-city transmission channels and for making through connections between inter-city circuits.

This system provides for direct teletypewriter connections between the customers or their employees at the sending point and at the receiving points. The connection is two-way so that questions can

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be asked and answers given. The speed with which the connection is established is comparable to that experienced in long distance telephone service, the average being about 1.3 minutes from the time a subscriber calls the operator until the conversation between subscribers begins. The service has grown until at the present time there are over 8,500 * subscriber stations which may be connected together in pairs or in groups for teletypewriter communication. The switching is done at about 150 switching centers scattered throughout the United States as shown in Fig. 1 and connected by over 500,000 miles of telegraph circuit.

This paper deals primarily with the transmission system used for passing the teletypewriter code signals between the customers. The details of the switchboards and signaling facilities, and the methods of handling customers' connections are described in another paper.[1] With the exception of the switchboards, the equipment used in *TWX* service is similar to that used in other telegraph services.

The teletypewriters are provided with a keyboard similar to that of a typewriter for sending, and the typing is done in capital letters either on a narrow tape or on a page, the page being used in the large majority of the stations. Printed forms may be used on the page machines if desired. The speed of operation is set for a maximum of 60 words per minute. The teletypewriters are of the start-stop type, using a 5-unit selecting code, each group of selecting impulses being preceded by a start impulse and followed by a stop impulse. The teletypewriter mechanism is operated from a local source of power, and in general all signaling current is furnished from central office power plants.

The line circuits may be any of the well known types utilizing 2 current values or line conditions of variable duration for the transmission of signals. Actually about 90 per cent of the circuit mileage used in the *TWX* service is of the carrier type, since this is the most economical type of facility for large groups over the longer distances. The line circuits will be discussed in more detail in another section of the paper.

ELEMENTS OF TELETYPEWRITER SIGNAL TRANSMITTING AND RECEIVING MECHANISM

To translate intelligence which is received in the form of a code the receiving mechanism must be capable of doing two things. First, it must identify the unit time intervals, and second, it must determine which of the 2 line conditions should be recorded for each time interval.

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* Since this paper was prepared the number of subscriber stations has increased to over 9,500.

[1] For all numbered references see list at end of paper.

Fig. 1—Map showing teletypewriter exchange service switching centers in the United States on April 1, 1936.

The first requisite is accomplished by maintaining a high degree of synchronism between the sending and receiving devices during the transmission of each character. The second is accomplished by providing satisfactory transmission facilities so that the mid-portion of each received signal element is the same as the corresponding signal element at the sending end.

TIMING ARRANGEMENTS

The sending and receiving devices are driven by motors which run at approximately the same speed. The receiving device is driven through a friction clutch so that it normally may be idle even though its motor is running. When a signal is received the receiving selector is released, makes one complete revolution, and again comes to rest. With this arrangement it is necessary to maintain synchronism only while one character is being transmitted, because a fresh start is made for each character, and the time intervals for the selecting impulses are measured from this starting point. Cumulative lack of synchronism, therefore, over long periods of time does not affect the accuracy of transmission. This is called the start-stop system.

The advantages of this arrangement are as follows:

(*a*) No elaborate means of synchronizing are required.
(*b*) The lag in the line is automatically taken care of because the receiving machine does not start until the first signal of a code combination is received.
(*c*) Multisection circuits and conference connections can be set up without any special line-up.
(*d*) Machines can be started and shut down without any special adjustment.
(*e*) Local power sources can be used for driving the subscriber's machine.

In actual practice speed is maintained within ± 0.75 per cent in either of two ways:

1. Where regulated frequency a-c. power is available, synchronous motors ordinarily will maintain the speed within ±0.17 per cent, which is well within the limit necessary for satisfactory transmission.
2. Where regulated frequency a-c. power is not available, governed motors are used for either alternating or direct current. These governors are designed so as to maintain the speed within ±0.75 per cent without attention over long periods of time. If the speed of the sending machine is out in one direction and that of the receiving machine in the opposite, the maximum difference may be 1.5 per cent.

Assuming no deformation of the wave shape between the sender and the receiver, the start-stop teletypewriter operating at 60 words per minute will stand about 7 per cent speed discrepancy before errors occur. In practice, however, there is deformation and therefore the speed discrepancy must be kept as low as practicable.

SENDING AND RECEIVING ARRANGEMENTS

The sending arrangement in a teletypewriter is required to do three things:

1. It must transmit a signal which will start the selecting cycle of the distant machine.
2. It must apply the proper current condition to the line for each of the 5 accurately spaced selecting time intervals.
3. It must send a signal which will return the line to the normal idle condition.

The teletypewriter operates in a local circuit in which current is flowing during the normal idle condition. The transmitting is done by opening and closing this circuit, causing zero current or normal current in it, the two conditions being referred to as "open" and "closed." The selecting cycle of the distant machine is initiated by opening the circuit at the sending teletypewriter. This is called the "start" signal. The five selecting signals follow and the line current during each of these time intervals depends upon the character which is being transmitted. Since the normal idle condition of the line is closed, the "stop" signal which is sent last in the train of signals is a "closed" signal.

The selecting arrangement in a receiving teletypewriter is also required to do three things:

1. It must start timing the signals when the start signal is received.
2. It must determine the line condition at the midpoint of each selecting interval.
3. It must come to rest during the stop interval following the 5 selecting signals.

A single electromagnet in the receiving machine converts the electrical pulses into mechanical operations of the selecting mechanism. This magnet controls an armature which is energized for the closed line condition and de-energized during the open line condition. By this means the 2 line conditions are converted into 2 positions of the magnet armature.

THEORY OF TELETYPEWRITER SIGNAL TRANSMISSION

In teletypewriter signal transmission at 60 words per minute (hereafter called 60-speed) the start pulse and each of the 5 selecting signal elements are normally of 0.022 second duration. The minimum length of the stop pulse is 0.031 second. In keyboard sending the maximum length of stop pulse depends upon the time the operator hesitates between the striking of the individual keys of the teletypewriter. Any lengthening or shortening of the signal elements in transmission is referred to as distortion and is expressed as a percentage of the normal length of a signal element. The fundamentals of signal transmission have been discussed thoroughly by various writers.[2, 3, 4] A few of these principles are enumerated here without any attempt to discuss them thoroughly.

1. With the transmitting arrangements usually employed the complete change in line condition at the sender is practically instantaneous.

2. To transmit accurately these sudden changes in the line condition would require a transmission channel capable of passing an infinitely wide frequency band.
3. With a transmission channel which will pass only a limited band of frequencies there will be alteration of the wave shape during transmission as the result of changes in magnitude and phase of the various components caused by the characteristics of the transmission channel, so that changes in line condition at the receiving end will be gradual and in general displaced from their proper position.
4. Theoretically all of the intelligence can be carried by transmitting waves of a maximum frequency equal to that of the fundamental of the signaling speed considering the time interval of each signal element as a half cycle.
5. Actually it is not economical either to transmit a very wide band of frequency or to provide terminal apparatus capable of accurately recording the intelligence when only a band equal in width to the frequency of the fundamental of the signaling speed is transmitted. The arrangement used in practice must, therefore, be a compromise between these two extremes.

Experience has shown that in order to use economically practical types of receiving apparatus it is generally necessary to have present in the received signals a substantial portion of the second and third harmonics of the frequency of the shortest signal element, which requires in the case of 60-speed teletypewriter signals the transmission of a frequency band width of somewhat more than 45 cycles. To illustrate this a typical 60-speed teletypewriter signal is shown graphically in the upper left-hand diagram of Fig. 2. This diagram represents potential applied to the line for a perfect teletypewriter letter "D." At the instant when the start pulse commences, as described previously, the voltage applied to the line assumes its "open" value S, called "spacing." This spacing condition continues for 0.022 second at the end of which time the voltage suddenly assumes its "closed" value M, called "marking." The marking voltage remains constant through the first signaling pulse (1) in the figure. The second and third elements of the teletypewriter "D" signal are spacing and during these intervals the current is again of its spacing value. In the fourth pulse it once more becomes marking for 0.022 second, and in the fifth pulse it is again spacing. After the fifth pulse the current assumes its marking value for the duration of the stop signal.

This teletypewriter "D" signal may be further analyzed by considering it to be made up of sine wave components of various frequencies and magnitudes with certain definite phase relationships. It will be found theoretically to contain a number of sine waves of frequencies from zero to infinity. The left-hand column of Fig. 2 shows a number of the more important harmonic components of the "D" signal, the relative magnitudes and phase relationships being as indicated. The first is the d-c. component; the second is a sine wave of the same period as the over-all signal, and is referred to as the first harmonic. The wave shown in part *c* of the figure is twice the frequency of the over-all signal and is referred to as the second harmonic. Following this in turn are shown the third to tenth harmonics.

The right-hand portion of the same figure shows the synthesis of this signal from component parts. From this figure it may be seen that by the time the seventh harmonic (curve *q*) or even the fifth harmonic (curve *p*) has been added, there is a resemblance between the resultant and the original wave.

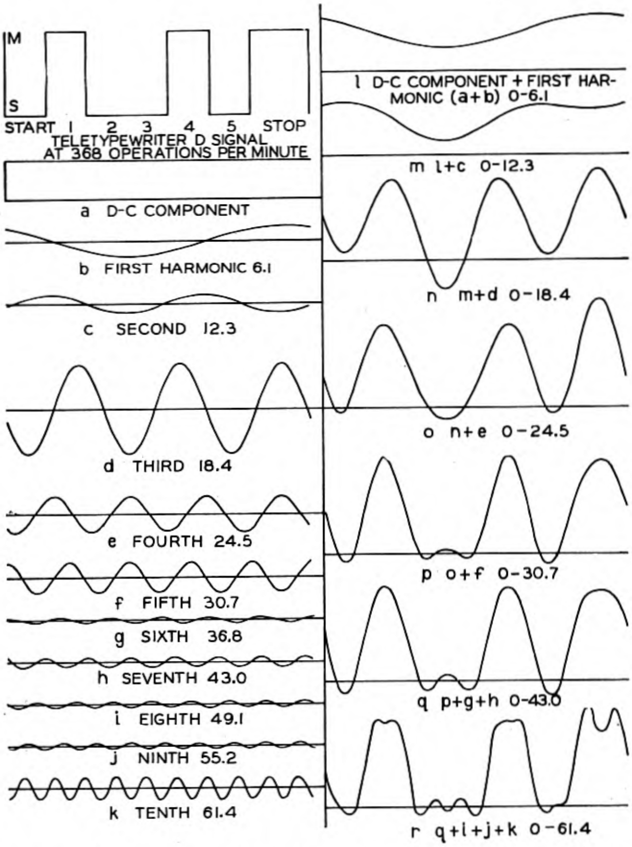

Fig. 2—Analysis of components of a teletypewriter "D" signal. Numbers on harmonic curves are frequencies in cycles per second.

As mentioned previously, the total intelligence transmitted by a given telegraph signal may be contained in a frequency band lying between zero and the fundamental frequency of the shortest signal element, i.e., the frequency at which the duration of the shortest element is a half cycle. In 60-speed teletypewriter transmission the shortest signal element is of approximately 0.022 second duration, and its fundamental frequency is about $1/0.044 = 22.7$ cycles per second. In the illustration in Fig. 2, this frequency would fall between that of curves *d* and *e* in the left-hand column and the character theoretically could be interpreted correctly with the transmission in correct phase relation of only the components up to and including the fourth harmonic (curve *o* in the right-hand column). As previously stated, however, while transmission of such a limited frequency range could be interpreted without error by an ideal receiving device, practical considerations of over-all economy make it desirable to transmit the wider frequency range mentioned.

TYPES OF DISTORTION

In order to design a satisfactory teletypewriter transmission system it is desirable to understand the effects of various types of distortion and mechanical variations in the sending and receiving mechanisms. Figure 3 shows schematically that part of the receiving mechanism which is of interest in explaining the effect of signal distortion on correct interpretation of the message. This includes a receiving selector magnet with its associated armature and armature extension, a locking lever, a stop latch, and a selector cam driven by a friction clutch. In the idle condition the selector magnet is energized and the magnet armature and armature extension are in the position shown, the selector cam being held from rotating by the stop latch. When a train of impulses representing a character is received the start pulse (spacing) allows the armature and armature extension to move to a position shown by the dotted lines and at the same time releases the stop latch. This latter operation permits the selector cam to start rotating. The speed of rotation and the starting position of the selector cam are normally so adjusted that the first depression (shown by *A*) will arrive at the locking lever at the time the middle of the first selecting impulse is being received. The locking lever will then fall into this depression and the locking wedge *B* will move toward the armature extension and lock it in the position it occupies at this instant. This determines which of the 2 line conditions will be recorded for this signal element. Immediately thereafter mechanical arrangements (not shown) will operate to transfer this information to the selection storing mechanism. This process will then be repeated for each of the other 4 selecting impulses.

After the 5 selecting impulses have been received the slightly longer stop impulse is received. During the latter part of this impulse an arm *C* on the receiving selector cam will strike the stop latch and the cam will be held until the reception of the start impulse for the next character.

An orientation device or range finder is provided which rotates the stop latch with respect to the locking lever and thereby changes the time at which selection occurs with respect to the beginning of the selecting cycle. Moving the orientation range finder in effect moves the solid vertical lines in Fig. 3, with respect to the signal, and with perfect signals they can be moved by an amount corresponding to one unit impulse. In other words the time of selection can be moved by ± 50 per cent without typing errors, as shown at *a* in the figure. (In an actual machine this range is less because of practical considerations of design, the time of selection being variable without errors over a range of about ± 40 per cent.)

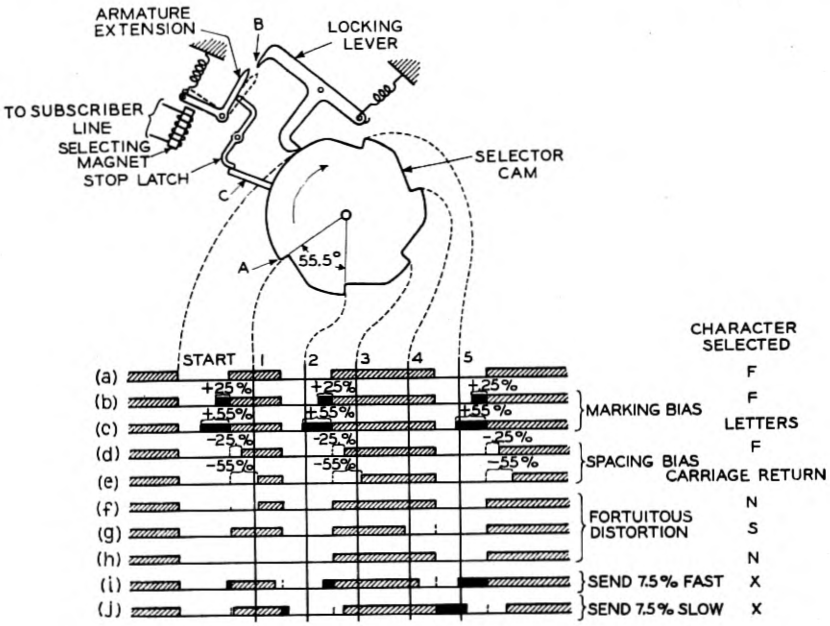

Fig. 3—Principles of selecting mechanism of a teletypewriter.

Distortion in teletypewriter signals may be "bias," which is a uniform lengthening or shortening of all the marking impulses, or it may be of other types which affect only certain of the signal elements.[4] Bias is divided about equally between the ends of the impulse when the signal is received from the line. However, because the selecting mechanism starts rotating at the beginning of the start impulse, the effect of bias is to shift all impulses forward or backward with respect to this time. The result of this is that effectively there will be an addition to or subtraction from the front of each marking impulse, with the rear of the impulses remaining unchanged.

In an ideal machine where selection would be made instantaneously the signal would be recorded correctly if it had the right condition (i.e., marking if it should be marking or *vice versa*) at the instant of selection. The particular times when the selections take place with the orientation setting at the middle of the range with perfect signals are shown, as mentioned before, by the vertical solid lines numbered 1 to 5, inclusive, in Fig. 3. Referring to cases *b* and *d* it may be seen that with 25 per cent bias the correct signal is being received at the point of selection and it will be interpreted correctly. However, referring to cases *c* and *e* it may be seen that more than 50 per cent bias will cause errors. In case *c* the second and fifth impulses will be falsely interpreted as marking and in case *e* the first and third impulses will be spacing instead of marking. Several examples of the effect of distortion other than bias in the received signals are illustrated in cases, *f*, *g*, and *h* of Fig. 3.

The effect of variations in teletypewriter motor speeds on operating margins is illustrated in Fig. 3 by cases *i* and *j*. Case *i* shows the result if the sending machine is faster than the receiving machine. It will be noted that as the speed discrepancy becomes greater the first error will be a false mark for the fifth impulse because a part of the stop impulse is received on the fifth position. If perfect signals are assumed, the speeds would have to be somewhat more than 7 per cent different to cause errors of this kind in a normal teletypewriter with the range finder set in the middle of the range, but if there is some signal distortion other than that from speed discrepancies, such as marking bias, smaller differences in speed would be sufficient to cause errors. Case *j* illustrates the conditions when the sending distributor is slower than the receiving distributor. It will be observed in this case that the first error as the speed discrepancy increased would also be in the fifth impulse as the result of either the fourth impulse being sufficiently prolonged to fall on the fifth selecting position, or the fifth impulse being so late in starting that it is not properly received on the fifth position.

In the illustrations large speed discrepancies have been used so that the shift of the signals could be shown readily on a drawing.

GENERAL TRANSMISSION DESIGN OF *TWX* NETWORK

Telegraph circuits comprising the transmission network employed in teletypewriter exchange service are laid out according to a fundamental plan similar to the toll switching plan [5] used in designing the toll telephone plant. The teletypewriter switching plan is designed to provide on the most economical basis the circuits necessary for satisfactory connection between any two stations in the country without any special line-up or adjustment of the circuits or apparatus.

Each switching point has a direct connection to each of the subscriber stations within its area (except for a few stations which are connected to the switchboards by a single channel carrier circuit operating over regular toll telephone circuits when a connection to these stations is desired). In addition it has direct toll circuits to one or more of the other switching points. Eight cities of considerable importance from the standpoint of switching in the national network are designated as "regional centers." These cities, New York, Atlanta, Chicago, St. Louis, Dallas, Denver, San Francisco, and Los Angeles, are interconnected largely by high grade direct circuits and ultimately will be interconnected completely by such facilities. Each of the regional centers has direct circuits to a number of smaller centers designated as "routing outlets" within a given area, which are also interconnected by direct circuits.

The other switching centers, called "teletypewriter centers," which are not required by their position in the networks to handle through business, have direct circuits to one or more routing outlets and may have direct connections to similar nearby centers if traffic justifies it.

The application of the teletypewriter switching plan is illustrated in Fig. 4. Considering only the toll circuits of the basic routes (solid lines connecting switching centers in the figure), it may be noted that within any area where the routing outlets are interconnected by direct circuits, the maximum number of teletypewriter toll lines required for connection between two stations in the area is 3. A very large percentage of the connections can, of course, be made with only one or two toll links. It may also be seen that, assuming all regional centers to be interconnected by direct circuits, a maximum of 5 toll links will serve to connect any two stations in the country, using only the basic routes.

In addition to these basic toll routes, supplementary routes are provided wherever the traffic warrants, as indicated by the dashed lines in the figure. These supplementary routes may be direct circuits between two teletypewriter centers, between a teletypewriter center and a routing outlet or regional center other than that through which it is normally served, or between a routing outlet in one area and a routing outlet or regional center in another regional area. It is obvious from the figure that the effect of these supplementary routes is to reduce the number of toll links and consequently the number of switches involved in certain connections.

The plan permits considerable flexibility with respect to arrangements for future expansion and changes, as growth can be taken care of by the provision of additional switching points or additional direct circuits with practically no change in the fundamental framework.

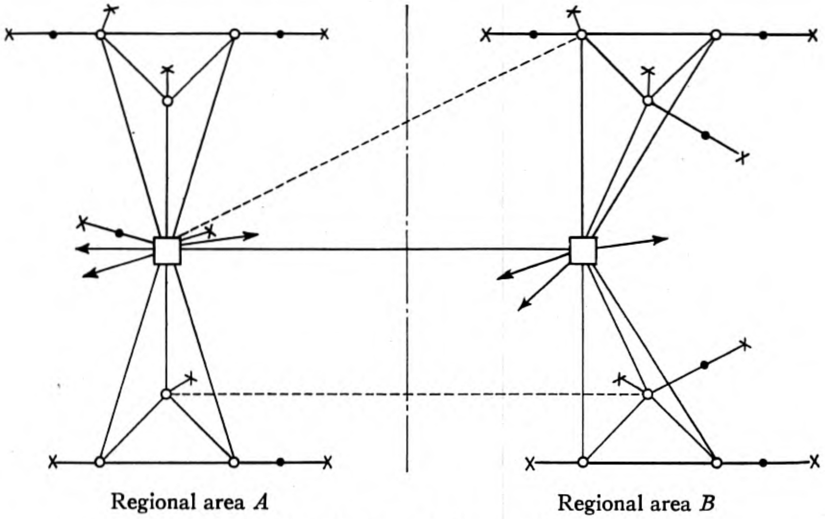

Fig. 4—Principle of application of teletypewriter switching plan.

□ Regional center
○ Routing outlet
● Teletype center
× Subscriber station
— Basic routes
- - Supplementary routes
→ Routes to other regional centers

TRANSMISSION REQUIREMENTS

In the consideration of the transmission requirements the following items are of importance:

1. The over-all distortion on all connections must be low enough to permit satisfactory service.
2. The distortion on all of the links which will at times be part of built-up connections must be sufficiently low to permit satisfactory transmission when forming a part of such connections.
3. The distribution of distortion between the various toll links and between those links and the subscriber lines should be such as to obtain the desired transmission results with a minimum cost for the plant as a whole.

TRANSMISSION COEFFICIENTS

The transmission requirements of the over-all connection or of the individual elements are expressed in terms of a system of telegraph transmission coefficients which may be compared roughly to the system of net losses used in telephone transmission work.

In teletypewriter toll circuits of one or more sections the over-all distortion is made up of increments from a number of sources. Experience has shown that in general the over-all distortion of a particular signal element is equal to the algebraic sum of the individual increments. For each specific piece of equipment or element of the circuit the sign and value of the distortion cannot be predicted exactly as they depend upon facts which vary with individual cases. However, representative values of the maximum distortion experienced in a period of moderate length with miscellaneous signals for different types of circuit and equipment may be determined with fair accuracy. Experience and probability theory indicate that the most probable value of the over-all distortion of a telegraph circuit may be computed by taking the square root of the sum of the squares of the corresponding values for the various component parts of the circuit. With this as a basis coefficients have been established for individual telegraph circuits of the various types employed in the *TWX* transmission system. These coefficients are, in general, proportional to the square of the maximum distortion experienced with severe signal combinations under comparatively unfavorable conditions of circuit adjustment, weather conditions, etc., taking into account what is known about the general stability of the particular facility concerned. An estimate may then be made of the transmission impairment to be expected in service with a teletypewriter circuit made up of a number of sections of various types by adding the coefficients of the component parts. For convenience the value of the coefficients has been so chosen that satisfactory operation normally will be obtained over a connection if the sum of the transmission coefficients for the subscriber lines, switchboard circuits, and toll lines involved does not exceed 10.

Using these coefficients the entire transmission system is designed to provide satisfactory transmission between any two subscribers or combinations of subscribers. It is found that subscriber lines less than about 5 miles in length contribute little or no distortion to the over-all connections. Those up to about 35 miles may contribute distortion so as to warrant allowing a coefficient as high as 1.0 or 1.5, and for those up to 50 or 60 miles the coefficient may be as great as 3.5 or 4.0.

The following discussion assumes that the subscriber lines have a coefficient of not more than 1.0 or 1.5 from the subscriber station to the jack connected to the teletypewriter toll line at the switchboard, leaving for the toll links of the connection a maximum coefficient of about 7.0 or 8.0. In the case of intra-area connections involving 3 toll links, a permissible coefficient of 8.0 for all the links of the connections would, of course, permit a coefficient of about 2.7 for each link. Correspondingly, a connection involving 5 links would permit a coefficient of only 1.6 per link. It happens, however, that the transmission capabilities of the teletypewriter circuits generally in use are such that none of the circuits has a coefficient of less than 2.0 and that single sections of circuit may lie in the range of about 2.0 to 5.0. Practically, the availability of the higher grade circuits is limited by reasons of economy since, for example, the multi-channel carrier telegraph facilities which have coefficients of 2.0 to 2.6 would be too expensive to use for routes where only a few circuits are required or for the shorter links. It is apparent, therefore, that an over-all coefficient of 7.0 to 8.0 cannot be realized on either 4 or 5 link connections without some means for overcoming the over-all distortion. For these cases the operators are provided with connections to regenerative repeaters, which are inserted in series with the circuit and retransmit the teletypewriter signals exactly as they were originally transmitted into the circuit at the sending end, provided they have not been distorted beyond the point where they can be correctly interpreted by the regenerative repeater. The latter has about the same signal distortion tolerance that a teletypewriter would have if the circuit terminated at that point. Thus the regenerative repeater wipes out the distortion of the preceding toll links and subscriber line so that the coefficient at its output will again be zero. The circuit layout for an actual connection is shown in Fig. 5 illustrating the use of a regenerative repeater.

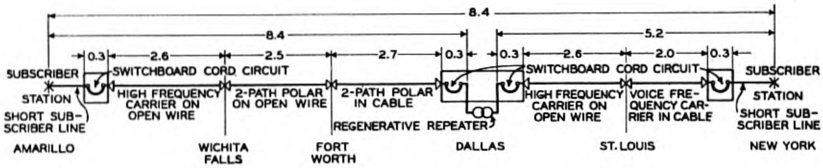

Fig. 5—Diagram of typical teletypewriter exchange service connection requiring regenerative repeater.
Numbers are transmission coefficients.

For the purpose of the teletypewriter exchange circuit layout, it is assumed that regenerative repeaters are available at the switchboards of all regional centers so they may be used to handle 4 and 5-link connections. They are required occasionally at routing outlets to provide satisfactory over-all results on 3-link connections. In the case of 2-link connections the use of regenerative repeaters is ordinarily avoided by limiting the coefficient of the subscriber line, switchboard, and first toll circuit to 5.0. For subscriber lines on which it is not economical to provide facilities having coefficients as low as 1.5 the traffic routing instructions call for the use of additional regenerative repeaters at suitable points.

The types of telegraph facilities that are used for these various classes of toll link and subscriber line are discussed farther on.

FACILITIES USED IN *TWX* NETWORK—TELETYPEWRITER STATIONS AND SUBSCRIBER LINES

A typical teletypewriter station, illustrated in Fig. 6, includes the sending and receiving equipment, together with power supply, and supervisory equipment for initiating a call, informing the attendant of an incoming call, or recalling the switchboard operator during the progress of a connection if desired. These features are described in detail in the paper on switchboards and signaling facilities referred to previously.[1]

Any one of several types of teletypewriter subscriber lines may be used to connect a station with the switchboard from which it is served, the type chosen depending upon conditions in the particular case. A large majority of subscriber lines, however, consist of cable pairs used exclusively for that purpose. In these the telegraph method employed is one in which polar signals (a positive potential for spacing and a negative potential for marking pulses or *vice versa*) are impressed on the subscriber line by a telegraph repeater in the cord circuit at the central office, and neutral signals (the circuit closed for marking and opened for spacing) are transmitted by the sending contacts of the teletypewriter at the subscriber station.

The polar signals transmitted from the central office are symmetrical and the transmission quality of these signals is not affected seriously by the capacitance of the cable loop. As is ordinarily the case in duplex transmission, the current impulses are transmitted differentially through two windings of a relay in the cord circuit repeater which responds to incoming signals but not to the outgoing differentially transmitted signals. To prevent the undesired response of this relay to the outgoing signals, it is necessary that the differential winding not connected to the subscriber line be terminated to ground through an impedance similar to that of the subscriber line. Since subscriber lines from a given type of switchboard are all arranged to use the same current value the resistance component of the station line impedance may be balanced by fixed resistance.

With cable circuits of appreciable length, however, the capacitance becomes of importance. Up to a certain length the effect of the capacitance on balance can be minimized by locating a substantial portion of the current limiting resistance in series between the subscriber line jack at the switchboard and the subscriber line. For longer circuits an impedance modifying network consisting of capacitance, inductance, and resistance in parallel is inserted in series with the circuit between the subscriber line jack and the subscriber line. The constants of this network are so chosen that the subscriber line will be satisfactorily balanced by the same cord circuit repeater balancing arrangement that is used for the shorter subscriber lines in the office.

Fig. 6—Typical teletypewriter subscriber station.

At the station the sending contacts and receiving relay or magnet are in series with the subscriber line. Signals from subscriber stations are formed simply by opening and closing the circuit at the sending contacts in accordance with the code for the characters being transmitted. When the contacts are closed a current flows in the subscriber line circuit for marking and when they are open this current becomes zero, transmitting a spacing signal.

On long cable pair subscriber line circuits with considerable bridged capacity, the wave shape of the current received in the central office is not symmetrical as regards the marking or spacing conditions, the rate of building up of the marking current being much faster than its rate of decay. This results in marking bias in the received signals. Conversely, in subscriber line circuits containing only series inductance and resistance, the received current builds up gradually to its marking value and decays to zero immediately when the sending contacts are opened for a space. By properly combining the inductance and capacitance, it is possible to produce substantially unbiased signals at the receiving end. In other words, by inserting series inductance in a cable circuit, it is possible to overcome the marking bias effect mentioned above so that practically no distortion occurs in the subscriber line.

The marking bias may also be reduced effectively by the use of series resistance in place of inductance at the subscriber station in cases where it is possible to add a sufficient amount of resistance without reducing the current below the desired value. The effect of series resistance used in this way is to delay the building up of the current when the teletypewriter sending contacts are closed after a spacing signal to compensate for the delay in decay of the received current after the contacts have opened.

Both of the above methods of reducing bias are in use in the present teletypewriter exchange plant. Figure 7 shows the wave shape of uniformly timed marks and spaces received over a 30-mile 19-gauge cable pair, illustrating the effect of the cable capacitance, and the manner in which a wave shaping arrangement, consisting primarily of inductance in this case, reduces the amount of marking bias in the received signal by retarding the building up of current at the start of each marking signal.

Although the majority of subscriber lines are in cables, it is sometimes necessary to serve stations at greater distances from the teletypewriter center or in situations where the use of cable pairs is not practicable. For these, other arrangements must be made. One method of serving such stations is by means of arrangements similar to those of the shorter toll circuits. Generally a telegraph repeater in an office in the vicinity of the subscriber station is used, and transmission between that repeater and the one in the teletypewriter center takes place in the same manner as over a toll circuit of similar length.

Another method for connecting to subscriber stations which cannot be cared for by a metallic cable pair employs a simple telegraph repeater installed as part of the subscriber station equipment. This arrangement as well as the one previously described has the advantage that it permits polar signals to be used in both directions over the subscriber line.

In a few cases which have arisen where telegraph facilities were not readily available between the teletypewriter center and a subscriber station, use has been made of a single-channel voice-frequency carrier telegraph arrangement by means of which the transmission takes place over standard telephone circuits. A small carrier telegraph terminal arrangement is mounted on the back of the teletypewriter table, and a corresponding carrier terminal is located in the teletypewriter center in a trunk circuit between the teletypewriter switchboard and the telephone toll board. Special operating procedures are set up so that whenever the subscriber initiates a call, connection is established by telephone operators over telephone circuits to the above mentioned carrier trunk circuit at the teletypewriter center, and the teletypewriter switchboard operator is notified

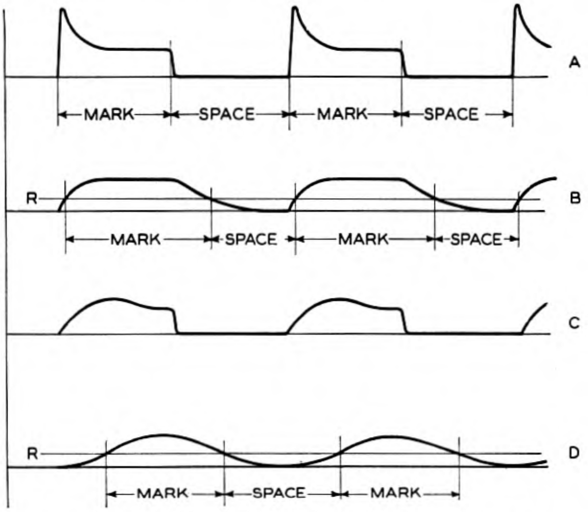

Fig. 7—Effect of wave shaping networks in long subscriber lines operated over cable pairs.

A—Current at subscriber station; no wave shaping network used.
B—Current in A as received at central office.
C—Current at subscriber station; loop equipped with wave shaping network.
D—Current received at central office; loop equipped with wave shaping network.
R—Current required to operate receiving relay of repeater in central office.

of the call and given the number of the subscriber by whom it is made. From the subscriber's standpoint calls are made with this equipment in practically the same manner as when ordinary telegraph facilities are employed.

SWITCHBOARDS

The switchboards used in teletypewriter exchange service contain facilities for interconnecting subscriber lines, connecting them with toll circuits, or interconnecting toll circuits as required, together with the necessary means for establishing and supervising the connections. They are described in considerable detail in the previously referred to paper on switchboards and signaling facilities.[1] As indicated in the discussion of subscriber lines, the transmission circuit through the switchboard is essentially a differential duplex telegraph repeater. One such repeater is connected between the cords of each pair. This repeater is so designed that it introduces very little distortion in the connection. The coefficient of the switchboard cord circuit is 0.3. Figure 8 is a schematic diagram showing the principle of the transmission circuit.

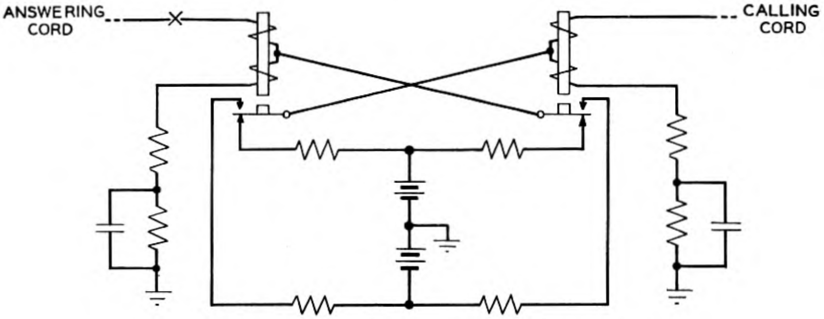

Fig. 8—Principle of switchboard transmission circuit.
Operator's teletypewriter inserted at × when required.

TOLL CIRCUITS

The toll circuits of the teletypewriter exchange network are of the standard types that are in general use for telegraph transmission. These include voice-frequency carrier telegraph systems on cable circuits [6] or on channels of carrier telephone circuits on open-wire lines, high-frequency carrier telegraph systems on open wires,[7] metallic systems on cables,[8] and two-path polar and differential-duplex grounded telegraph circuits.[9] An idea of the relative capabilities of these types of facilities may be obtained from Table I which shows the coefficients of a single section of each type.

TABLE I

TRANSMISSION COEFFICIENTS FOR 60-SPEED TELETYPEWRITER EXCHANGE CIRCUITS

Type of Circuit	Coefficient per section *	Maximum Section Length Normally Used, Miles
D-C. grounded system on open wire	2.5 to 4	300
D-C. metallic system on cable circuits	2 to 3	150
High frequency carrier system on open wire	2.6	1,150
Voice frequency carrier system on cable or open wire circuits	2.0 to 2.2	3,500

From the coefficients given in the table and the earlier discussion of the teletypewriter switching plan, it is apparent that the carrier systems, voice-frequency or high-frequency, where available, are most suitable for the longer backbone toll circuits of the nationwide network. For the short circuits of from 100 to 200 miles where cable plant is available, the metallic telegraph circuits on cable are extensively used, while for the scattering circuits of similar length, and most of the shorter toll circuits, use is made of two-path polar and differential duplex facilities. In some instances where single section facilities of the required grade are not available between two centers, regenerative repeaters permanently associated with multi-section circuits are used to provide satisfactory over-all circuits. Also in certain instances where circuits are not required for through switching, multi-section circuits without regenerative repeaters are sometimes provided and classified "for terminal purposes only."

All the components of the network—teletypewriters and their associated subscriber lines, transmission circuits in the switchboards, and toll circuits interconnecting the switchboards—are designed to give a satisfactory over-all transmission performance with a minimum cost for the plant as a whole. Results obtained in service indicate that the system is meeting a commercial need and that its performance is satisfactory, but developments are continually under way to effect further improvements in service and economies in operation as experience is gained with the system.

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* The term "section" as here used designates the part of a telegraph circuit between 2 telegraph repeaters or a section of a telegraph circuit without any intermediate telegraph repeaters. For example, a telegraph repeater section operated by the voice-frequency carrier telegraph method is that part of the circuit between carrier telegraph terminal sets, regardless of the number of intermediate telephone repeaters in the carrier circuit.

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A New Telephotograph System *

By F. W. REYNOLDS

Transmission of photographs over telephone wires was begun commercially several years ago, but recent improvements have increased to 11 by 17 inches the size of photograph that could be transmitted and have made it possible for the picture to give much more information. The new machines used for sending and receiving photographs are described in this paper, and the requirements and control of the wire system necessary to prevent imperfections in the picture and to permit switching of sending and receiving stations are discussed.

A TELEPHOTOGRAPH message service between New York, Chicago, and San Francisco was initiated in April 1925 by the Bell System, and was extended during the following two years to five additional cities. Experience in the operation of this service, using equipment previously described,[1] indicated that a number of improvements were desirable in order to meet more satisfactorily the apparent requirements of this form of communication. Development work was undertaken to effect these improvements, and this paper describes the new equipment and some of the features involved in establishing a leased wire telephotograph network connecting 26 cities as shown in Fig. 1.

During the eight years of operation of the first Bell System telephotograph service the performance of the system was observed, analyses made of the material transmitted, and opinions formulated regarding the acceptability of the received pictures. The early equipment required the preparation of the material for transmission as a film transparency in an area not exceeding 4¼ inches by 6½ inches. This relatively small image field combined with the use of 100 scanning lines per inch and the added photographic operations to prepare the material for transmission were considered as limiting the usefulness of this new service. For example, in transmitting many of the forms of printed matter it was necessary to divide the copy into overlapping sections, to transmit each piece separately and to assemble the sections as a composite picture at the receiving point. Obviously this procedure could not be applied advantageously to a photograph or news picture and therefore the maximum information content of such transmissions was limited by the small size of image field and the

* Published in *Electrical Engineering*, September 1936. Presented at A. I. E. E. Southwest District meeting, Dallas, Texas, October 26–28, 1936.

[1] For all numbered references see list at end of paper.

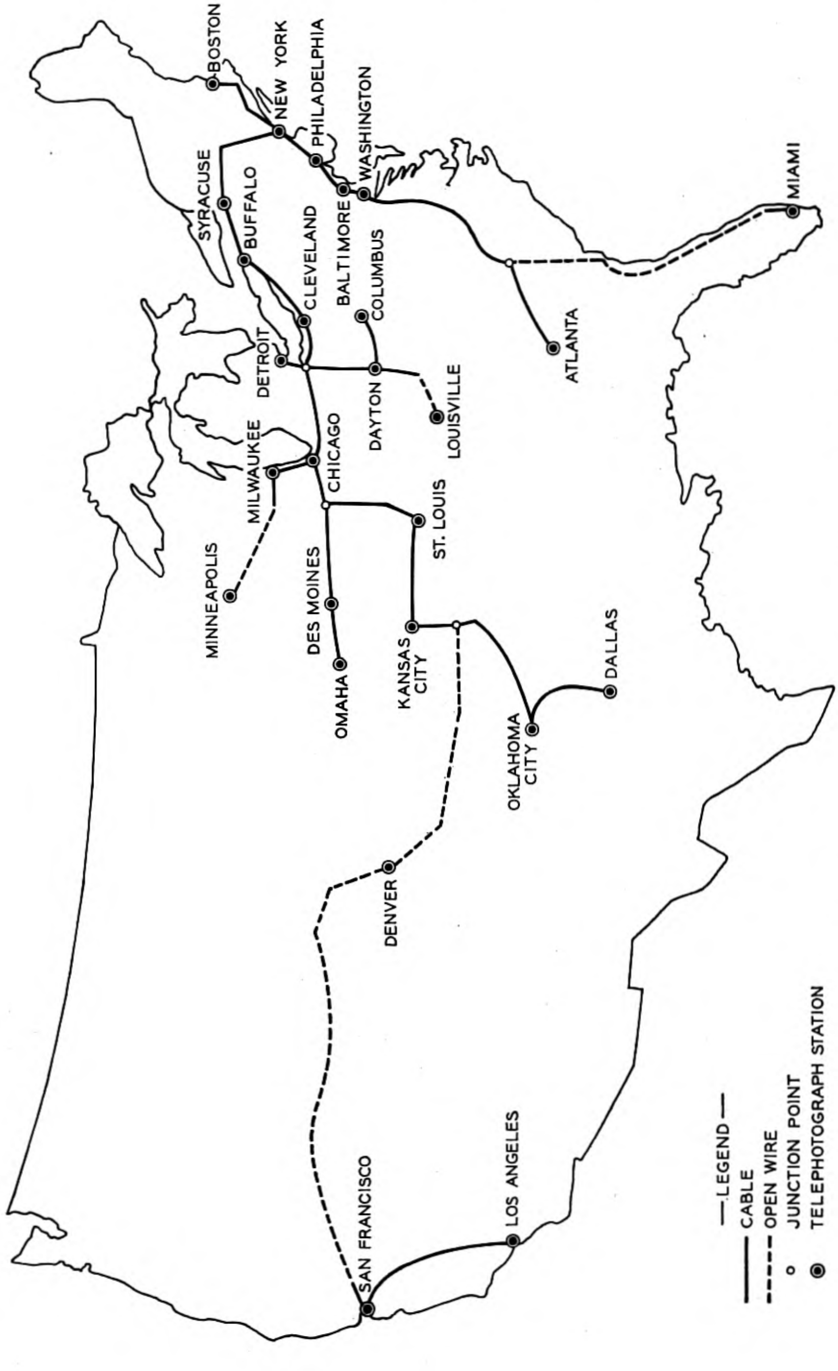

Fig. 1—A leased wire telephotograph network in the United States.

number of scanning lines employed. Certain types of pictures such as portraits, small groups, and others of a rather limited information content were transmitted satisfactorily with this early equipment, but transmissions of those pictures containing much greater amounts of information frequently were regarded as inadequate.

In formulating specific requirements for the new telephotograph system consideration also was given to the increasing interest in news pictures and to the trend in this country toward improvement of newspaper halftone reproduction. The former public demand for pictures of the occasional catastrophe or outstanding news event is today apparently being supplemented by an interest in the pictorial reporting of even minor news items. These factors are reacting to elevate the standards for acceptable telephotographs to a plane where newspaper halftone reproduction of original and transmitted pictures may soon be comparable in quality and information content. The requirements met by the new telephotograph system are summarized briefly in the following paragraphs.

Scanning

Pictures are scanned by reflected light at 100 lines per inch. This permits direct transmission from original subject matter in the majority of cases without recourse to special preparation such as photographic copying.

Size of Image Field

A useful image field is provided for scanning and reproducing pictures of various sizes up to and including 11 inches by 17 inches. This area is sufficient to accommodate most sizes of subject matter likely to be encountered in telephotography and is well adapted to transmission of black and white information such as financial statements, advertising layouts, and the like. Furthermore, it provides a practical method of varying the information content of received pictures by using original prints of appropriate sizes. This point is illustrated in Figs. 9 and 10, which are reproductions from transmissions made from prints of the same subject which were respectively 4¼ by 6⅛ inches and 10 by 14½ inches. The useful circumference of the picture cylinder employed is 11 inches. In the case of news pictures, which are ordinarily distributed as 8 by 10 inch photographic prints, the remaining one-inch space on the circumference of the cylinder may be utilized for transmitting the caption as part of the picture.

Speed of Transmission

The image field in the new equipment is scanned at 100 lines per inch with a velocity of 20 inches per second, which results in the transmission of one inch of picture per minute, measured along the axis of the picture cylinder. This rate of scanning produces essential signal frequencies extending approximately from zero to 1,000 cycles per second and is more than double the speed of transmission used in the earlier equipment. However, by employing the single-side-band method of transmission it has been possible to use this speed of transmission over telephone circuit facilities of normal band width but specially modified as described in a later section.

Synchronism

Operation of the earlier Bell System telephotograph equipment over long telephone circuits indicated the desirability of providing improved means for synchronizing the sending and receiving equipment. Accordingly, development work was undertaken, and local frequency sources of the required stability were made available to permit independent speed control without transmitting synchronizing signals. Experimental oscillator units were installed for tests at three telephotograph stations about two years after the opening of the public telephotograph service in 1925. Experience gained from the use of these oscillators, which were vacuum tube driven tuning forks maintained within close temperature limits, indicated that this method was practicable, although the particular arrangements employed at that time could be advantageously improved.

A new design of tuning fork controlled oscillator has been provided in the new equipment whose frequency can readily be adjusted and maintained constant to within a few parts in a million. This difference in speed between sending and receiving machines is so slight that skewing of the received picture is not noticeable.

Starting and Phasing

The simultaneous starting of all machines participating in the transmission and reception of a picture is effected by means of a signal sent over the line by the transmitting machine. Phasing of the machines is automatic, since all are started simultaneously from the same angular position by a positive action clutch. This requirement is similar to that met by the earlier equipment, but more difficult to fulfill because of the use of a much larger picture cylinder. It required the development of a new type of clutch which would permit a gradual increase in velocity of the cylinder and yet be positive in action. The fulfillment of this requirement is important as it assures accurate phasing without consuming valuable circuit time, irrespective of the number of machines involved in a transmission.

Design

In addition to meeting the above general requirements the new design includes arrangements for daylight operation, a new type of driving motor, and scanning with a pulsating beam of light whereby the photoelectric current can be amplified by a-c. methods.

DESCRIPTION OF THE NEW TELEPHOTOGRAPH EQUIPMENT

The general specifications outlined in the preceding paragraphs are embodied in the new telephotograph equipment now being manufactured. Telephotograph equipment of this type for a station arranged to send and receive pictures consists of a sending machine and a receiving machine mounted on separate tables (see Figs. 2 and 3),

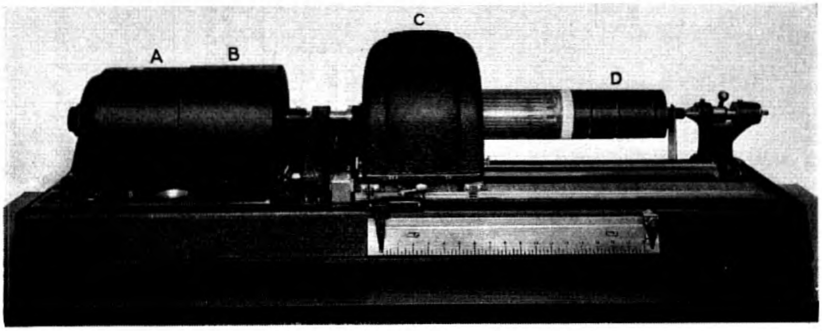

Fig. 2—Telephotograph sending machine.

A—Motor.
B—Clutch.
C—Optical system.
D—Picture cylinder.

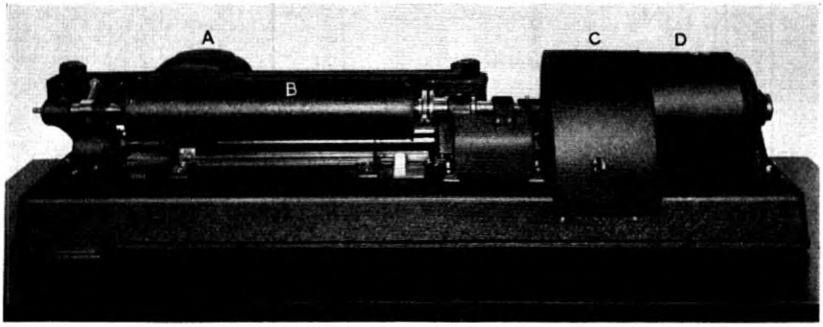

Fig. 3—Telephotograph receiving machine.

A—Optical system.
B—Cylinder housing.
C—Clutch.
D—Motor.

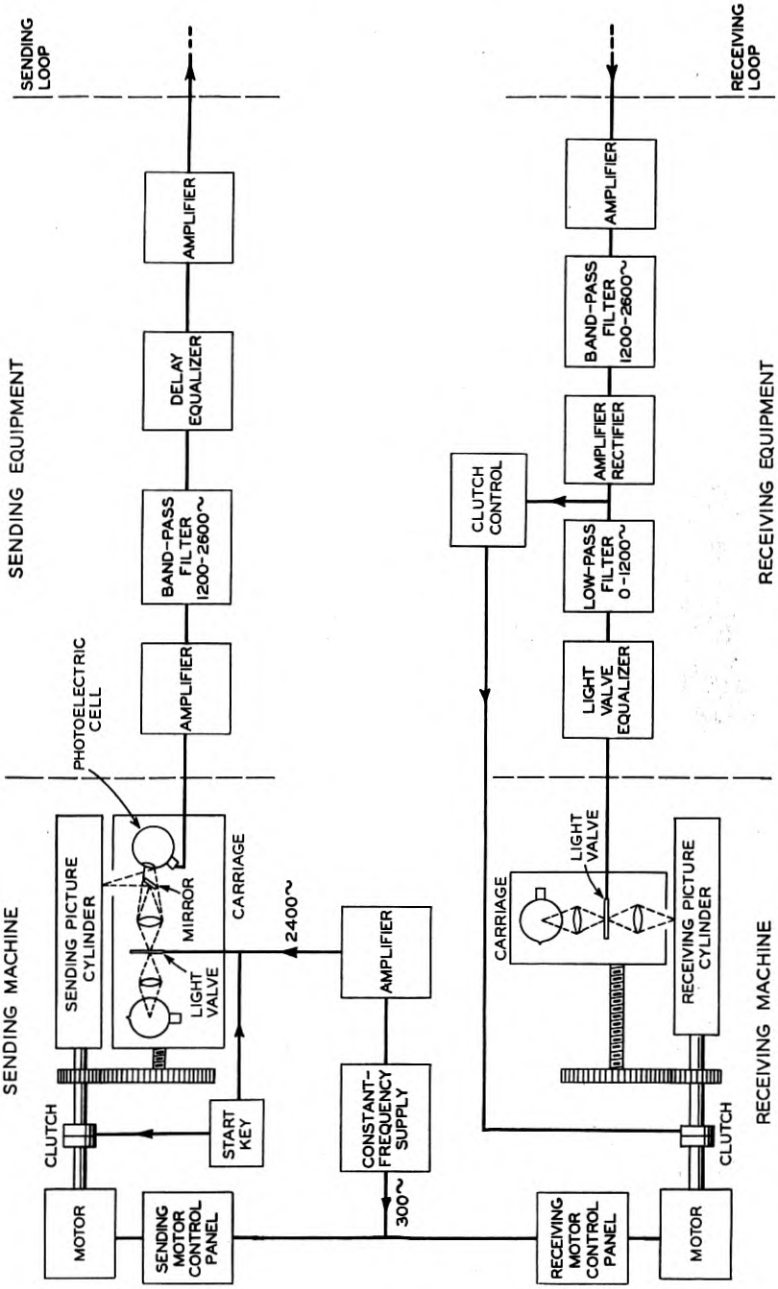

Fig. 4—Schematic diagram of sending and receiving equipment for one station.

two bays of relay-rack-mounted apparatus, and a cabinet of power supply equipment. A third bay comprising loop terminating arrangements, telephone, and loud speaker equipment may be furnished by the telephone company if ordered by the customer. This telephotograph equipment connected by suitable circuits will transmit pictures and other forms of graphic information from point to point or from one to a number of points simultaneously.

Figure 4 is a schematic diagram illustrating the functional relationships of the various units of this equipment. Certain features of these units that may be of special interest have been selected for description in the following.

Motor and Associated Speed Control Circuit

Although the driving motor for the telephotograph machine is essentially of the d-c. shunt type, it functions in combination with its associated speed control equipment as a synchronous unit and upon starting locks automatically in synchronism with the frequency generated by the local carrier and motor control oscillator. This is accomplished in a manner similar to that previously used in television equipment demonstrated by the Bell System.[2, 3] An inductor type generator built into the frame of the motor delivers an a-c. output of 300 cycles per second at the normal speed of the motor, 100 r.p.m. The output of the generator is impressed upon the plates of two vacuum tubes the grids of which are energized by the 300-cycle output of the carrier and motor control oscillator as shown in Fig. 5.

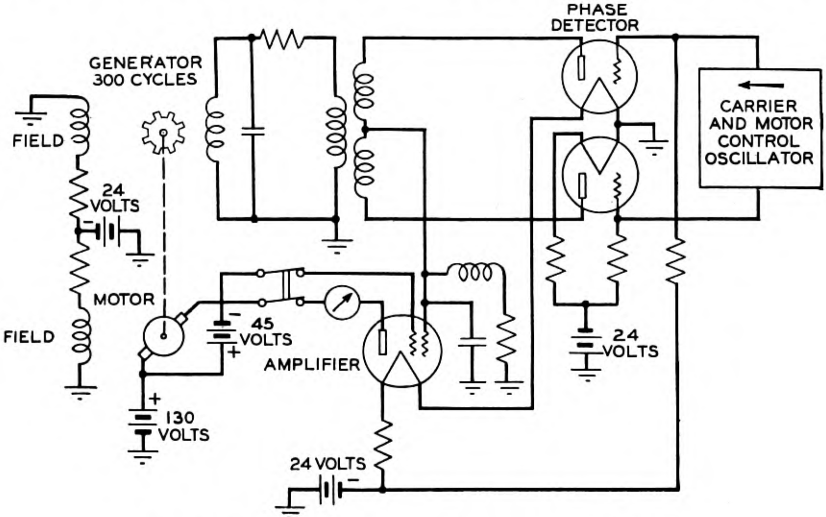

Fig. 5—Telephotograph machine motor control circuit.

These tubes act as a phase detector and vary the input voltage across an amplifier which supplies the total armature current of the motor. Armature rather than field control is employed to obtain faster and more complete regulation. The capacitor across the terminals of the generator armature, tuning the circuit to a frequency slightly in excess of 300 cycles per second, and the coupling impedance between phase detector and amplifier acting as a low-pass filter, assist in preventing hunting of the motor.

Clutch

Connection between driving motor and picture machine is made through a positive action clutch electrically operated. This clutch gradually applies the driving torque to the picture machine during the starting interval. It operates on the principle of storing energy in a coiled spring during the first part of the starting interval while the velocity of the machine is increasing and then allowing this energy to be released gradually by an escapement mechanism while the parts of the clutch are assuming their normal operating position. The time interval required for complete operation of the clutch corresponds to three or four revolutions of the picture cylinder but variations in the length of this interval do not affect the accuracy of phasing, inasmuch as the latter is determined by the time of operation of the clutch trip magnet and each receiving machine may be readily adjusted to compensate for this variation.

Circuit arrangements associated with the clutch of the receiving machine permit its operation from a starting signal received over the line from the transmitting machine.

Sending Optical System

The optical system of the sending machine is arranged to direct a scanning light beam upon the surface of the picture which is mounted on a cylinder. This scanning beam, attenuated by reflection from the various shades of the picture, is directed to a photoelectric cell. The illumination is obtained from a small incandescent lamp and is interrupted in passing through the aperture of a double ribbon light valve. This double ribbon light valve, which is a modification of a type previously described,[4] is actuated by the picture carrier frequency, 2,400 cycles per second, and its interruption of the scanning light beam permits the use of a-c. methods of amplification of the photoelectric currents. Aside from its general simplicity and freedom from the usual difficulties experienced with rotating light choppers, this type of interrupter readily effects a sinusoidal variation in illumination.

It is obvious that, since the illumination incident upon the picture is pulsating at the carrier frequency, the currents present in the output of the photoelectric cell will consist of the picture signal currents and the carrier frequency modulated by these currents, the picture itself acting as a simple direct product modulator.

Filters and Delay Equalizer

The application of single-side-band transmission methods to the present telephotograph equipment has resulted in the design of electrical filters of rather unusual phase shift and attenuation-frequency characteristics. It has previously been pointed out in connection with a discussion of telegraph transmission theory [5] that three conditions should be fulfilled for single-side-band transmission:

1. The system should have a linear phase shift-frequency characteristic.
2. The sluggish in-phase component of the signal resulting from a displacement of the carrier from the middle of the transmitted band should be eliminated.
3. The received quadrature component resulting from the loss of the component of the side band suppressed, equal in magnitude but opposite in sign, should also be eliminated.

The first two conditions are met by the careful design of a delay equalizer network and a special filter giving a suitably shaped admittance characteristic for the system. This characteristic exhibits a type of symmetry about the carrier frequency which would result in a superposition of the regions adjacent to the carrier if rotated about this point. Consequently the attenuation of the filters and associated delay equalizer should be 6 decibels greater at the carrier frequency than at the middle of the band of the transmitted frequencies, in addition to meeting the requirement of a linear phase shift-frequency characteristic. Over-all attenuation and phase shift-frequency characteristics of the filters and equalizer of the sending and receiving equipment of the present design are shown in Fig. 6.

In regard to the third condition for single-side-band transmission, experiments have shown that the effect in received pictures of the quadrature component is not of practical importance in the present equipment. The quadrature component is determined essentially by the slope of the signal envelope which is in turn restricted by the equivalent transfer admittance characteristic [6] of the scanning aperture, and by the slope of the filter characteristic to meet condition 2.

Receiving Optical System

The receiving optical system of the new telephotograph equipment is similar in its general aspects to that employed in the earlier Bell System equipment. Illumination from an incandescent lamp is directed to the receiving photographic emulsion through the aperture of a single ribbon light valve. The latter, however, is operated by the rectified picture currents instead of by the modulated picture carrier current as used in the earlier equipment. This change results in very simple yet efficient optical arrangements for receiving a variable density constant line width picture with no apparent structure. The aperture of the light valve, which is uniformly illuminated by the incandescent lamp, is adjusted so that the width of its image on the receiving emulsion is 0.01 inch. The height of the aperture, which determines the exposure, is regulated by the instantaneous position of the light valve ribbon and this is proportional to the received picture

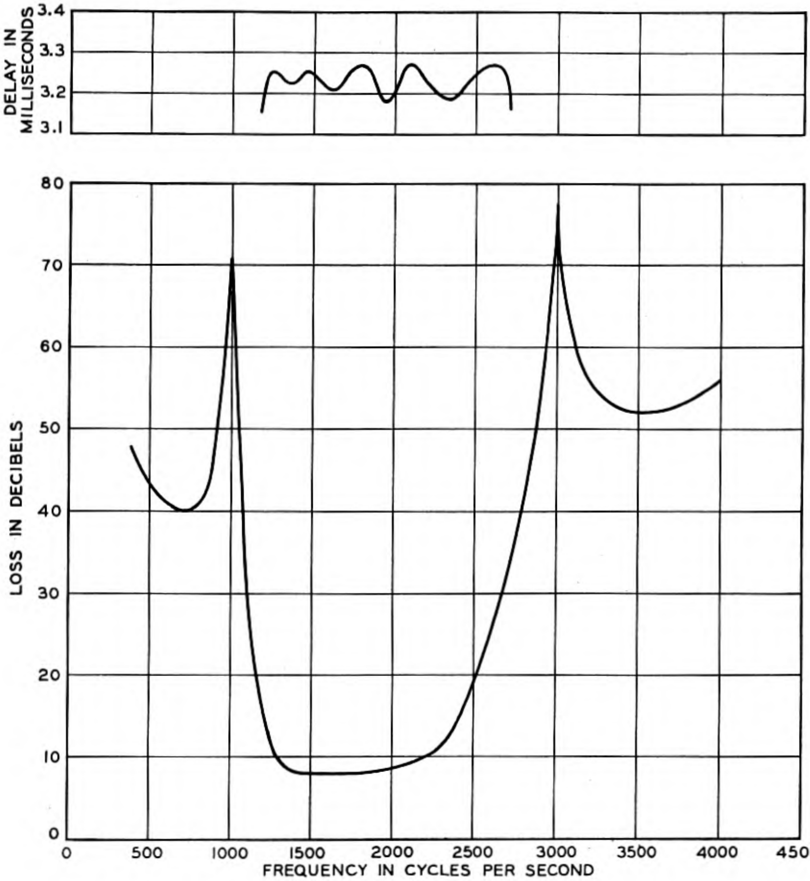

Fig. 6—Over-all characteristics of filters and delay equalizer.

currents. A uniformly illuminated field is obtained at the light valve aperture with a minimum loss of light by using a sphero-cylindrical condenser lens which focuses the diameter of the helical filament of the lamp without imaging individual turns of the helix at the plane of the aperture. Imaging of the lamp filament with the usual type of spherical condenser lens would result in non-uniformity of illumination not only because interstices between individual turns of the helix have an intrinsic brilliancy much greater than the outer surface of the filament but also because of the angular variation of the masking effect of the turns of the helix upon the illumination emerging from the interstices. The ribbon of the light valve is tuned mechanically to resonance at 1,200 cycles per second, and is shunted by an equalizer [7] consisting of inductance, capacitance, and resistance in series which is tuned to the resonant frequency of the ribbon, thereby producing a flat response-frequency characteristic over the useful range of signal frequencies.

Carrier and Motor Control Oscillator

This portion of the equipment furnishes the carrier frequency of 2,400 cycles per second and the motor control frequency of 300 cycles per second accurate to within a few parts in a million. The arrangements used consist of a 300-cycle tuning fork within a temperature regulated container, a vacuum tube amplifier circuit designed to provide controlled regenerative operation of the fork, and a vacuum tube harmonic generator for supplying the carrier frequency.

Although this general method for obtaining a constant frequency is old and has been described previously,[8, 9, 10] in view of its importance in the operation of the present telephotograph equipment it may be of interest to indicate briefly the specific arrangements employed.

The tuning fork is made of a heat treated nickel chromium steel alloy to obtain a small frequency-temperature coefficient and is mounted in a thermostatically controlled metal cylinder wound with a heating coil over which are wrapped alternate layers of copper and felt to provide attenuation of heat transfer.[11] The pick-up and drive coils associated with the fork are connected to the vacuum tube amplifier circuit as shown in Fig. 7. The frequency of a fork is affected by a number of factors including temperature, amplitude of vibration, and aging of the material. Since it is impracticable to maintain constant all of the factors involved, it is necessary to provide means for occasional adjustment to meet the requirements for constancy desired in picture transmission. In the present equipment the temperature of the fork is maintained within ± 0.1 degree of its nominal value of 50 degrees centigrade; two adjustments are provided for changing the amplitude, one of which varies the grid potential of a vacuum tube which acts to limit the current supplied the driving coil, and the other, a variable capacitor in the circuit containing the

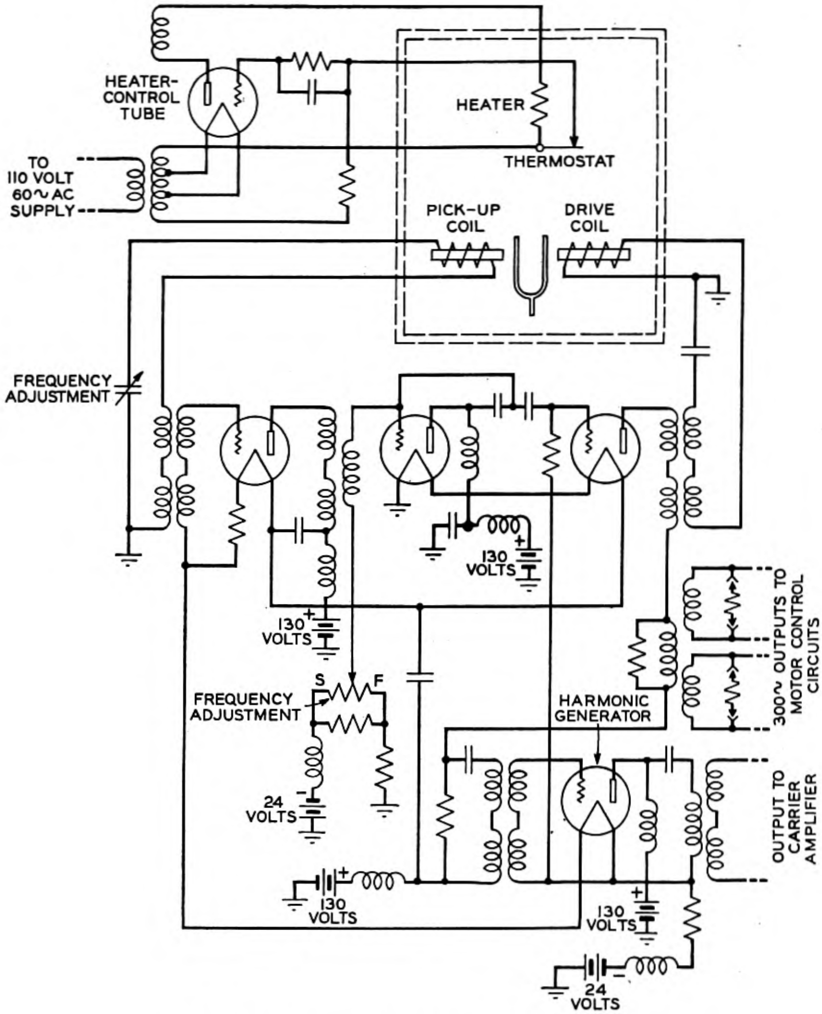

Fig. 7—Carrier and motor control oscillator.

pick-up coil varies the phase relation between the currents in the drive and pick-up coils. Three outputs are provided from the oscillator, two for the sending and receiving motor control circuits and the third for the carrier frequency supplied the sending light valve.

All of these outputs terminate in high impedance circuits and have no appreciable reaction upon the constancy of operation of the fork.

LINE FACILITIES USED WITH THE NEW TELEPHOTOGRAPH EQUIPMENT

Requirements for the communication channel used in the transmission of pictures are obviously dependent upon the characteristics of the telephotograph equipment employed and the amount of degradation resulting from transmission which can be tolerated. In general, telephotograph equipment capable of recording the transmitted signals with a degree of fidelity of the order required for good pictures may also record certain extraneous disturbances in the transmission channel which will appear as blemishes on the received picture. The more important of these disturbances are abrupt variations in line net loss, delay distortion, certain types of noise, echoes, and crosstalk. With the exception of delay distortion which is more pronounced for the new equipment because of its higher speed of transmission, the requirements relating to the other disturbances are comparable to those applying to the earlier Bell System equipment. Experience over a period of years with the earlier equipment indicated that selected telephone circuits, specially conditioned to adapt them to picture transmission and established as a regular network, could be relied upon to give consistently good results. This general procedure has been followed in establishing wire networks for use with the new telephotograph equipment and unretouched reproductions of typical news pictures received over such circuits are shown in Figs. 8 and 11.

The circuit facilities employed with the new telephotograph system are 4-wire H-44-25 side circuits in cable [12] where available and elsewhere 2-wire open-wire [13] side and physical circuits.* These facilities are provided with delay equalizer networks for the frequency range from 1,200 to 2,600 cycles per second and precautions are taken to minimize various transmission disturbances. Means are provided, controlled by the sending telephotograph equipment, to prevent operation of the transmission regulating network relays on cable circuits during the transmission of a picture, and to obtain one-way transmission over 2-wire circuits. A wire network of nearly 8,000 miles established as outlined above and connecting 26 stations of the new telephotograph equipment has been in operation for more than a year, giving reliable and technically satisfactory service.

* A side circuit is a physical circuit that is used for one of the paths of a phantom circuit; the notation H-44-25 indicates a loading coil spacing of 6,000 feet, inductance of physical or side circuit loading coils 44 millihenries, and inductance of phantom circuit loading coils 25 millihenries.

Transmission Requirements

The effects of extraneous line disturbances may or may not be particularly objectionable in a specific case, depending upon their magnitude and form and also on the nature and use of the received picture. Furthermore, the predominance of the recorded disturbance may also be affected by normal variations in the adjustments of the telephotograph equipment. It is not practicable, therefore, to establish precise limits for the transmission requirements. The following values are mentioned as illustrative of the order of magnitude for some of the more important requirements applying to circuits used with the new telephotograph equipment, and which experience has shown will give generally satisfactory results.

(*a*) *Line Net Loss*

Abrupt variations in line net loss of 0.2 decibel or greater usually will produce a noticeable change in shade of the received picture. However, a gradual variation in net loss occurring over a period of minutes is less objectionable and in many instances a change of as much as 2 or 3 decibels during a transmission can be tolerated.

(*b*) *Noise*

Noise of a single-frequency type is likely to be recorded in the received picture as an objectionable *moiré* pattern if the difference between the maximum signal and interference energy is less than 50 decibels. However, if the interference energy is distributed over a relatively wide frequency band an energy difference of about 35 decibels usually can be tolerated.

(*c*) *Delay Distortion*

Delay distortion introduced by the circuit, if of sufficient magnitude, may produce multiple outlines along the edges of objects or lines in the received picture and result in a loss or general masking of picture detail. In order that this effect may be inappreciable in pictures received with the new telephotograph equipment it is desirable that the maximum deviation in envelope delay throughout the useful frequency band (1,200 to 2,600 cycles per second) be less than ± 300 microseconds.

D–C. Control Circuit

Sudden small variations in line net loss are normal on toll cable circuits in the United States as the result of the stepping of the regulating network relays, which, under control of a pilot wire regulator, compensate for the effect of temperature changes on the attenuation

Fig. 8—Telephotograph received at New York from Miami. Size of received picture was 7¾ by 13½ inches. Reproduced by courtesy of the Associated Press.

Fig. 9—Telephotograph. Received $4\frac{1}{4}$ by $6\frac{1}{8}$ inches with 100 lines per inch. Reproduced by courtesy of the Associated Press.

Fig. 10—Telephotograph. Received 10 by 14½ inches with 100 lines per inch. Reproduced by courtesy of the Associated Press.

Fig. 11—Telephotograph received at New York from Baltimore. Size of received picture was $8\frac{3}{4}$ by $14\frac{1}{2}$ inches. Reproduced by courtesy of the Associated Press.

of the circuit. Since these sudden variations in net loss produce noticeable changes in shade of the received picture, means similar to those employed with the earlier Bell System telephotograph equipment have been made available to prevent these relays from operating while a picture is being transmitted. Simple types of control units actuated by signals transmitted over a control circuit are connected to each regulating repeater associated with the picture circuit. This control circuit consists of two one-way d-c. channels obtained by compositing the telephotograph circuit and extended to each telephotograph station over simplexed loop arrangements. The control circuit is also arranged to perform other functions such as effecting one-way transmission of the 2-wire circuits during a picture transmission. The operation of the control circuit normally is performed automatically at the sending telephotograph station.

Inasmuch as the transmission requirements for this control circuit are very lenient compared with those for telegraphy, it has been possible to employ simple types of d-c. repeaters as illustrated in Fig. 12. A signal from the subscriber's sending equipment operates the receiving relay of the station repeater, which in turn places a ground on the *M* lead and thus transmits the signal to all line repeaters which may be associated with this junction. Only one direction of operation at a time is possible so that when a sending telephotograph station takes control at the beginning of a picture transmission the control circuit is operated and remains in this condition until released automatically at the end of the transmission. A slow release circuit is provided in the d-c. repeater used at regulating network points on the cable circuits and also in another type of repeater, not shown but used on open-wire circuits to obviate false operation of the repeaters as the result of interruptions of less than two seconds duration.

Delay Equalization

Delay equalization [14] of telephotograph circuits is not new, but was applied in 1925–26 to certain medium-heavy loaded toll cable circuits between New York and Boston which were used in the early Bell System telephotograph service. (This application was discussed in reference 14 relative to delay distortion, and examples of transmitted printed matter were reproduced.) However, because of the increased speed of transmission of the new telephotograph equipment and the demand for longer circuits for picture transmission it has been necessary to make further application of delay equalization to some of the more common types of circuits used for this purpose.

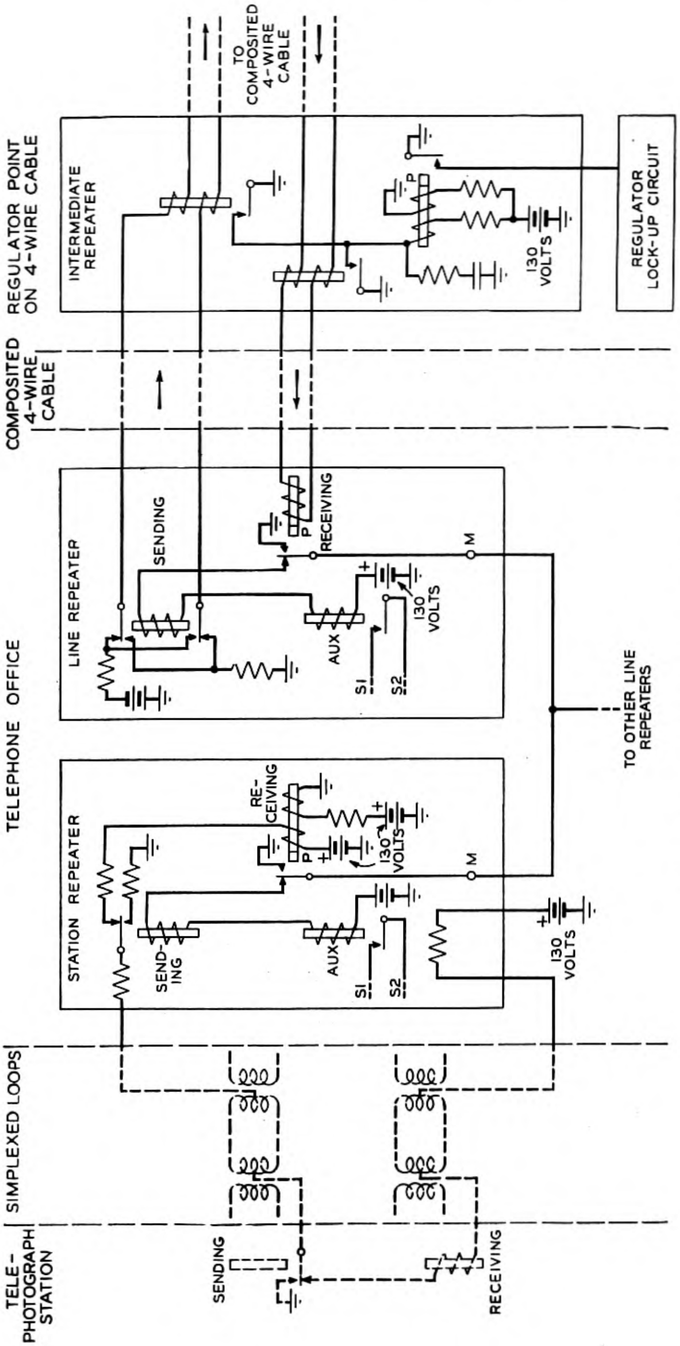

Fig. 12—D-c. control circuit repeaters.

Delay distortion in H-44-25 cable circuits, which is largely the result of the loading, has been compensated by delay networks consisting of a basic unit correcting for 150 miles of composited 19-gauge side circuit, adjustable in 10-mile steps, and a "mop-up" unit of four sections for more complete compensation. A balanced lattice type of structure was used in the design of these equalizers. Figure 13 illustrates the application of equalizer units to cable circuits and shows the delay characteristics before and after equalization. Similar types of delay equalizers have been applied to open-wire circuits, in which case it is the equipment located at the repeater stations rather than the line itself which is responsible for delay distortion. The delay equalizers are normally located at terminal and bridging points on the telephotograph network and at some intermediate points such as junctions of open-wire and cable circuits.

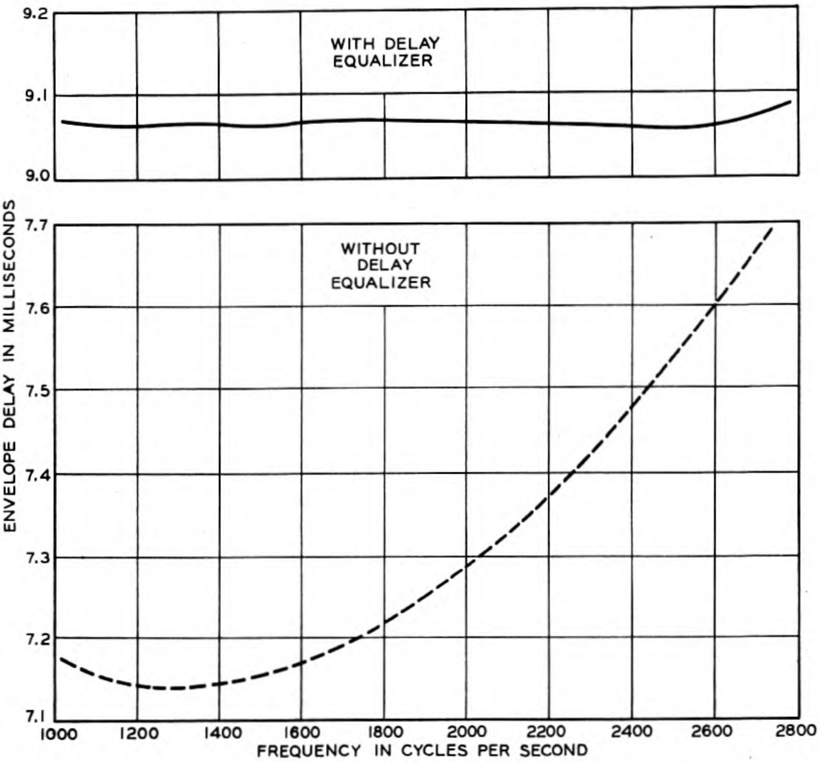

Fig. 13—Delay characteristic of 135 miles of H–44 repeatered and composited side circuit before and after equalization.

TELEPHOTOGRAPH NETWORKS

One of the obvious advantages of network operation of telephotograph stations is that it offers a means for rapid and simultaneous distribution of facsimile information and pictures to a large number of receiving points. This method of operation appears to be particularly advantageous for use by the large news-picture gathering and distributing agencies giving a nation-wide service. Such network operation of a number of telephotograph stations presents additional requirements, not mentioned in the preceding paragraphs, which may be of general interest.

Requirements encountered in connecting a large number of sending and receiving stations were that any sending station should be able to transmit a picture simultaneously to all receiving stations, and that any one station could be selected as the transmitting point, establishing a new direction of transmission with a minimum loss of time. The situation has been met by permanently bridging each telephotograph station, consisting of separate sending and receiving equipment, to the wire network on a 4-wire basis using separate sending and receiving station loops and performing automatically such switching operations as may be involved in altering the direction of transmission.

Typical arrangements which have been used at a bridging point on a telephotograph network are illustrated in Fig. 14. Suppose, for example, that the telephotograph station at this point wishes to transmit a picture to the network. Operation of a key associated with the subscriber's telephotograph transmitting equipment sends out a d-c. signal over the simplexed loop to the control circuit station repeater at the local telephone office. Since this repeater is multipled with the d-c. repeaters associated with each of the telephotograph circuits connected at this point, the signal is transmitted over the entire network and the switching operations performed to place the circuits in condition to send a picture from this point. The d-c. repeaters at the local telephone office also cause short circuits to be applied to the incoming transmission paths which are connected to the bridging networks, thus preventing the temporarily inactive parts of the circuit from contributing possible disturbances to the outgoing paths being used. This figure also indicates the switching operations performed on the 4-wire terminating set. At the conclusion of the transmission the d-c. control circuit is automatically released by the transmitting machine and the circuits returned to the initial two-way condition permitting any station on the network to seize control of the circuits for picture transmission. Signal lamps are provided at all d-c. repeater points and are actuated by the d-c. control circuit to indicate when pictures are being transmitted over the network and also the direction of transmission.

The problems involved at junction points in connecting a number of circuits, particularly of the 4-wire type, have been simplified through the use of a new form of bridging network. Although this situation could be met by employing unilateral devices such as vacuum tube amplifiers, it was found that comparable results could be obtained simply and at less expense with interconnected resistance type pads. Two designs of such networks, essentially alike except for the values of attenuation provided, are in use, one for cable and the other for open-wire circuits. These bridges are used not only at junctions of

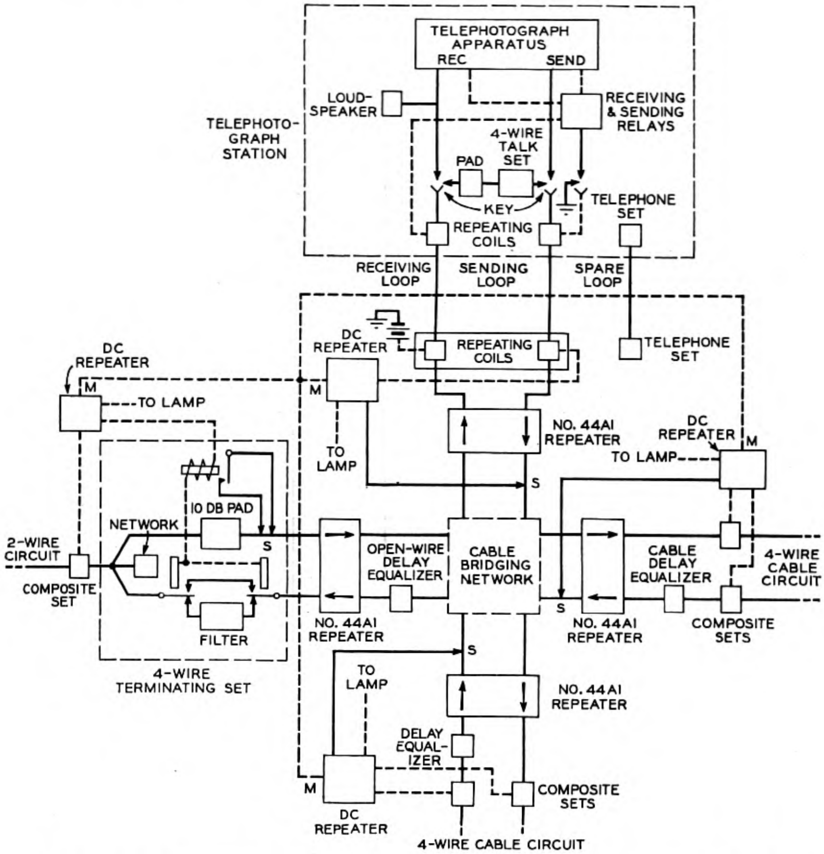

Fig. 14—Schematic diagram of arrangements at a typical bridging point.

circuits forming the network but also at all points at which telephotograph stations are connected.

A single line schematic of the type of bridging network employed is shown in Fig. 15 (upper left), and a more complete representation of a portion of the network used on cable circuits is shown in Fig. 15 (lower right). Current entering the bridge, for example at the West input, traverses three direct paths of equal attenuation and leaves at East output and branch A and branch B outputs. There are, of course, numerous indirect paths between the West input and each of the bridge outputs; for example, there are two parallel paths to each output. Each of these two paths has three times the attenuation of a direct path and the current through it is 180 degrees out of phase with that through a direct path because of the reversals shown in the wiring. However, the aggregate of all of the indirect paths does not appreciably alter the loss between input and output of this bridge as calculated by neglecting them. It may be noted that the two directions of transmission for the same circuit are connected by six parallel paths each of which has three times the attenuation of a direct path between an input and output of the bridge. The currents through three

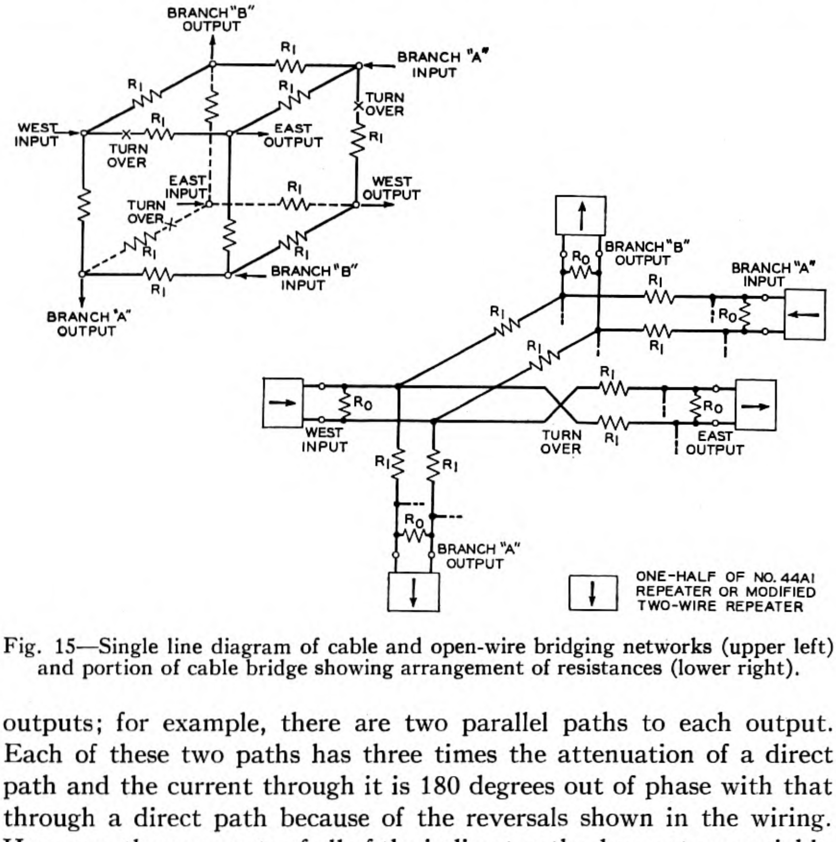

Fig. 15—Single line diagram of cable and open-wire bridging networks (upper left) and portion of cable bridge showing arrangement of resistances (lower right).

of these paths are 180 degrees out of phase with the currents in the others, and hence would result in infinite attenuation of the echo were it not for small unbalance currents. Measured crosstalk losses for the echo paths in excess of 70 decibels have been obtained for these bridging networks manufactured with ordinary tolerances.

Certain auxiliary features may also be incorporated in telephotograph networks to assist in their operation and perform other related functions. For example, telephotograph methods are not efficient in their present form for the rapid exchange of operating instructions; therefore telephone facilities may be associated with a telephotograph network for use by the customer in coordinating the operation of this system. Arrangements may be used whereby such voice communication may be carried on over the telephotograph circuit between picture transmissions, and loud speakers may be bridged on the circuit for monitoring purposes.

ACKNOWLEDGMENT

The attainment of this objective in telephotograph development and the establishment of the present leased wire network has engaged the initiative and resourcefulness of several score of individuals at the Bell Telephone Laboratories, Inc., the Western Electric Company, and the American Telephone and Telegraph Company. In reviewing the advances which have been made, the practical limitation of space has made it impossible to discuss in greater detail the various phases of the work and to render individual recognition to all who have contributed to the solution of the problems involved. Among those most intimately concerned and through whose efforts the many details have been worked out and correlated are W. A. Phelps and P. Mertz of the Bell Telephone Laboratories, Inc., and I. E. Lattimer of the American Telephone and Telegraph Company.

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Equivalent Networks of Negative-Grid Vacuum Tubes at Ultra-High Frequencies

By F. B. LLEWELLYN

It is shown that the equivalent network of negative-grid vacuum tubes both at low and at very high frequencies may be expressed in many different forms. Several are suggested and the advantages of two are described in some detail. One of these is closely analogous to that which is in general use at low frequencies and requires only the addition of resistive components in series both with the cathode-grid and the grid-plate capacitances to make it applicable to frequencies where transit time effects are appreciable though moderately small. The resistance in series with the grid-plate capacitance is negative in sign. In this form of the equivalent network, electron transit times do not introduce a phase angle into the amplification factor.

The paper is divided into two parts. The first gives a descriptive interpretation of the results while the second contains the mathematical manipulations.

PART I

WHEN the equivalent network of a vacuum tube is mentioned, it brings to the mind of practically every radio engineer a certain combination of resistances and capacitances together with an internal μ-generator which has become familiar through years of use. Historically, this equivalent network did not spring into being full grown like Athena from the forehead of Zeus, but was the result of a slow and painful development. The beginnings of the equivalent network of negative-grid vacuum tubes are to be found in the work of Nichols where it was pointed out that a non-linear resistance is the equivalent of a fixed resistance in series with a generator. As a second step, Van der Bijl's relation states that the plate current in a vacuum tube is a function of the plate voltage plus a constant times the grid voltage. This constant was identified with our well-known amplification factor μ and it was an easy step thereafter to combine the Van der Bijl and Nichols relations and represent the vacuum tube by the equivalent network shown in Fig. 1.

Here the cathode is located at C and the plate at P. Between them the vacuum tube is represented by the internal plate resistance r_p acting in series with the fictitious generator $\mu_0 V_g$. This equivalent naturally represents conditions between the cathode and plate at very low frequencies only, because the low-frequency impedance between the grid element and the other electrodes is so high that it can safely be disregarded. Such an equivalent network was satisfactory only so

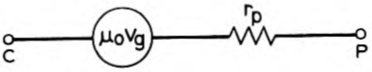

FIGURE 1

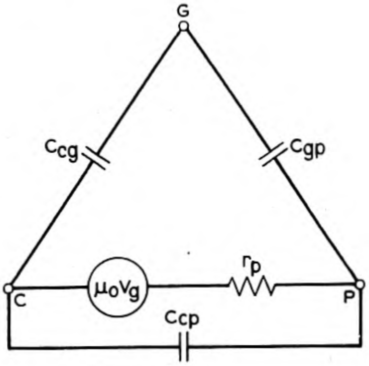

FIGURE 2

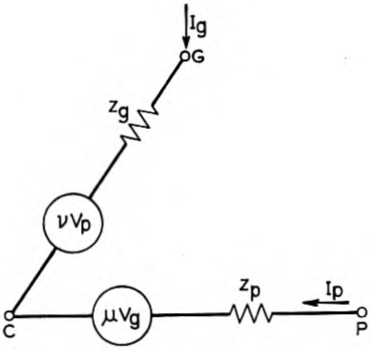

FIGURE 3

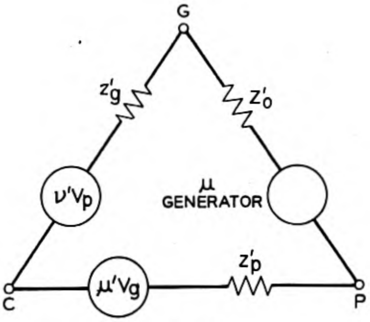

FIGURE 4

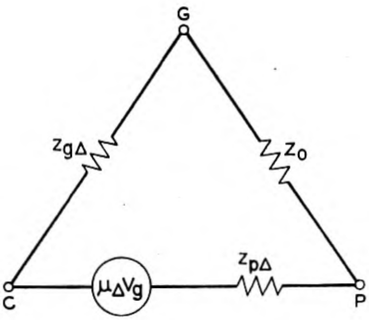

FIGURE 5

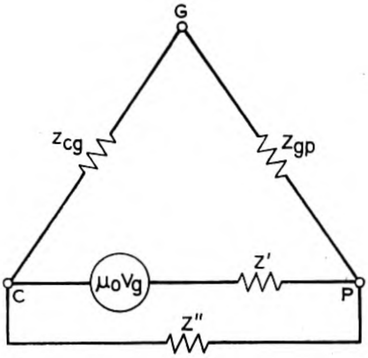

FIGURE 6

Figs. 1–6—Equivalent vacuum tube networks.

long as frequencies were low enough to allow this last approximation to remain valid. With the advent of higher frequencies it became evident that the internal tube capacitances played an important role in the operation of the device. The lengths to which early workers went to include the capacitance effects are illustrated by the complicated formulas on page 207 of Van der Bijl's well-known book on Thermionic Vacuum Tubes. Further study, however, showed that the complication could be overcome largely by a modification of the simple network of Fig. 1 so that capacitances are introduced between all three elements of the vacuum tube. The result is Fig. 2 which has been adequate in the past for all purposes. In comparatively recent years, however, increasing frequencies demand that a further revision be made.

The necessity for revision first became evident with the discovery that the impedance measured between grid and cathode when a very large condenser was placed between plate and cathode, showed an important resistive component at very high frequencies so that the simple combination of Fig. 2 involving only capacitances for the grid-cathode and grid-plate impedance was no longer valid. The tools for effecting the modification of Fig. 2 are available [1] and already have been employed to a certain extent. These tools are the result of a theoretical analysis of the motions of electrons within vacuum tubes and started from fundamentals. With the reservation that they apply strictly to planar rather than cylindrical tube structures, the results should therefore require little further modification for some time to come.

The first result of theoretical analysis was to produce an equivalent network which, on the face of it, resembles Fig. 2 only remotely, but which can be shown [1] to be exactly equivalent at low frequencies. This generalized theoretical network is shown in Fig. 3. It may be seen to consist of two branches only, which exist respectively between cathode and grid and between cathode and plate. Both branches contain internal generators and, in general, the impedance in neither branch is a pure resistance but depends upon a number of factors including the time required by electrons in traversing the vacuum tube. The immediate query which results from inspection of Fig. 3 is "What has become of the grid-plate path?" The answer to this lies in the definition of current in Fig. 3 so that the cathode-plate path is included in the network as shown. This definition of current is merely the generalized one adopted years ago by Maxwell when he

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[1] F. B. Llewellyn, "Operation of Ultra-High-Frequency Vacuum Tubes," *Bell Sys. Tech. Jour.*, Vol. XIV, pp. 632–665, October 1935.

realized that a change in electric intensity produces precisely the same effect in a circuit as does an actual motion of charge. In Fig. 3 this means that the current entering the branch between cathode and grid for example consists not only of ordinary conduction current but also of displacement current so that the current in the cathode-grid mesh is the whole current flowing into the grid element. Likewise, the current in the cathode-plate mesh is the whole current flowing into the plate element of the tube.

In Part II straightforward transformation of the equations representing Fig. 3 shows that it may be represented just as well by an infinite number of other equivalent networks. Naturally our aim is to choose the form of network which is easily adaptable to the greatest number of practical applications, and the one that suggests itself primarily for this purpose contains the fewest number of internal generators. A second consideration in the choice of the best equivalent network is that the network should resemble the familiar delta equivalent of Fig. 2 as closely as may be, so that results based on that figure may be interpreted readily in terms of the more general network.

Fig. 2 is actually a modified form of a delta network. The most general delta would be the one shown in Fig. 4 which consists of three series branches, each containing an internal generator in series with an impedance. When the mathematical transformations from Fig. 3 to Fig. 4 are carried through, it is found that a proper choice of definitions for the various impedances reduces Fig. 4 to the network shown in Fig. 5. Here only one internal generator remains, but that generator acts in series with the internal plate impedance of the tube so that Fig. 5 does not quite conform to the popular network where a capacitance is assumed to shunt the internal generator by acting directly between plate and cathode. However, again it can be shown that Fig. 5 may be transformed to Fig. 6 and by a proper choice of the two impedances Z' and Z'', the internal generator reduces merely to our familiar low-frequency amplification factor multiplied by the grid potential variation.

Thus Fig. 6 with the associated definitions of impedance represents the generalized form of the equivalent network of negative-grid vacuum tubes and is valid until the velocity of the electrons approaches that of light or until the distance between elements of the vacuum tube becomes comparable to the free-space wave-length of any ultra-high frequency considered. The expressions for the various impedances in Fig. 6 are naturally long and complicated. However, at frequencies where the effects of transit time of the electrons are only moderately important, the complication reduces enormously and we have Fig. 7.

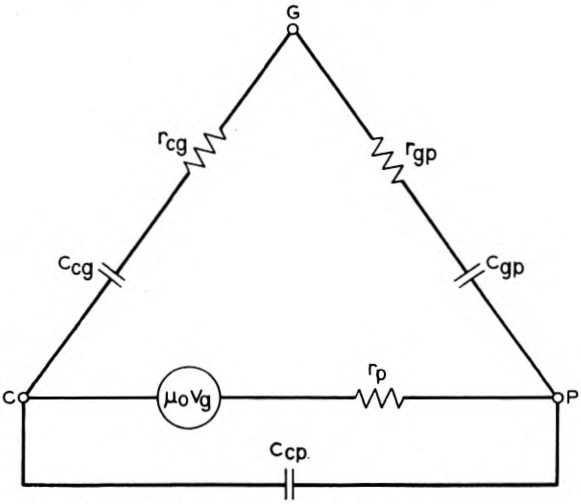

Fig. 7—General equivalent of vacuum tubes valid for moderately high frequencies.

This is nearly identical with the well-known equivalent which was shown in Fig. 2, and the modification consists only of the addition of series resistors in the internal cathode-grid and cathode-plate paths. A phase angle in the amplification factor is avoided by the resistances in series with the capacitances.[2] The impedance in series with the μ-generator is the well-known internal plate resistance as given by the slope of the static characteristic of the tube. The capacitances are likewise those we have used all along at lower frequencies, but the mathematics now enables their dielectric constants to be computed. Fig. 7 will be found to be valid at any of the frequencies for which negative-grid tubes are now contemplated for commercial application, including those where the transit angle is about half a radian.

Much has been said and written of late years about the active grid loss.[1, 3, 4, 5] In Fig. 7 this would be determined by placing a large

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[2] It can be shown that measurements published in a paper "Phase Angle of Vacuum Tube Transconductance," F. B. Llewellyn, *Proc. I. R. E.*, Vol. 22, August 1934, may be interpreted as well in terms of the phase angle of the grid-plate impedance. If the phase angle of the latter is α, and the angle measured for the paper is θ, then

$$\sin^2 \alpha = 1 - \frac{C'}{C} + \frac{\sin \phi \cos \phi \tan \theta}{\omega^2 LC},$$

where C' is the grid-plate capacitance of the cold tube, C of the hot tube, and ϕ is the phase angle of the inductive branch of the tuned circuit used in the experiments.

[1] Loc. cit.

[3] J. G. Chaffee, "The Determination of Dielectric Properties at Very High Frequencies," *Proc. I. R. E.*, Vol. 22, August 1934.

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[5] D. O. North, "Analysis of the Effects of Space Charge on Grid Impedance," *Proc. I. R. E.*, Vol. 24, January 1936.

condenser between cathode and plate and measuring the input impedance. The result of computing the impedance from Fig. 7 agrees with that formerly presented[1] as, of course, it should, since both results were derived from the same fundamental analysis. This agreement, however, is mentioned by way of giving an example which checks the algebraic manipulations which were employed in arriving at Fig. 7.

Finally the values of the various elements in Fig. 7 are summarized in Table I. The formulas naturally are very long and their greatest use probably is in describing the simple circuit of Fig. 7 where the values of the various elements can actually be measured or computed as convenient.

TABLE I

REFERRING TO FIG. 7

Let C_{cg}', C_{gp}', C_{cp}' be capacitances of cold tube,

$$y = \frac{x_p}{x_c} \text{ be ratio of } g - p \text{ to } c - g \text{ spacing,}$$

$$h = \frac{T_p}{T_c} \text{ be ratio of } g - p \text{ to } c - g \text{ transit time,}$$

$$M = \frac{4}{3}(y - h^3)(1 + h) - 2h^2 + h^4,$$

$$N = (y - h^3)(9 + 44h + 45h^2) - 51h^2 - 105h^3 - 27h^4 + 27h^5,$$

$$C_{cp} = \frac{4}{3} C_{cp}' \left[\frac{1 + y + \dfrac{\mu_0 y}{y - h^3}}{1 + M + \mu_0} \right] \left[1 + h - \frac{3}{2} \frac{h^2}{y - h^3} \right],$$

$$r_p = \text{same as at low frequencies,}$$

$$C_{cg} = C_{cg}' \left[\frac{1 + y + \dfrac{\mu_0 y}{y - h^3}}{1 + M + \mu_0} \right] \frac{M}{y},$$

$$r_{cg} = \left[\frac{r_p(y - h^3)}{45\mu_0(1 + M + \mu_0)M^2} \right] \left[(\mu_0 + 1)N + \frac{45\mu_0 h^4}{(y - h^3)} M \right],$$

$$C_{gp} = C_{gp}' \left[\frac{1 + y + \dfrac{\mu_0 y}{y - h^3}}{1 + M + \mu_0} \right],$$

$$r_{gp} = - \left[\frac{r_p(y - h^3)}{45\mu_0(1 + M + \mu_0)} \right] \left[N - \frac{45\mu_0 h^4}{y - h^3} \right].$$

The easiest way to visualize the equations is to apply them to a special case which can be approached experimentally; namely the condition that the time required by electrons in moving from grid to plate is much shorter than the cathode-grid time. When this is the case, the formulas reduce to those shown in Table II. These show

TABLE II

REFERRING TO FIG. 7

Let C_{cg}', C_{gp}', C_{cp}' be capacitances of cold tube,

$$y = \frac{x_p}{x_c} = \text{ratio of } g - p \text{ to } c - g \text{ spacing},$$

$$h = \frac{T_p}{T_c} = \text{ratio of } g - p \text{ to } c - g \text{ transit time}.$$

Then when $h \rightarrow 0$:

$$C_{cp} = \frac{4}{3} C_{cp}' \left[\frac{1 + y + \mu_0}{1 + \frac{4}{3} y + \mu_0} \right],$$

$$r_p = \text{same as at low frequencies},$$

$$C_{cg} = \frac{4}{3} C_{cg}' \left[\frac{1 + y + \mu_0}{1 + \frac{4}{3} y + \mu_0} \right],$$

$$r_{cg} = \frac{9}{80} \frac{r_p}{\mu_0} \left[\frac{1 + \mu_0}{1 + \frac{4}{3} y + \mu_0} \right],$$

$$C_{gp} = C_{gp}' \left[\frac{1 + y + \mu_0}{1 + \frac{4}{3} y + \mu_0} \right],$$

$$r_{gp} = -\frac{1}{5} \frac{r_p}{\mu_0} \left[\frac{y^2}{1 + \frac{4}{3} y + \mu_0} \right].$$

that the cathode-plate and cathode-grid capacitances have dielectric constants greater than unity, but that the grid-plate capacitance has a dielectric constant less than unity. The cathode-grid resistance is positive, and the grid-plate resistance is negative.

The outstanding result of this investigation of the network representing the negative-grid tube is the demonstration of the slight modification required in our conventional network to make it accurate even in the ultra-high-frequency range. The amplification factor is the familiar low-frequency one, and at moderately high frequencies, the only alteration needed in the conventional diagram is the addition of two small but very important resistances, one in the cathode-grid path and one in the grid-plate path, where the resistance in the latter path is negative in sign.

PART II

In a recent paper,[1] general equations have been derived which describe the behavior of vacuum tubes at ultra-high frequencies. In

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[1] Loc. cit.

the case of negative-grid triodes and referred to Fig. 8, these equations take the general form:

$$V_p + \mu V_g = I_p z_p, \tag{1}$$

$$V_g - \nu V_p = I_g z_g, \tag{2}$$

where

$$\left.\begin{aligned}\mu &= \frac{(Z_1 + Z_2) - (Z_2 + Z_3 + Z_c)}{Z_c + Z_g},\\ z_p &= \frac{(Z_2 + Z_3 + Z_c)Z_g + (Z_1 + Z_2)Z_c}{Z_c + Z_g},\\ \nu &= \frac{Z_c}{Z_2 + Z_3 + Z_c},\\ z_g &= \frac{(Z_2 + Z_3 + Z_c)Z_g + (Z_1 + Z_2)Z_c}{Z_2 + Z_3 + Z_c},\end{aligned}\right\} \tag{3}$$

and the Z's may be expressed in terms of the tube geometry and d-c. current or voltage by means of equations (80)–(84) in the reference. In these relations the currents, I_p and I_g, denote the total current reaching plate or grid, respectively, and hence include both the conduction current carried by the electrons themselves and the displacement current arising from the change of electric force. With this meaning of current, (1) and (2) contain the complete description of the performance of the tube, and separate consideration of the grid-plate current, usual in low-frequency methods, is unnecessary because that current is already included in I_p in (1).

The equivalent network represented by (1) and (2) is shown in Fig. 8. Only two currents are involved, I_p and I_g, but, also two internal generators, μV_g and νV_p, are required. For some purposes, an equivalent network which corresponds more nearly with the usual low-frequency delta arrangement is desirable. Such an equivalent may be obtained from (1) and (2) in conjunction with Fig. 9 which shows the relation between currents in a delta network and those of Fig. 8. In Fig. 9 no restriction is yet placed upon the three currents, I_1, I_2 and I_3, so that in general they all may be allowed to include both conduction and displacement components. From Fig. 9

$$I_p = I_1 + I_2, \tag{4}$$

$$I_g = I_3 - I_2. \tag{5}$$

Here are two equations expressing the three unknowns, I_1, I_2 and I_3, in terms of the currents I_p and I_g, which are assumed to be known.

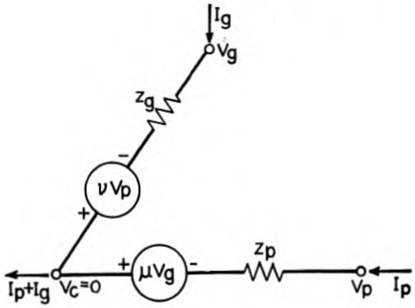

FIGURE 8

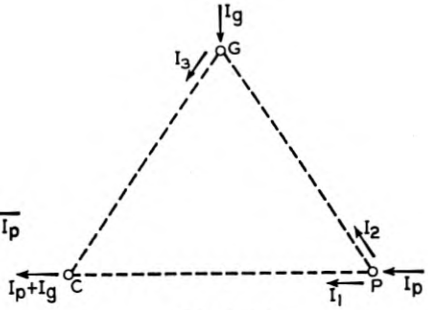

FIGURE 9

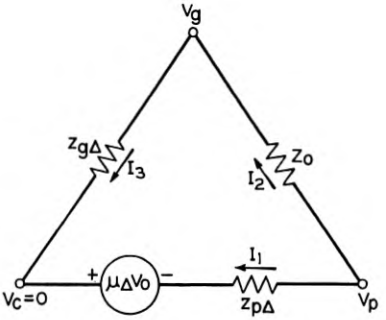

FIGURE 10

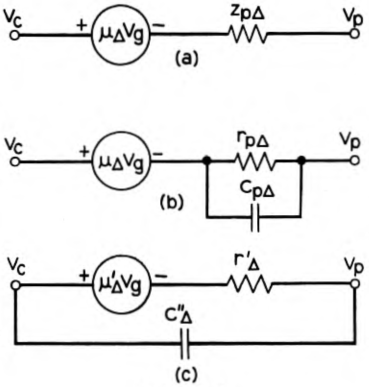

FIGURE 11

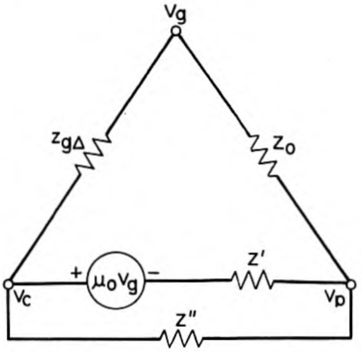

FIGURE 12

Fig. 8—Equivalent network of vacuum tube from equations (1) and (2).
Fig. 9—Relation between currents of delta network and those of Fig. 8.
Fig. 10—Equivalent delta network.
Fig. 11—Equivalent cathode-plate paths.
Fig. 12—Modified delta network equivalent to Fig. 10.

It is obvious that a third equation is needed before the unknowns can be found. But (4) and (5) express all the relationships that are necessary for the equivalence of Figs. 8 and 9. It follows that we are at liberty to impose arbitrarily a third restriction upon the currents in Fig. 9.

The choice of this restriction may be made in many ways, each resulting in a different network, all equivalent however to Fig. 8 and to the vacuum tube. For example, I_1 might be defined as consisting of conduction current only. Such a choice might seem at first sight to be a desirable one because it corresponds rather well with the conception of the cathode-plate path as being determined by electron movement at low frequencies. If it were adopted, however, the generalized network resulting would be found to be quite awkward, involving two or more internal generators and complex amplification factors.

The simplest network would be the one involving the fewest number of internal generators, and the restriction adopted in the following analysis for the currents in Fig. 9 is made with that object in view. The result, as will be shown, corresponds at low frequencies with the usual concept of the tube, and gives a high-frequency network where neither the cathode-grid nor the grid-plate paths contain internal generators.

The restriction which accomplishes this result is obtained by placing

$$V_p - V_g = I_2 Z_0, \tag{6}$$

so that (4), (5) and (6) determine the internal currents, I_1, I_2 and I_3, in terms of the external currents I_p and I_g, and the, as yet, arbitrary impedance Z_0.

The solution of (1) to (6) yields

$$V_p + V_g \left[\frac{\mu + \dfrac{z_p}{Z_0}}{1 - \dfrac{z_p}{Z_0}} \right] = I_1 \left[\frac{z_p}{1 - \dfrac{z_p}{Z_0}} \right], \tag{7}$$

$$V_g - V_p \left[\frac{\nu - \dfrac{z_g}{Z_0}}{1 - \dfrac{z_g}{Z_0}} \right] = I_3 \left[\frac{z_g}{1 - \dfrac{z_g}{Z_0}} \right]. \tag{8}$$

The choice of (6) eliminates the internal generator from the grid-plate path, but still leaves the impedance Z_0 to be defined at will. From (8) it is evident that the internal generator is eliminated from the cathode-grid path if Z_0 is chosen so that

$$\nu = z_g/Z_0. \tag{9}$$

The impedance Z_0 will accordingly be taken to be defined by (9). The result is that the fundamental equations for Fig. 9 become:

$$V_p + \mu_\Delta V_g = I_1 z_{p\Delta}, \tag{10}$$

$$V_g = I_3 z_{g\Delta}, \tag{11}$$

$$V_p - V_g = I_2 Z_0, \tag{12}$$

where

$$\left.\begin{aligned} \mu_\Delta &= \frac{Z_1 - Z_3}{Z_g}, \\ z_{p\Delta} &= Z_2 + Z_3 + Z_c + \frac{Z_c}{Z_g}(Z_1 + Z_2), \\ z_{g\Delta} &= Z_g + \frac{Z_c(Z_1 + Z_2 + Z_g)}{Z_2 + Z_3}, \\ Z_0 &= Z_1 + Z_2 + \frac{Z_g}{Z_c}(Z_2 + Z_3 + Z_c). \end{aligned}\right\} \tag{13}$$

The various definitions in (13) are seen to be slightly simpler than those in (3) but it must be remembered that the delta-network involves one more current-path than the original ultra-high-frequency network, Fig. 1. The delta corresponding to (10)–(13) is shown in Fig. 10.

At frequencies only moderately high, all of the impedances in Fig. 10 are composed of combinations of ordinary resistances and capacitances. Both $z_{g\Delta}$ and Z_0 consist of a condenser and resistor in series.

In the case of the cathode-plate path in Fig. 10, the equivalent combination of resistance and capacitance may be represented by either a parallel combination of resistance and capacitance which is in series with the μ-generator, as shown at (*b*) in Fig. 11, or a μ-generator of different value acting in series with a resistance, and the whole being shunted by a capacitance connected between cathode and plate, as shown at (*c*) in Fig. 11. The latter picture is in more strict accord with conventional practice but the mathematical relationships involve a choice of definitions for μ. It is found by trial that this choice may be made so that μ in Fig. 12 is defined merely as μ_0, its low-frequency value, and is independent of frequency. When this definition is adopted, we have in general the equivalent network of Fig. 12 which holds at high as well as low frequencies. This differs from Fig. 10 in the cathode-plate path only, and Z', Z'' are defined as follows, where μ_0

is the low-frequency amplification factor:

$$Z' = \mu_0 \left[\frac{(Z_2 + Z_3 + Z_c)Z_g + (Z_1 + Z_2)Z_c}{Z_1 - Z_3} \right], \tag{14}$$

$$Z'' = \mu_0 \left[\frac{(Z_2 + Z_3 + Z_c)Z_g + (Z_1 + Z_2)Z_c}{\mu_0 Z_g - Z_1 + Z_3} \right]. \tag{15}$$

Figure 7 is the form taken by Fig. 12 for moderately high frequencies where transit angle effects are just beginning to become noticeable.

In general, the formulas for the impedances in the delta network are just as long as in the original network of Fig. 8. The delta may, however, have an advantage in view of its wide use in low-frequency work, and of the fact that the amplification factor for the delta can be expressed without involving the transit angle, and hence does not contain a phase shift.

Forces of Oblique Winds on Telephone Wires

By J. A. CARR

In aerial line design it is advantageous to know the effect of oblique winds as well as cross winds. This paper gives the results of wind tunnel tests made on 0.104-inch and 0.165-inch diameter wires for each 10° angle of obliquity between 0° and 90° using wind velocities of 30 to 90 miles per hour in steps of 10 miles per hour. These results are then analyzed to determine (1) their compliance with the law of dynamic similarity and (2) the magnitudes of the various wind components. From these analyzed results an expression is developed for the force of oblique winds in terms of the component normal to the wires.

IN connection with studies of wire arrangements on open-wire lines [1] which Bell Telephone Laboratories have had under way for some time, it became necessary to evaluate the resistance of wires to winds. The method of evaluating the force of winds normal to the wires has been studied by many investigators and there is a considerable amount of data in the literature on this subject. The contrary was found to be true in the case of oblique winds or those not normal to the line. This latter case has been described briefly in the records of a test made in the National Physical Laboratories [2] (British) on a 0.375-inch diameter smooth wire at a wind velocity of 40 feet per second (27.3 m.p.h.) with the wire at angles to the wind ranging from 0° to 90° (normal) in steps of 10° and also in the records of M. Gustave Eiffel,[3] who made a similar test at somewhat higher velocities. Since the wires we are concerned with range from about 0.1 to 0.2 of an inch in diameter and the wind velocity ranges from about 30 to 90 miles per hour, it appeared desirable to conduct a series of wind tunnel tests that would extend these data and more fully meet our requirements. Tests along these lines were arranged with the Guggenheim School of Aeronautics at New York University.[4] Subsequently, a series of tests was made in the New York University wind tunnel on 0.104-inch and 0.165-inch diameter smooth copper wires for each 10° angle ranging from 0° to 90° using wind velocities of 30 to 90 miles per hour in steps

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[1] "Motion of Telephone Wires in Wind," D. A. Quarles, *Bell System Technical Journal*, April 1930.

[2] Reports and Memoranda No. 307, January 1917, entitled "Tests on Smooth and Stranded Wires Inclined to the Wind Direction," by E. F. Relf and C. H. Powell.

[3] "Nouvelles Recherches sur La Résistance De L'Air et L'Aviation," book by M. G. Eiffel.

[4] These tests were conducted by Professor Alexander Klemin and his associates.

of 10 miles per hour. The readings so obtained are here studied and analyzed.

The wire set-up used in the wind tunnel is shown in the accompanying picture (Fig. 1) and is similar to that used by Eiffel.[3] It comprised a five-foot frame of 0.375-inch diameter steel in which five wires of either the 0.104-inch or 0.165-inch size were mounted. A spacing of 2.75 inches was used between the centers of the wires. The frame of wires was installed in the approximate center of the nine-foot section of the tunnel with the shorter axis of the frame in a horizontal plane and perpendicular to the axis of the tunnel. This arrangement was convenient for connections to the weighing mechanism and permitted the frame to be rotated about its short axis.

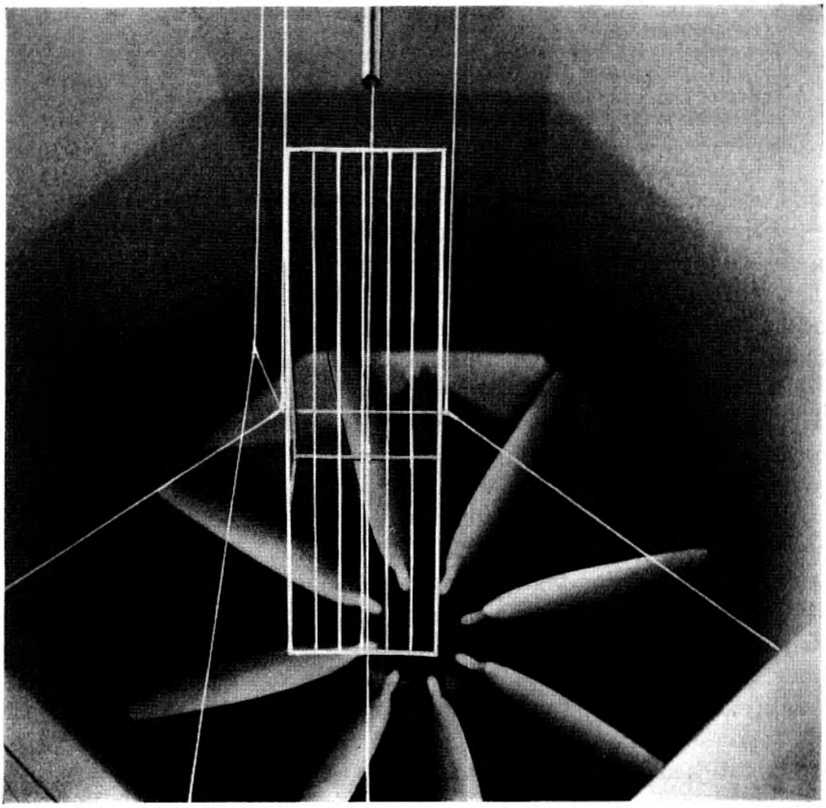

Fig. 1—Wind tunnel setup.

During each step in the test the horizontal (drag) and vertical (lift) forces on the frame of wires were measured at least three times. At the completion of the series of tests on each size of wire the test lengths were cut out of the frame leaving about 2 inches of each wire at each end and the series of tests repeated so that the net drag and net lift figures could be determined. The purpose of leaving the short lengths of wire at each end was to provide a correction for the interference effects introduced at the ends of the wires. This practice was probably effective as it will be shown later that, where comparisons could be made, the results obtained in these tests agree satisfactorily with those previously obtained. This is true even though the frame comprised a fairly large proportion of the total resistance especially when the angle between the wind and the frame was small. The case when the wind and wires were parallel (tangential) has been omitted from the results because of the large proportion of the total resistance as well as the interference offered by the frame and because of its relative unimportance to this study.

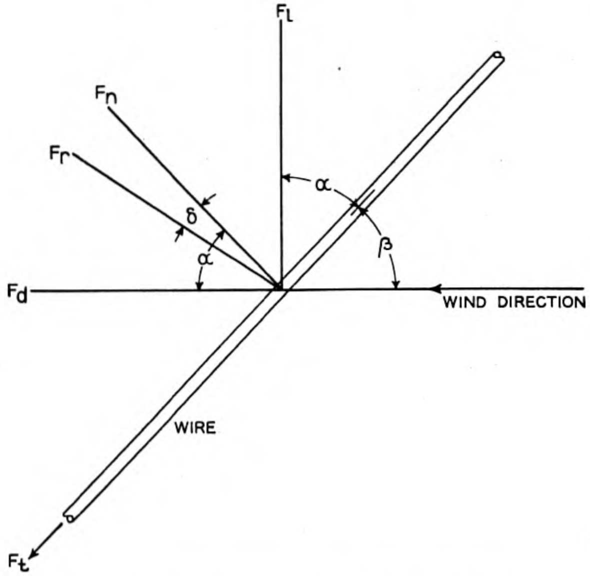

Fig. 2—Force components of wind on wires.

F_d = Force along the direction of wind—drag.
F_l = Force across the direction of wind—lift.
F_r = Resultant force.
F_n = Force normal to the wire.
F_t = Force along the wire—tangential.

Figure 2 shows the forces on the wires to which consideration has been given here. From this diagram it can be seen that with values of the net drag (F_d) and lift (F_l), the normal force (F_n), the resultant force (F_r), the tangential force (F_t) and the angle (δ) between the resultant and normal forces can be determined through the following relationships:

$$F_n = F_l \sin \alpha + F_d \cos \alpha = F_r \cos \delta, \tag{1}$$

$$F_r = \sqrt{F_d^2 + F_l^2} = \sqrt{F_n^2 + F_t^2}, \tag{2}$$

$$F_t = F_d \sin \alpha - F_l \cos \alpha = F_r \sin \delta, \tag{3}$$

$$\delta = \alpha - \text{arc tan} \frac{F_l}{F_d} = \text{arc tan} \frac{F_t}{F_n} \cdot \tag{4}$$

The only term in these equations which is not defined above is α. This is the angle between the wire and the normal to the wind or between the wind and the normal to the wire.

The data determined through the use of these relationships are given in the accompanying Tables I (0.104-inch wire) and II (0.165-inch wire). The forces in these tables are given in terms of pounds per foot of wire.

TABLE I

0.104-INCH DIAMETER WIRE

V	α	F_n	F_t	F_r	δ	$\frac{F_n}{(\cos \alpha)^2}$	K	
30	0	0.0194	0.000000	0.0194	0	0.0194	0.000207	
	10	0.0189	0.000431	0.0190	1.3	0.0195	0.000208	
	20	0.0177	0.001203	0.0178	3.9	0.0200	0.000214	
	30	0.0149	0.001940	0.0151	7.3	0.0198	0.000212	
	40	0.0119	0.002540	0.0122	12.0	0.0203	0.000217	
	50	0.0083	0.002650	0.0086	18.0	0.0200	0.000215	
	60	0.0047	0.002230	0.0052	25.4	0.0188	0.000201	$\bar{X} = 0.000211$
	70	0.0021	0.001560	0.0026	36.7	0.0180	0.000194	
	80	0.0008	0.001050	0.0013	53.9	0.0265	0.000283	$\bar{X} = 0.000217$
	90	—	—	—	90.0	—	—	
40	0	0.0358	0.000000	0.0358	0	0.0358	0.000215	
	10	0.0334	0.000570	0.0334	1.1	0.0345	0.000207	
	20	0.0300	0.001520	0.0301	2.9	0.0341	0.000204	
	30	0.0252	0.002510	0.0254	5.6	0.0336	0.000202	
	40	0.0199	0.003150	0.0202	9.0	0.0340	0.000204	
	50	0.0144	0.003360	0.0149	13.0	0.0350	0.000210	
	60	0.0087	0.003180	0.0093	20.0	0.0348	0.000210	$\bar{X} = 0.000207$
	70	0.0041	0.002450	0.0049	30.0	0.0350	0.000211	
	80	0.0014	0.001450	0.0020	46.1	0.0467	0.000279	$\bar{X} = 0.000216$
	90	—	—	—	90.0	—	—	

TABLE I—(*Continued*)

V	α	F_n	F_t	F_r	δ	$\frac{F_n}{(\cos\alpha)^2}$	K	
50	0	0.0578	0.000000	0.0578	0	0.0578	0.000222	
	10	0.0550	0.000863	0.0551	0.9	0.0570	0.000218	
	20	0.0494	0.001980	0.0495	2.3	0.0565	0.000215	
	30	0.0412	0.003170	0.0414	4.4	0.0550	0.000211	
	40	0.0323	0.003970	0.0325	7.0	0.0550	0.000207	
	50	0.0233	0.004350	0.0235	10.7	0.0565	0.000217	
	60	0.0147	0.004010	0.0153	15.2	0.0586	0.000226	$\bar{X}=0.000217$
	70	0.0070	0.003000	0.0076	23.2	0.0600	0.000230	
	80	0.0026	0.002120	0.0033	40.0	0.0867	0.000339	$\bar{X}=0.000232$
	90	—	—	—	90.0	—	—	
60	0	0.0854	0.000000	0.0854	0	0.0854	0.000228	
	10	0.0787	0.000950	0.0788	0.7	0.0812	0.000217	
	20	0.0708	0.002350	0.0710	1.9	0.0801	0.000214	
	30	0.0592	0.003730	0.0595	3.6	0.0790	0.000210	
	40	0.0475	0.004960	0.0476	6.0	0.0811	0.000211	
	50	0.0346	0.005340	0.0352	8.7	0.0842	0.000224	
	60	0.0221	0.005100	0.0230	12.8	0.0884	0.000236	$\bar{X}=0.000220$
	70	0.0117	0.004270	0.0125	20.0	0.1000	0.000267	
	80	0.0039	0.002710	0.0047	35.3	0.1288	0.000345	$\bar{X}=0.000239$
	90	—	—	—	90.0	—	—	
70	0	0.1183	0.000000	0.1183	0	0.1183	0.000233	
	10	0.1130	0.001180	0.1131	0.6	0.1170	0.000225	
	20	0.1020	0.002860	0.1023	1.6	0.1155	0.000227	
	30	0.0873	0.004950	0.0873	3.2	0.1164	0.000228	
	40	0.0650	0.005800	0.0652	5.1	0.1105	0.000217	
	50	0.0467	0.006070	0.0472	7.4	0.1130	0.000222	
	60	0.0298	0.005900	0.0306	11.1	0.1190	0.000234	$\bar{X}=0.000227$
	70	0.0159	0.004930	0.0168	17.0	0.1370	0.000267	
	80	0.0063	0.003730	0.0072	31.3	0.2100	0.000410	$\bar{X}=0.000251$
	90	—	—	—	90.0	—	—	
80	0	0.1570	0.000000	0.1570	0	0.1570	0.000236	
	10	0.1510	0.001310	0.1510	0.5	0.1565	0.000232	
	20	0.1390	0.003400	0.1392	1.4	0.1575	0.000237	
	30	0.1213	0.005720	0.1215	2.7	0.1617	0.000243	
	40	0.0918	0.007050	0.0920	4.4	0.1560	0.000235	
	50	0.0615	0.007100	0.0618	6.6	0.1485	0.000223	
	60	0.0385	0.006600	0.0392	9.7	0.1540	0.000231	$\bar{X}=0.000234$
	70	0.0208	0.005600	0.0216	15.0	0.1778	0.000267	
	80	0.0086	0.004500	0.0096	28.0	0.2865	0.000428	$\bar{X}=0.000259$
	90	—	—	—	90.0	—	—	
90	0	0.2010	0.000000	0.2010	0	0.2010	0.000239	
	10	0.1921	0.001670	0.1921	0.5	0.1990	0.000235	
	20	0.1788	0.003740	0.1790	1.2	0.2020	0.000240	
	30	0.1546	0.005950	0.1550	2.2	0.2060	0.000245	
	40	0.1190	0.008220	0.1192	3.9	0.2030	0.000241	
	50	0.0840	0.008500	0.0844	5.8	0.2040	0.000241	
	60	0.0514	0.007930	0.0518	8.8	0.2060	0.000168	$\bar{X}=0.000230$
	70	0.0281	0.006530	0.0288	13.1	0.2400	0.000285	
	80	0.0127	0.005500	0.0136	24.0	0.4210	0.000500	$\bar{X}=0.000266$
	90	—	—	—	90.0	—	—	

TABLE II

0.165-INCH DIAMETER WIRE

V	α	F_n	F_t	F_r	δ	$\frac{F_n}{(\cos \alpha)^2}$	K	
30	0	0.0328	0.000000	0.0328	0	0.0328	0.000221	
	10	0.0319	0.000559	0.0319	1.0	0.0329	0.000222	
	20	0.0287	0.001153	0.0287	2.3	0.0325	0.000219	
	30	0.0243	0.001710	0.0245	4.0	0.0324	0.000218	
	40	0.0187	0.002158	0.0188	6.6	0.0319	0.000215	
	50	0.0133	0.002450	0.0136	10.4	0.0322	0.000217	
	60	0.0074	0.002540	0.0078	19.0	0.0296	0.000199	$\bar{X} = 0.000216$
	70	0.0032	0.001900	0.0037	30.8	0.0276	0.000184	
	80	0.0010	0.001330	0.0018	47.7	0.0331	0.000223	$\bar{X} = 0.000213$
	90	—	—	—	90.0	—	—	
40	0	0.0606	0.000000	0.0606	0	0.0606	0.000230	
	10	0.0570	0.000800	0.0570	0.8	0.0580	0.000223	
	20	0.0508	0.001600	0.0508	1.8	0.0575	0.000218	
	30	0.0427	0.002235	0.0428	3.0	0.0570	0.000216	
	40	0.0342	0.002990	0.0343	5.0	0.0582	0.000221	
	50	0.0240	0.003880	0.0243	9.2	0.0580	0.000220	
	60	0.0155	0.004150	0.0160	15.0	0.0620	0.000235	$\bar{X} = 0.000223$
	70	0.0074	0.003500	0.0082	25.2	0.0637	0.000240	
	80	0.0023	0.001840	0.0029	39.2	0.0760	0.000289	$\bar{X} = 0.000232$
	90	—	—	—	90.0	—	—	
50	0	0.0969	0.000000	0.0969	0	0.0969	0.000235	
	10	0.0907	0.001110	0.0908	0.7	0.0940	0.000226	
	20	0.0819	0.002145	0.0820	1.5	0.0925	0.000235	
	30	0.0692	0.003260	0.0693	2.7	0.0923	0.000224	
	40	0.0562	0.004330	0.0563	4.4	0.0956	0.000232	
	50	0.0408	0.005060	0.0410	7.1	0.0986	0.000229	
	60	0.0259	0.005490	0.0265	12.0	0.1035	0.000251	$\bar{X} = 0.000233$
	70	0.0119	0.004635	0.0127	21.4	0.1025	0.000247	
	80	0.0043	0.002790	0.0049	34.0	0.1430	0.000346	$\bar{X} = 0.000247$
	90	—	—	—	90.0	—	—	
60	0	0.1425	0.000000	0.1425	0	0.1425	0.000240	
	10	0.1350	0.001420	0.1350	0.6	0.1393	0.000234	
	20	0.1250	0.002900	0.1251	1.3	0.1415	0.000238	
	30	0.1059	0.004250	0.1060	2.3	0.1410	0.000238	
	40	0.0862	0.005740	0.0866	3.8	0.1470	0.000246	
	50	0.0607	0.006680	0.0610	6.3	0.1470	0.000246	
	60	0.0372	0.006750	0.0378	10.3	0.01485	0.000251	$\bar{X} = 0.000242$
	70	0.0180	0.005960	0.0190	18.3	0.1550	0.000259	
	80	0.0071	0.003900	0.0081	29.2	0.2360	0.000398	$\bar{X} = 0.000261$
	90	—	—	—	90.0	—	—	
70	0	0.1970	0.000000	0.1970	0	0.1970	0.000244	
	10	0.1850	0.001608	0.1850	0.5	0.1908	0.000236	
	20	0.1660	0.003260	0.1660	1.1	0.1990	0.000233	
	30	0.1420	0.004960	0.1420	2.0	0.1895	0.000233	
	40	0.1180	0.006600	0.1185	3.2	0.2010	0.000249	
	50	0.0845	0.007860	0.0850	5.3	0.2050	0.000253	
	60	0.0528	0.008270	0.0535	8.9	0.2110	0.000261	$\bar{X} = 0.000244$
	70	0.0270	0.007230	0.0280	15.0	0.2310	0.000285	
	80	0.0118	0.005310	0.0129	24.3	0.3940	0.000484	$\bar{X} = 0.000275$
	90	—	—	—	90.0	—	—	

TABLE II—(*Continued*)

V	α	F_n	F_t	F_r	δ	$\frac{F_n}{(\cos\alpha)^2}$	K	
80	0	0.2610	0.000000	0.2610	0	0.2610	0.000247	
	10	0.2520	0.001765	0.2520	0.4	0.2610	0.000246	
	20	0.2330	0.003560	0.2330	0.9	0.2640	0.000250	
	30	0.2030	0.005310	0.2031	1.5	0.2710	0.000256	
	40	0.1650	0.007200	0.1652	2.5	0.2807	0.000266	
	50	0.1130	0.008310	0.1136	4.2	0.2740	0.000259	
	60	0.0722	0.008850	0.0727	7.0	0.2890	0.000273	$\bar{X}=0.000257$
	70	0.0400	0.008500	0.0409	12.0	0.3450	0.000324	
	80	0.0178	0.006860	0.0190	21.2	0.5930	0.000559	$\bar{X}=0.000298$
	90	—	—	—	90.0	—	—	
90	0	0.3335	0.000000	0.3335	0	0.3335	0.000250	
	10	0.3262	0.001920	0.3263	0.3	0.3380	0.000251	
	20	0.3050	0.003670	0.3050	0.7	0.3450	0.000258	
	30	0.2720	0.005680	0.2730	1.2	0.3627	0.000271	
	40	0.2235	0.007640	0.2240	1.9	0.3815	0.000285	
	50	0.1525	0.008950	0.1530	3.3	0.3690	0.000276	
	60	0.0982	0.009690	0.0985	5.6	0.3930	0.000294	$\bar{X}=0.000269$
	70	0.0562	0.009480	0.0570	9.6	0.4840	0.000359	
	80	0.0252	0.008430	0.0266	17.6	0.8400	0.000625	$\bar{X}=0.000319$
	90	—	—	—	90.0	—	—	

In characterizing the normal force of oblique winds, curves were plotted between the normal force (F_n) and the angle (α) between the wind and the normal to the wires. Figures 3 (0.104-inch wire) and 4 (0.165-inch wire) show these curves.

In studying the significance of these curves and the underlying data, consideration was first given to the extent to which the case of normal winds ($\cos\alpha = 1$) followed the law of dynamic similarity. This law states, in effect, that for any two geometrically similar bodies moving through a fluid,

$$F = \rho V^2 f\left(\frac{VD}{\nu}\right) \cdot \tag{5}$$

Here, F is the unit force at either of two similarly situated points on the two bodies, ρ is the fluid density, V is the velocity of the body, D a linear quantity depending on the dimensions of the body and ν is the kinematic viscosity of the fluid. The function (VD/ν) is the well known Reynolds number and the key to dynamic similarity requirements in model experiments made at ordinary velocities. The principle of dynamic similarity is satisfied as long as the Reynolds number is held constant.

In Report No. 102 [5] of the National Physical Laboratories is given an

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[5] Reports and Memoranda No. 102, November 1914, entitled "Discussion of the Results of Measurements of the Resistance of Wires" by E. F. Relf.

empirical curve of the resistance of smooth wires to winds normal to the wire. In preparing this curve equation (5) was rewritten in terms of the total force on a diameter length of wire, namely

$$F_c = \rho V^2 D^2 f\left(\frac{VD}{\nu}\right). \tag{5a}$$

Then $F_c/\rho V^2 D^2$ was plotted as the ordinate and $\log_{10}(VD/\nu)$ as the abscissa. If the normal wind data obtained in the studies of Bell Telephone Laboratories were consistent with those given in this Report No. 102[5] a plot of the points determined through the use of equation (5a) should lie reasonably close to this curve. Figure 5 gives this curve and a plot of the normal wind results. These points appear to show satisfactory agreement.

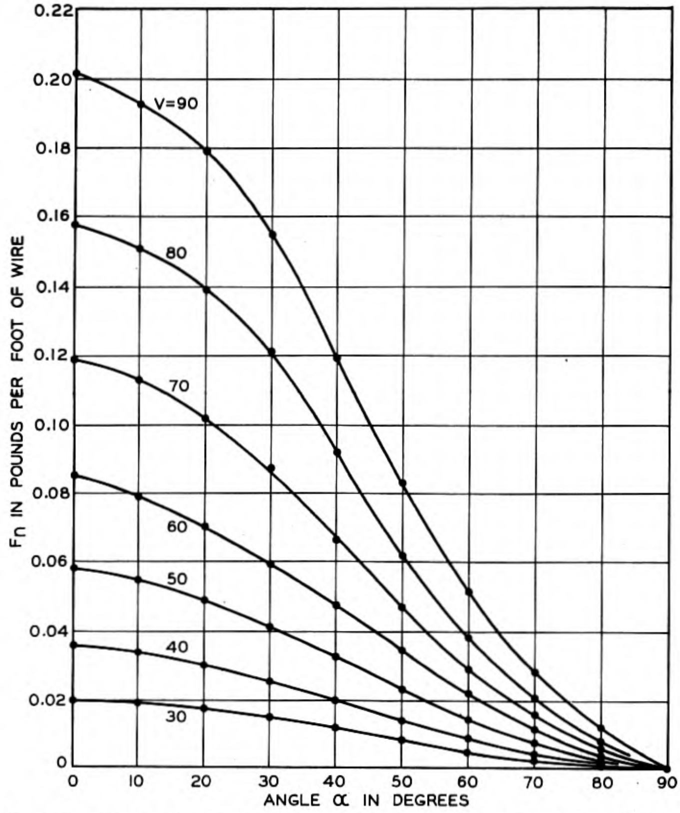

Fig. 3—Graphic relation between the force (F_n) normal to the wire and the angle (α) of wind direction from normal—0.104-inch diameter wire.

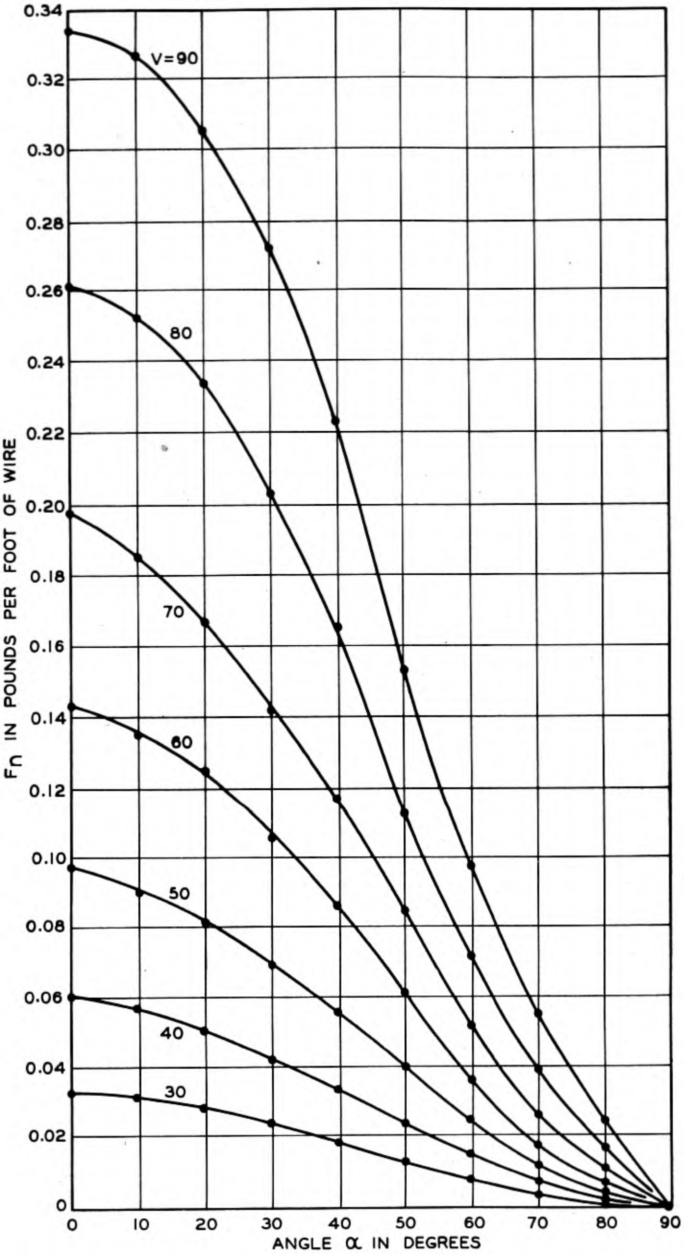

Fig. 4—Graphic relation between the force (F_n) normal to the wire and the angle (α) of wind direction from normal—0.165-inch diameter wire.

In the case of oblique winds it was found from an analysis of the data that the normal component of the force was closely proportional to $\cos^2 \alpha$ over a range of angles from 0° to 60° from normal in the case of each actual velocity and each size of wire. The values of $F_n/\cos^2 \alpha$ are given in the accompanying Tables I (0.104-inch wire) and II (0.165-inch wire). This agrees with the results obtained by Relf and Powell.[2] However, they used only one size of wire and one wind velocity in their tests. Expressing this result in terms of the normal force gives,

$$F = (K' \cos^2 \alpha)_{V,\ D=\text{constant}}.$$

This empirical expression suggested that a form of relation existed similar to that for the case of normal winds (equation 5a). Studying the results with this in mind the following equation was obtained,

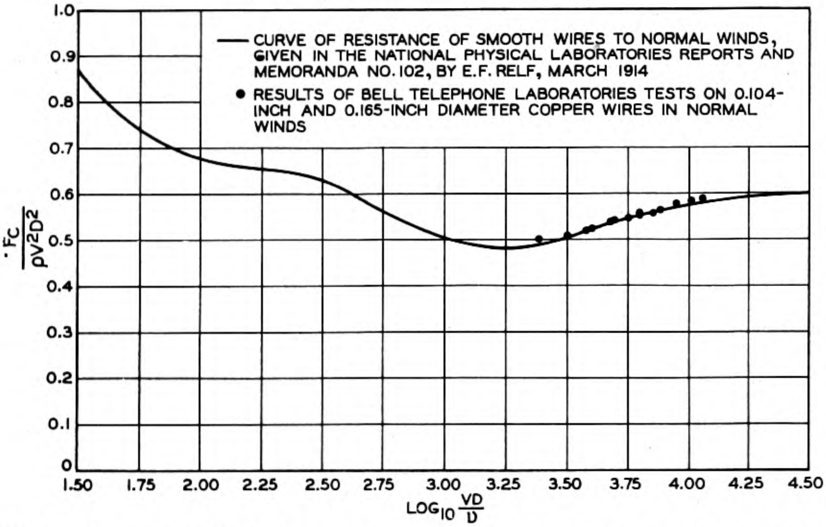

Fig. 5—Comparison of Bell Telephone Laboratories results for normal winds with the National Physical Laboratories (British) results.

$$F_c = \rho V^2 \cos^2 \alpha D^2 f\left(\frac{VD}{\nu}\right).$$

This form of expression holds over the range of Reynolds number (VD/ν) covered and, also, over the range of angles from 0° to 60° from normal.

Since ρ (air density) and ν (kinematic viscosity of air) are constant for a particular atmosphere this equation becomes

$$F_n = K(V \cos \alpha)^2 D. \tag{6}$$

Here, F_n (the normal component of wind force) is measured in pounds per foot of wire. The diameter (D) of the wire is in inches and the actual wind velocity (V) is in miles per hour. This is the familiar equation for the force of normal winds with the addition of the term, $\cos^2 \alpha$.

Values of the constant (K) found for each value of the actual velocity (V) and angle are given in Table I (0.104-inch wire) and Table II (0.165-inch wire). The arithmetical averages ($\overline{X}$) of the constants for angles up to and including 60° and for angles up to and including 80° in the case of each velocity (V) are also given in these tables. As in the case of normal winds and as indicated by equation (6) K varies with the product of velocity and wire diameter (VD).

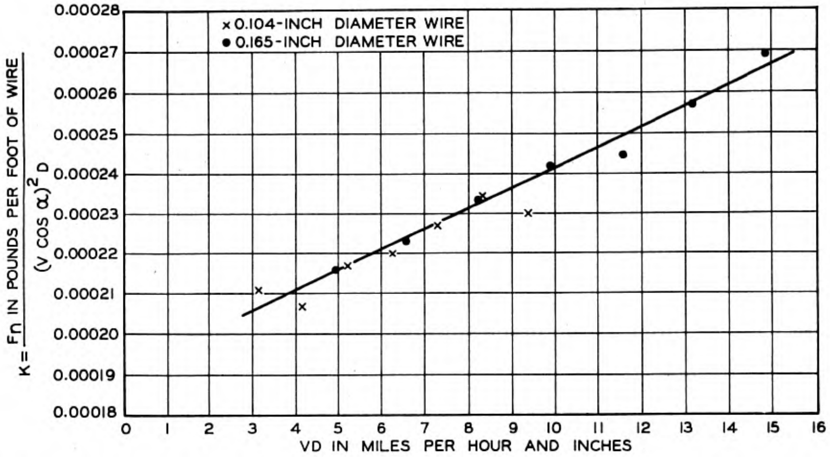

Fig. 6—Values of the Constant (K) in Equation $F_n = K(V \cos \alpha)^2 D$ for variations of the angle (α) of wind direction from normal—range, 0° to 60°, inclusive.

The relation between the average constant (K) for angles up to and including 60° and the product of velocity and wire diameter (VD) is summarized in the accompanying Fig. 6.

While our interest was centered mainly in evaluating the normal force of an oblique wind as stated above, some consideration has been given to the tangential force of an oblique wind and the variability of the angle between the normal and resultant wind forces.

The tangential forces of the oblique winds were determined by equation (3). Curves, for both sizes of wire, of tangential forces plotted against the angle α are given on Figs. 7 and 8 for all velocities (30 to 90 m.p.h.) used in the tests. The tangential force, of course, is a relatively small quantity as compared to the normal force. For this reason some inconsistencies in the data and non-uniformity in the curves might be expected, particularly when plotted to such a large scale as used in these graphs. In Reports and Memoranda of the National Physical Laboratories [2] it appeared from their results that this force was not only small but fairly constant. The results of the tests reported here indicate that while the force is low in magnitude, it varies with the obliquity and the velocity of the wind and the diameter of the wire. In the case of 0.104-inch wire it increases from zero until the angle α (between the wind and the normal to the wire) is about 50° and then decreases as this angle increases. The action is similar in the case of 0.165-inch wire except the maximum is reached when α is about 60°. Whether this shift in the maximum with the wire diameter is real, and how far it would continue, is not clear since only two diameters of wire were tested. For 0.104-inch wire the variation in the force with

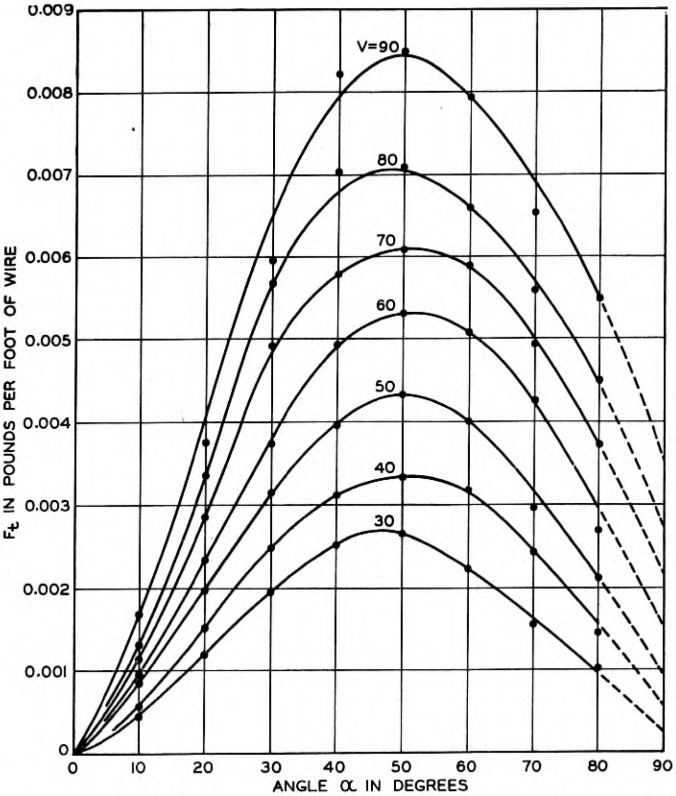

Fig. 7—Graphic relation between the wind force along the wire (tangential-F_t) and the angle (α) of wind direction from normal—0.104-inch diameter wire.

wind velocity when α equals 50° ranges from 0.00265 to 0.00850 pound per foot of wire for a range of velocities from 30 to 90 m.p.h. In the case of 0.165-inch wire and an angle (α) of 60° the variation ranges from 0.00254 to 0.00969 pound per foot of wire for the same range of velocities. As mentioned above the frame in which the wires were tested comprised such a major portion of the total resistance when the angle α approached 90° or the wind and wires were about parallel that the data for these cases were not considered reliable. In plotting the curves in Figs. 7 (0.104-inch wire) and 8 (0.165-inch wire) the tangential force for 90° was estimated and to indicate this the curves are dotted between the angles α of 80° and 90°.

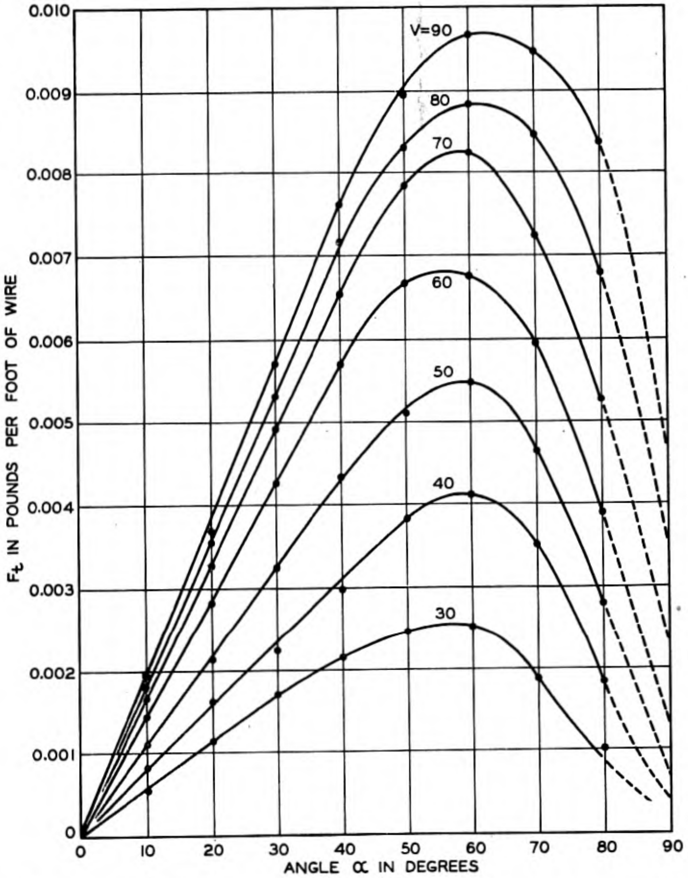

Fig. 8—Graphic relation between the wind force along the wire (tangential-F_t) and the angle (α) of wind direction from normal—0.165-inch diameter wire.

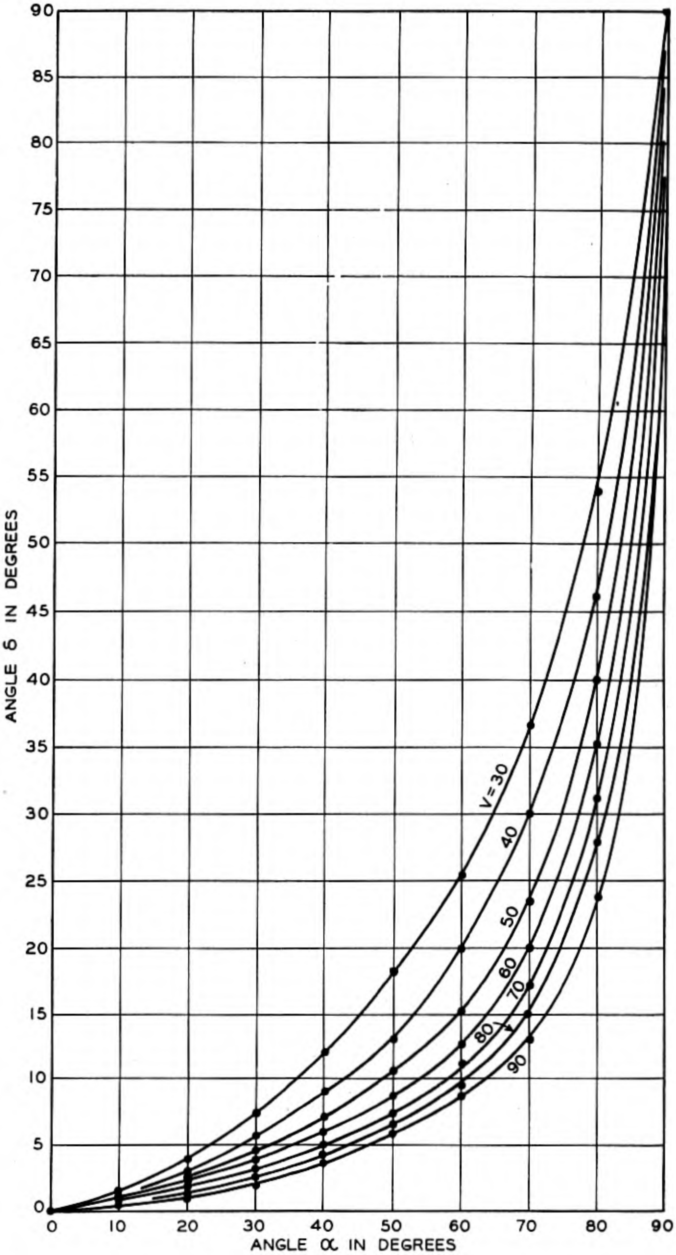

Fig. 9—Graphic relation between the angle (δ) of direction of resultant force from normal to the wire and the angle (α) of wind direction from normal—0.104-inch diameter wire.

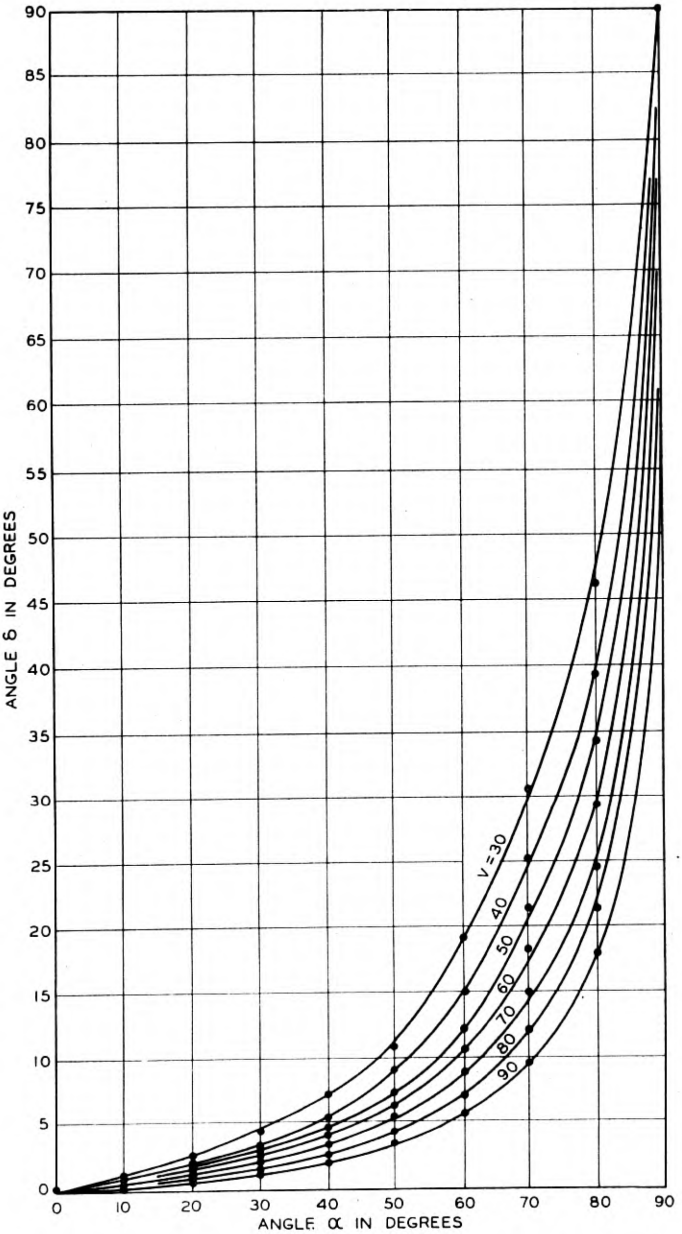

Fig. 10—Graphic relation between the angle (δ) of direction of the resultant force from normal to the wire and the angle (α) of wind direction from normal—0.165-inch diameter wire.

The angle (δ) between the resultant and normal wind forces was determined through the use of equation (4). The variations in this angle with the obliquity of the wind or the angle α are given for both sizes of wire in Figs. 9 (0.104-inch wire) and 10 (0.165-inch wire). From these graphs the following relations appear to exist in this range:

(*a*) For a given angle α the magnitude of the angle δ is inversely proportional to the product of velocity and wire diameter (VD),

$$\delta = \left(\frac{K_1}{VD}\right)_{\alpha=\text{constant}}.$$

This relation can be written

$$\delta = \left(\frac{K_2}{\left(\dfrac{VD}{\nu}\right)}\right)_{\alpha=\text{constant}},$$

where VD/ν is the familiar Reynolds number.

(*b*) For each size of wire and a given actual wind velocity the angle δ increases with the angle α. Hence, $\delta = f(\alpha,\ V,\ D)_{V,\ D=\text{constant}}$. Since the Reynolds number can also be considered constant

$$\delta = \varphi(\alpha,\ VD/\nu)_{V,\ D,\ \nu=\text{constant}}.$$

CONCLUSION

These tests indicate that the normal force on a wire due to an oblique wind is proportional to the square of the resolved component of the actual wind velocity for angles up to 60° from the normal to the wire. The expression for the normal force per unit length of wire is $F_n = K(V \cos \alpha)^2 D$, where V is the actual wind velocity and D is the wire diameter. The tangential component is relatively small as compared to the normal component.

Corrosion of Metals—II. Lead and Lead-Alloy Cable Sheathing

By R. M. BURNS

This paper discusses the corrosion of cable sheathing in the aerial and underground cable plants. Corrosion does not appear to be a primary factor affecting the life of aerial cables; failure of these cables occurs usually from intergranular embrittlement and is minimized by the use of alloy sheathing. It is shown that corrosion of cable sheathing in conduit occurs by means of the operation of small corrosion cells on the surface of the sheath or by the leakage of current from the sheath to ground. The driving force of these corrosion cells arises from some chemical inhomogeneity in either the metal or the surrounding environment. The course and the character of corrosion is determined chiefly by the influence of the constituents of the environment on the operation of these cells. These constituents may be classed as corroding or protective;—the corroding including oxygen, nitrates, alkalies and organic acids, while the protective are silicates, sulfates, carbonates, soil colloids and certain organic compounds. Cable sheathing buried directly in soils is seriously corroded by differential aeration-cell action resulting from physical contact of relatively large soil particles and metal. In general it is concluded that corrosion of cable sheathing is influenced more by the nature of the environment than by the chemical composition of the metallic material. The incidence of corrosion of cable sheathing is small owing to the maintenance of non-corrosive chemical and electrical environments in the cable plant.

THE intricate cable network of the telephone system offers numerous opportunities for the occurrence of corrosion. The property damage resulting from perforation of the sheathing by corrosion and the attending costly interruption of service have served to make the prevention of cable failure a matter of primary concern. The relatively low incidence of actual corrosion failures can be attributed largely to the vigilance of the electrolysis engineers and the plant forces.

Cable sheathing is one of the largest single uses of metallic lead. In 1929 it exceeded even that employed in the manufacture of storage batteries and constituted about 27 per cent of the entire consumption in this country. In the past fifteen years over two million tons of lead have gone into the communications and power cable plants. In the Bell System alone there are about 180,000 miles of lead alloy covered cables, about forty per cent of which are underground. About 95 per cent of the total mileage of telephone wires is in cable, the proportion of open wire construction decreasing each year.

The earliest telephone cables were of the type employed in telegraph practice, the individual wires being insulated with rubber or gutta percha and the core covered with a rubber or textile sheathing. The first lead-covered telephone cables were made by David Brooks, Jr., and were installed in the year 1880. These consisted of cotton-covered wires drawn into a lead pipe—a moisture-proofing compound of rosin and paraffin being forced afterward into the pipe and allowed to solidify by cooling. The Western Electric Company began the manufacture of lead-covered telephone cables in 1881. These were of the so-called "Patterson" type and employed cotton-covered wires drawn into a lead pipe after which melted paraffin charged with carbon dioxide under high pressure, was forced into the pipe and allowed to cool, forming thereby a solid cake of paraffin between the core and the pipe. Cotton-wrapped wire alone took the place of this structure in 1884 and some four years later paper began to be substituted for cotton. Beginning in 1882 telephone cables were sheathed with an alloy of 97 per cent lead and 3 per cent tin, which continued to be the standard composition for cable sheathing in the Bell System until 1912. The general adoption of the present standard alloy of lead with 1 per cent antimony in that year has afforded substantial economies and a sheathing of high resistance to fatigue cracking. Recently, a new development, lead hardened with 0.03–0.04 per cent calcium, has shown in laboratory tests some promise as a cable sheathing material. In England ternary alloys of lead with cadmium and tin or with cadmium and antimony have been proposed. Unalloyed commercial lead is the covering generally used for power cables.

The lead which best lends itself to the manufacture of lead-antimony cable sheathing is a high-copper, low-bismuth chemical grade of lead of the following nominal composition:

Silver	0.002 to 0.02%
Copper	0.04 to 0.08%
Bismuth	0.005% (max.)
Arsenic, antimony and tin together	0.002 (max.)
Zinc	0.001 (max.)
Iron	0.0015 (max.)
Lead (by diff.)	99.90

There is no evidence that the copper content of this lead has any significant effect upon corrodibility when used in 1 per cent antimony sheathing, although it does appear to be a factor in certain other uses. Indeed, chemical composition appears to be of lesser importance than environmental influences in the corrosion of cable sheathing. The prevention of corrosion failures is mainly a matter of providing and maintaining non-corrosive chemical and electrical environments.

While the choice of lead as a cable sheathing material was dictated primarily by physical requirements, notably its adaptability to extrusion, corrosion resistance has been a large factor undoubtedly in its successful use. It has long been recognized that lead is one of the least corrodible of metals. Its dull unreactive character is synonymous with inertness. Widely used in ancient times for water pipes, roofings, caskets, linings for public baths, etc., many specimens have come down to us in nearly perfect states of preservation. The Romans, for example, employed lead water pipes in fifteen standard sizes usually ten feet in length [1] and some of these pipes are said to be in use today. In the form of roofings many examples exist which are five centuries old. It seems likely that corrosion has been less destructive than war to the original lead roofs of medieval cathedrals and buildings. Once a protective film has formed on lead the metal may be preserved indefinitely if not physically disturbed. In the air this film is usually an oxide while in the case of underground burial the film which forms on lead may be a silicate or in some cases merely a film of hydrogen shielded by the presence of soil colloids. In other instances sulfates and carbonates exert a retarding influence. Whether or not a protective film forms depends largely upon the character of the environment to which the metal is exposed. Under unfavorable conditions, such as exposure to acetic acid vapors, strong alkalies or contact with large soil particles, lead may be readily corroded. Purity of the metal plays a minor role in corrodibility in the atmosphere although it may affect its behavior in soil waters and other electrolytes.

The widely different conditions of exposure which prevail in the aerial and underground cable plants make it desirable to consider them separately. Corrosion caused by stray electrical currents, since it occurs mainly in the underground plant, will be discussed under that heading.

CORROSION OF AERIAL CABLES

Corrosion is not a primary factor in the life of aerial cables. Failure of these cables is usually due to cracking and confined to sections which are subjected to repeated stresses or in some cases to prolonged mechanical vibration.[2] It is now recognized that the nature of the environment affects the endurance of metals to such stressing and vibration, and the term "corrosion-fatigue" has been applied to the embrittlement and cracking which result from the simultaneous application of tensile and compressive stresses and corrosive media.

The resistance of lead to corrosion-fatigue is lowered, for example, by exposure to the atmosphere.[3] Evidently the protective oxide coating which forms on lead in the air [4] is not only ineffective in preventing intercrystalline fracture under repeated stressing, but actually constitutes an accelerating factor. The specific volume of lead oxide is greater than that of the metal from which it is derived[5] and it has been suggested that the presence of the oxide provides some sort of leverage which aids embrittlement.[6] It is possible that differential aeration cell action may be involved for it is conceivable that the surface oxide film in the region of the grain boundaries is the most susceptible to rupture, producing thereby areas which are anodic to the adjacent unfractured surfaces.

Intercrystalline corrosion of lead may be produced in the laboratory merely by immersion of the specimen in a solution of nitric acid and lead acetate.[7] The attack in this case, as also in the case of the simultaneous action of tensile stress and corrosion, occurs along the grain boundaries leaving individual grains of lead which retain the characteristics of the original metal.[8] While intergranular corrosion of this type can be produced in lead of high purity, the rate of attack in a given medium is usually a function of the purity of the metal.

Exclusion of the atmosphere or the use of coatings of certain oils or grease have been shown to retard the rate at which lead is embrittled by corrosion-fatigue.[9] More practical means of minimizing the intergranular failure of cable sheathing lies in modification of the composition of the sheathing.

Alloying with 3 per cent tin, or 1 per cent antimony materially increases the resistance of lead to intercrystalline embrittlement.[10] The antimony alloy has a considerably greater fatigue resistance than pure lead as measured in a certain type of laboratory fatigue test[11] but decreases in time, or when the alloy is cold worked, owing to an agglomeration of the dispersed antimony particles which occurs particularly in the region near the grain boundaries.[12] Lead alloyed with 0.04 per cent calcium and suitably age-hardened has been shown in laboratory tests to have a much higher resistance to fatigue failure than the 1 per cent antimony alloy.[13] Certain ternary alloys of lead containing cadmium are said to possess marked resistance to fatigue failure.[14] More recently lead containing 0.1 per cent tellurium has been shown to be about 3-fold more resistant than ordinary lead to mechanical vibration.[15] It should be emphasized that all of these comparisons of fatigue resistance were made in laboratory tests and are not based on field experience.

From the foregoing it will be seen that for the most part the aerial cable plant does not present a serious corrosion problem. The importance of the unavoidable environmental influences on sheath embrittlement is minimized by the use of lead alloy sheathing together with proper methods of cable suspension. Other types of lead corrosion are rare in aerial cables.

CORROSION OF LEAD DIRECTLY BURIED IN SOILS

It is not the practice of the Bell System to bury lead-covered cables directly in the soil without the use of a protective coating. Recognition of the corrosion hazard involved in such construction is one of the considerations which led to the use of conduit for the housing of even the first cables which were placed underground. The more recent actual experience of certain small users with soil corrosion has served to confirm the soundness of this practice. The idea that cable sheathing might be buried safely in direct contact with soils was suggested by the fact that lead had been widely used as water pipes.[16] Many miles of telephone cables accordingly were laid directly in the earth, notably in Indiana, and frequently with unfortunate results.

In certain sections where it is considered economical to bury cables in the ground, a coating has been devised for the protection of the sheathing against corrosion. This consists in wrapping the lead-alloy sheathed cable with asphalt-impregnated paper followed by one or more layers of jute impregnated with a preservative compound, and in some cases steel tape armoring over which there is wrapped a final layer of jute. The structure is flooded with asphalt before and after each serving of paper and each layer of jute. The steel tape is employed where there exists any danger of induction from power lines; it may be omitted in locations where there is little likelihood of trouble from this source.

Before discussing the corrosion of cables in conduit, which is the principal concern of the present paper, it will be of interest to review the results of corrosion studies which have been made on lead and lead-alloy sheathing materials buried directly in soils. In addition to the presence of soluble salts, the underground environment in this case involves direct contact of the metal with relatively large soil particles and aggregates—a markedly heterogeneous condition. These points of contact of soil particles and metal become areas of reduced oxygen concentration as compared with surrounding regions of the metal surface which are more freely accessible to the soil atmosphere. The resulting oxygen concentration cells with a driving force of approximately 100 millivolts provide one of the most important means by which metals corrode in soils. The use of conduit affords an effective barrier against soil action of this character. Silt deposits which sometimes occur on cables in conduit do not give rise to differential aeration action probably because under such circumstances cathodic polarization of the corrosion cells is maintained.[17] This inhibitive function of soil colloids has been observed recently in connection with a study of the corrosion-fatigue of drill pipe[18] and appears to be an important factor in the retardation of corrosion in certain soils.

The most extensive soil corrosion test is that which has been carried on under the auspices of the National Bureau of Standards.[19] In this test, specimens of both ferrous and non-ferrous metals were buried in 48 different soils in various parts of the country. Commercial lead and lead containing 1 per cent antimony were placed in these locations and specimens of these have been removed from time to time. These studies have shown that lead and the lead-antimony alloy are corroded by most soils, but at lower rates than are ferrous metals[20]—losses in weight averaging but 10 per cent and depth of pitting about 25 per cent of those shown by the iron and steel specimens. After approximately 10 years exposure in 18 soils the lead-antimony alloy was found in the majority of cases to be slightly but definitely more corroded than was commercial lead.

A smaller but more intensive soil corrosion test on lead and certain lead-alloys has been carried on by the Bell Telephone Laboratories in five typical soils in the general vicinities of Lafayette and Monon, Indiana. Three grades of lead * and alloys of these leads with antimony in amounts from 0.8 per cent to 2.5 per cent and with 3 per cent tin were chosen for this test. The specimens consisted of flat plates one square decimeter in area prepared from metal which had been extruded in the form of tape. Before burial these plates were degreased with carbon tetrachloride and scoured with fine sea sand. Five specimens of each material were buried at each location in a horizontal position at a depth of two feet. After a period of four years the specimens were removed from the soil, and after removal of the corrosion products, the losses of weight and the maximum depth of pitting determined.

The values for loss of weight are represented graphically in Fig. 1, in which all of the metallic materials are compared in each of the soils. The arithmetical averages are shown in all cases by means of broken lines. The maximum depth of pitting results showed a close correspondence to the losses of weight. For example, it was least in the Plainfield fine sand and the Fox silt loam and greatest in the Miami silt loam. The only specimens perforated by pitting were the lead-tin alloy and these only in the last mentioned soil.

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* The grades of lead employed in this test and in the sulfation tests described later in this paper are designated as: Corroding or A.S.T.M. Grade I, 99.94 per cent lead; Chemical or A.S.T.M. Grade II, 99.90 per cent lead; and Common or A.S.T.M. Grade III, 99.85 lead. The principal impurity in chemical lead is copper, and in common lead, bismuth. The term "corroding" applied to the high purity product arose in connection with its use in the manufacture of white lead; it does not imply greater corrodibility.

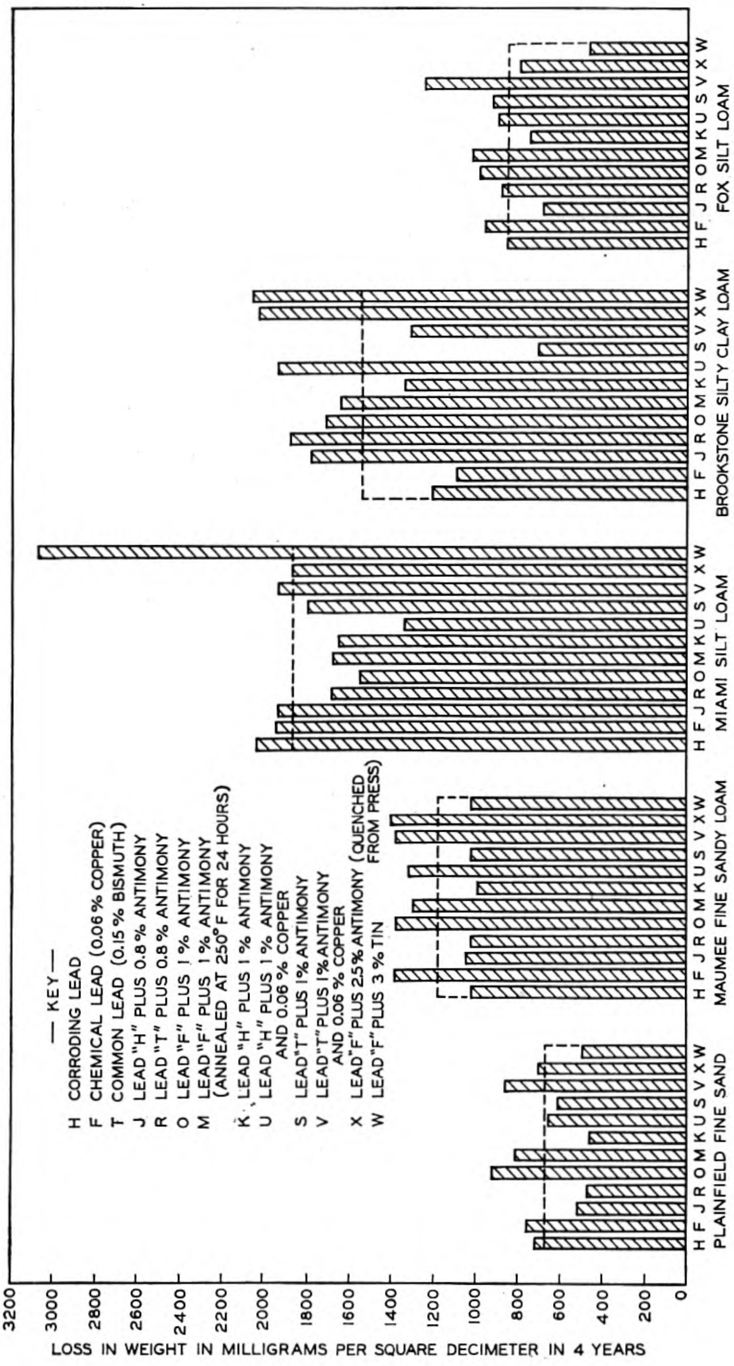

Fig. 1—Comparison of the corrosiveness of five soils toward lead and certain lead-alloys.

It will be seen that of the two variables, soil character and alloy composition, the former is decidedly the more important in its effect upon rate of corrosion. From an inspection of the data it would appear that there is no definite trend of corrodibility which may be correlated with composition. From a statistical analysis of the data obtained in this test it was concluded that variations in alloy composition within the scope of the test had no significant effect upon the corrosion behavior of the materials. In other words, the variations observed may be ascribed to chance and there is no indication of a significant difference in the rates of corrosion of lead and lead-antimony alloys when buried directly in the earth.

Corrosion of Cables in Conduit

The conduit mainly employed in the underground cable plant of the Bell System is a good grade of vitrified clay with glazed surfaces. Creosoted wood is widely used, particularly for single subsidiary cables. Wood has been employed extensively for main cables on the Pacific Coast where it offered an economical advantage. Steel or iron pipes find a limited application for certain special cases such as dips and relatively sharp bends. Heavy paper or fibre generally embedded in concrete has been used in a few instances. Concrete conduit has been employed by the utilities for power cables and in the telephone field to some extent abroad [21] but the danger of corrosion has militated against its adoption by the Bell System. It is possible that the greater heat dissipation of power cables as compared with telephone cables renders concrete conduit less hazardous for power cable use.

The environment to which underground cables in conduit are exposed is complex and varied. It is impossible to exclude moisture and soil air or vapors from the conduit. Surface waters may enter the cable compartments by way of the manholes and soil waters may seep through at duct joints or at small fissures which sometimes develop. The soil atmosphere tends toward higher concentrations of carbon dioxide and lower oxygen than the outside air; it is often high in humidity resulting in the condensation of drops of moisture on the sheathing. Acetic acid vapors arising from wood conduit or other sources may contaminate the duct air. Muddy soil waters may deposit a layer of silt on the sheathing. These waters contain varying amounts of salts, acids or alkalies. Free lime leached from concrete structures or caustic alkali produced, as indicated in the following paragraph, by the electrolysis of sodium chloride are the principal alkaline constituents. Even leakage from sewers is sometimes a contaminating influence which induces corrosion.

In addition to chemical influences, the electrical condition of the cable with respect to earth or to other adjacent metallic structures has an important bearing on corrosion. Where it can be done without jeopardy to other structures, it is desirable to maintain the cable network very slightly (of the order of 0.2 volt) negative or cathodic to earth. There is evidence that under this condition the sheathing is less readily corroded by couple action of a miscellaneous character. At appreciably higher negative potentials alkali or lime salts may be electrolyzed producing thereby caustic alkali or free lime which are corrosive to sheathing. On the other hand, an electrically positive condition of the cable may be conducive to the ordinary "stray-current" or anodic corrosion.

The Origin and Nature of Corrosion Cells on Cable Sheathing

The mechanism by which cable sheathing corrodes in conduit involves the replacement by the metal of hydrogen or another metal in compounds present in the surrounding environment—a process which has been described in some detail in a previous paper.[22] Most commonly, the dissolving lead replaces hydrogen from water. The areas or points on the sheathing at which lead dissolves are the anodes of small corrosion cells, the cathodes of which are the regions at which hydrogen is deposited. The driving force of these cells arises either from some chemical or physical inhomogeneity of the metal, or some inhomogeneity of the environment. Their electrolytic operation is influenced by the conductance and chemical nature of the environment, and by the size and distribution of the anodic and cathodic areas.

Corrosion cells owing their origin to sheath composition are exemplified by the presence of two metallic phases, one of which is lead and the other either an impurity, such as copper, bismuth, nickel, zinc, etc., or a hardening agent such as tin, calcium, cadmium, or antimony. Copper and antimony, for example, are cathodic to lead under the prevailing conditions and facilitate the discharge of hydrogen. The small proportion of cathodic area on the metal surface in both cases, however, will result in high cathodic current densities inducing polarization, and a low rate of corrosion except perhaps in acid solutions where the potential of the lead-hydrogen cell will be increased. This acceleration in acid solution is borne out by laboratory corrosion tests which show that the rate of corrosion of lead containing 3 per cent tin is about 50 per cent greater and lead containing 1 per cent antimony is about 10 per cent greater than that of soft lead in dilute (0.001 molar) acetic acid. Antimonial lead is said to corrode more rapidly than pure lead in humic acids.[23]

Relatively larger areas of copper deposited upon the cable by replacement from copper salts have been observed to promote corrosion of the sheathing. Scraps of copper wire corroded in manholes by saline waters are believed to have been the source of the copper compounds in such cases.

Wiping solder in contact with sheathing at the splicing sleeve provides still another example of a corrosion cell originating from the contact of diverse metals. Laboratory measurements of the potential of this couple in dilute chloride, alkali and acid solutions show solder is usually the anodic or corroding electrode. The observed potential differences in hundredth molar solutions at room temperature were as follows:

Solution	Potential Difference in Millivolts
Potassium chloride	6 ± 3
Caustic soda	11 ± 3
Acetic acid	20 ± 8

Similarly, the 3 per cent tin-lead sheathing in contact with 1 per cent antimony sheath would give rise to a galvanic couple in which the former would be anodic but by smaller values of potential than given above for the solder-sheath couple. Ordinarily in the soil water environments which prevail in the underground plant the potentials of neither of these couples is sufficient to maintain current flow and there is no evidence of attack. The few cases of corrosion of this type which have been observed, and which have been characterized by pitting of the solder and even of the sleeving (where this was 3 per cent tin) are believed to have arisen in electrolytes somewhat alkaline in nature which contained abnormally low concentrations of film-forming constituents such as silicates, sulfates or organic colloids.

In general, the influence of metallic composition upon corrodibility may be readily detected by measuring the rate of sulfation of the metallic material in sulfuric acid.[24] This test provides a method of measuring surface activity and affords a means of comparing the relative rates at which similar alloys tend to corrode in corrosive environments or tend to become passive in the presence of film-forming constituents. The sulfation-times measured by means of a recording potentiometer have been determined on specimens of leads of various compositions and for several cable sheath alloys in 7-normal sulfuric acid. The averages of four determinations made on each material bore the following relationship to each other, assuming the sulfation time of spectroscopically pure lead to be one hundred:

Spectroscopically pure lead (99.999% lead)	100
Corroding lead (A.S.T.M.—Grade I, 99.94% lead)	80
Chemical lead (A.S.T.M.—Grade II, 99.90% lead, contains 0.06% copper)	65
Common lead (A.S.T.M.—Grade III, 99.85% lead, contains 0.13% bismuth)	70
Corroding lead alloyed with 1.5% tin, and 0.25% cadmium	85
Chemical lead alloyed with 1.5% tin and 0.25% cadmium	75
Corroding lead alloyed with 3% tin	70
Chemical lead alloyed with 0.04% calcium	80
Corroding lead alloyed with 0.04% calcium	75
Common lead alloyed with 0.04% calcium	55
Corroding lead alloyed with 0.5% antimony and 0.25% cadmium	25
Chemical lead alloyed with 0.5% antimony and 0.25% cadmium	25
Chemical lead alloyed with 1.0% antimony	20

From an inspection of these results it appears that the surface reactivity of lead is markedly increased by the presence of impurities or by alloying with small amounts of other metals. Of the hardening agents chosen for study, tin, tin and cadmium, and calcium exert the smallest influence on rate of sulfation, while antimony, whether used alone or with cadmium, has the most pronounced effect. The presence of small amounts of copper appears to have an accelerating effect upon reactivity as does also the presence of bismuth. This adverse effect of bismuth has been noted in connection with the use of lead in sulfuric acid plants.[25] Since the environment in which cables are used contains both corrosive and film-forming substances this comparison of rates of sulfation of lead and its alloys is not necessarily a direct indication of the relative rates of corrosion of these materials when used as cable sheathing.

It is well known that the intensity with which metals tend to ionize is affected by their physical state, small crystals and strained structures possessing higher intensities and therefore more electronegative or anodic potentials than large crystals and annealed structures. In the case, however, of lead and most lead-alloys suitable for cable sheathing, self-annealing occurs at ordinary atmospheric temperatures, and for this reason it is highly improbable that corrosion is ever initiated as a result of physical condition of the metal.[26] In the laboratory it was found that lead intensively worked at liquid air temperatures, where self-annealing does not occur, was from 2 to 3 millivolts electronegative to annealed lead when measured immediately afterward at 25° C. in 0.2 normal lead-acetate solution. This potential difference was reproducible but could not be maintained for more than ninety minutes at room temperature.

It is conceivable that scratching or mechanical injury of cable sheathing, such as might occur during installations, could give rise to the familiar metal-metal oxide corrosion cell. The operation of this cell has been demonstrated in a laboratory experiment in which pieces of lead covered with litharge were freshly scratched after being submerged in water.[27] It is of significance that although corrosion readily occurred in this experiment, there was no attack if the scratch were exposed to the atmosphere for two hours before submersion of the specimen. In other words, the oxide film on lead is readily self-healing and injury to it is unlikely to cause corrosion.

Turning to a consideration of corrosion cells originating from the exposure of the sheathing to an inhomogeneous environment, reference has already been made in discussing soil corrosion to the nature and the importance of oxygen concentration cells, and to the protection which the conduit affords against this hazard. Cables in conduit are seldom subject to contact with the character of inert objects which lead to the establishment of oxygen concentration cells. Relatively large hard particles are generally the most effective agents in producing differential aeration. In the laboratory, lead can be pitted by contact with a glass rod when submerged in a dilute sodium chloride solution. There are a few instances in which cables in conduit appear to have corroded by means of oxygen concentration cells. For example, there is evidence that deep pits in sheathing produced by the leakage of stray currents to earth have continued to deepen to the point of perforation of the sheathing, after removal of positive potential conditions. The bottoms of such pits are less accessible to oxygen and appear in some cases to function as the anodic elements in differential aeration cells. Cases of this kind are generally diagnosed by the field forces as "old action."

Another, but rather uncommon, example of oxygen concentration cell has been observed in the use of a porous duct plugging material contaminated with acetic acid. In this case it seems likely that the naturally protective oxide film on the sheathing was destroyed by the acid following which this region, owing to the exclusion or partial exclusion of oxygen, became anodic to the adjacent areas which were freely accessible to air. Contamination with acetic acid does not appear to be essential to this action since other cases have been reported in which the duct plugging material was free from acid.

Finally there exists the possibility of large scale differential aeration cells where one cable of a multiple run is placed, owing to space limitations, in a dip under a large sewer, but bonded to the other cables. Such a cable may suffer severe corrosion in the region of the dip as a result of the lower oxygen content of the atmosphere in this duct as compared to that prevailing in the other ducts.

The discussion of differential environments has related so far only to oxygen concentration. In a similar manner, underground cables may be exposed to different hydrogen ion, metal ion or salt concentrations and where the demarcation between concentration zones is sufficiently pronounced may give rise to differential concentration cells, the driving forces of which have theoretical values of 29.5 millivolts per ten-fold difference in ion concentration. An examination of the Rhineland cable which connects Berlin and Cologne has shown that the most extensive corrosion occurred at points where there was an abrupt change in the character of the soil or geological structure.[28] There is usually sufficient diffusion and circulation of underground waters to equalize ionic concentrations and prevent the development of cells of this type assuming serious proportions.

Effect of Environment on Operation of Corrosion Cells

The nature of the more common electrolytic cells by means of which cable sheathing corrodes has been discussed at some length. Consideration will now be given to the manner in which various environmental factors influence the operation of these cells. In general, these factors may be classified either as corroding or film-forming agents, although their influence will depend quite as much upon their concentration as upon their specific nature. It is meaningless to report that a metal corrodes or does not corrode in this or that electrolyte unless full experimental details are given. Only with a complete knowledge of the condition of a metal surface and of the nature and concentrations of the components of its environment can the resulting behavior be predicted. For example, it has been shown that it is often the ratio of the concentrations of film-forming to corroding substances which determines the character of attack.[29] For high values of this ratio, the metal will be protected; for low values it will be uniformly corroded, but for intermediate values of this ratio, the surface will be only partly protected with the result that corrosion will be localized in the form of destructive pitting. With these limitations in mind, some of the principal constituents of the environment which affect the behavior of cable sheathing may be classified as follows:

Corroding	*Protective*
Oxygen	Silicates
Nitrates	Sulfates
Chlorides	Carbonates
Alkalies	Colloidal substances
Organic acids	Certain organic compounds

Of the corroding elements, oxygen is the most important in its effect upon the operation of corrosion cells. Owing to the high potential required to discharge hydrogen on pure lead (i.e., its high hydrogen over-voltage) these cells tend to cease functioning owing to cathode polarization. The role of metallic impurities of lower overvoltage in discharging hydrogen has already been considered. Oxygen, it is obvious, aids corrosion by depolarizing cathodic areas on the surface of the sheath. That the effect of oxygen is proportional to its partial pressure in the atmosphere has been found in a laboratory study, the results of which are given in Fig. 2. In this experiment six specimens of extruded chemical lead, each of an area of one square decimeter, were prepared for test by degreasing with carbon tetrachloride, and the tarnish film removed by dipping in dilute acetic acid (one part of acid to five parts of water). These specimens washed and dried, and weighed to the nearest milligram, were submerged in large jars of distilled water which had been previously saturated with purified nitrogen, oxygen or various mixtures of the two. The corresponding atmospheres were maintained above the surface to the water during the test. After a period of 18 hours the specimens were removed, washed and the losses of weight determined.

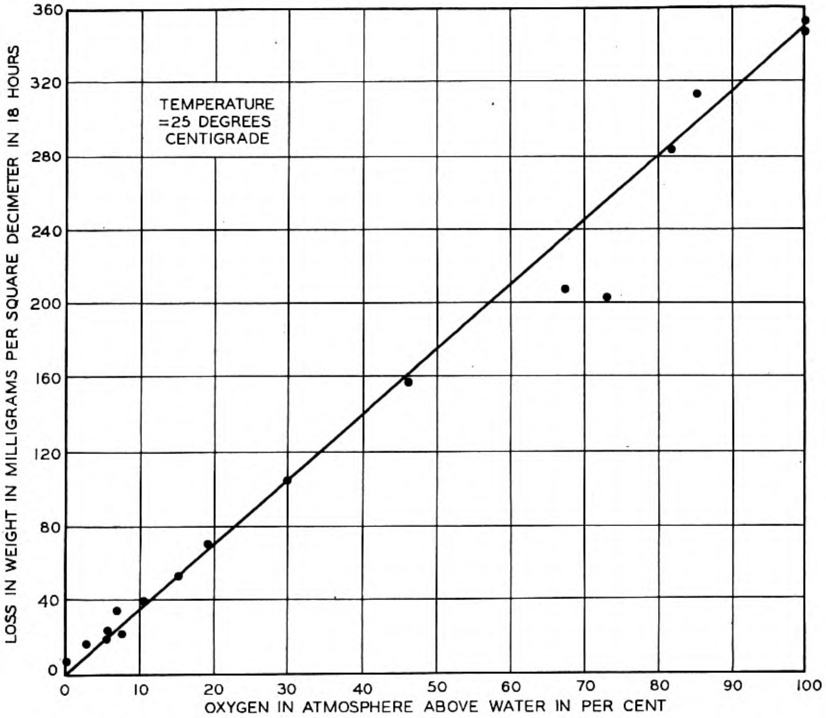

Fig. 2—Effect of oxygen on corrosion of lead submerged in distilled water.

A number of cases of cable sheath corrosion have been attributed to the presence of nitrates in the duct electrolyte. The nitrate content of most soil waters is very low—a few parts per million ordinarily—but occasionally contamination from industrial plants or from sewers, the organic matter from which may undergo nitrification, has led to a several fold increase. Concentrations of nitrate from 20 to 425 parts per million have been found in the electrolyte from locations where failure of the sheathing occurred. It has been shown that solutions containing a thousand parts of nitrates per million are markedly corrosive to lead.[30] Another investigator reports that the addition to natural soft waters of nitrates in excess of 50 parts per million increases their corrosiveness about 20 per cent, higher quantities of nitrate being required to produce this effect in hard waters.[31] Often the corroded region of the sheath is black in appearance owing to the presence of loosely adherent, finely divided lead (possibly oxidized) and antimony which accumulates by some sort of undermining action during the rapid attack. The formation of this black coating in the presence of nitrates is reported by others.[32]

The mechanism of nitrate action at the cathodes of corrosion cells is similar to that of oxygen and of lower concentrations of oxidants in general, and consists in depolarization. In addition, the high solubility of lead nitrate prevents an appreciable polarization of anodic areas. It is of interest to note that in the presence of nitrates, in the form of nitric acid, oxygen furnishes but little additional acceleration of corrosion. For example, in 30 per cent nitric acid, the ratio of the rate of corrosion in the presence of oxygen to the rate in the absence of oxygen has been shown to be 1.1, while in 20 per cent hydrochloric acid and glacial acetic acid, this ratio is 10.0 and 10.9, respectively.[33]

Cable sheathing is little affected by the chloride content of most ground waters. In tests, for example, in which chlorides were added to natural waters, there was no increase in corrosion when the chloride content was of less than 1000 parts per million, a value seldom attained in soil waters.[34] Even infiltration of sea water does not constitute a corrosion hazard unless the cable is markedly negative to earth. Indeed, in sea water the corrosion of lead may be retarded by an encrustation of lead chloride which forms on the surface of the metal, as well as by the lower prevailing oxygen content. Extruded bars of lead and lead containing 1.6 per cent antimony, 60 cm. in length and 2.87 cm. in diameter exposed for four years to tidal action have shown losses in weight of 0.65 per cent and 0.51 per cent, respectively,[35] but doubtless mechanical erosion was an important factor in this rather drastic test. Laboratory tests made on lead foil in a sodium chloride solution show that the rate of corrosion increases with increasing salt concentration up to a maximum at 1 per cent and that at concentrations of 3 per cent, which corresponds roughly to that of sea water, the rate is markedly less.[36] The favorable experience with cables submerged in sea water or mixtures of sea water and soil waters indicates that corrosion inhibitive agents exert under these exposures a predominating influence. The effect of the chloride content of the duct electrolyte must be mainly one of increasing the conductivity, there being insufficient concentrations in relation to the concentration of film-forming substances to produce even pitting or local attack.

A type of cable sheath corrosion of considerable importance is that which is fostered by alkalies. It is characterized usually by the formation in the region of attack of deep red crystals of lead monoxide or litharge. Occasionally the yellow form of litharge or a greenish hydrated lead monoxide may appear, but in one case where the strength of caustic was so great as to cause discomfort upon handling the cable, no colored compounds developed. The red monoxide crystallizes out of saturated solutions of alkali plumbites which are formed by the solution of lead in alkalies.[37] It can be produced in the laboratory by immersing specimens of lead in saturated lime water and aerating the solution for several days with carbon dioxide-free air. The appearance of this red oxide on cable sheathing is a certain indicator of alkali attack. If detected before failure of the cable, the action can be stopped usually by removing the source of the alkali and thoroughly flushing the cable conduit with water.

A source of alkali affecting underground cables is concrete conduit and occasionally other concrete structures. Free lime in the surface layers of fresh concrete is usually converted by the action of carbon dioxide into calcium carbonate within a few weeks and this is less alkaline in nature. Seepage of moisture through concrete which may occur in less dense grades of this product may leach free lime from within. At the Panama Canal water seeping through the concrete floors and walls of lock chambers caused serious corrosion of the sheathing of power cables in a short time. Analysis of the seepage water disclosed high alkalinity. In the same locality a telephone cable in vitrified clay conduit was corroded by the seepage of water through cement sacks used for wrapping the conduit joints.[38] Greater attention is being given recently to the production of concrete conduit of greater impermeability, lower alkalinity and to "curing" methods. The use of high alumina cement, which is much less corrosive to cable sheathing,[39] has been proposed.

Another important source of alkali is the electrolysis of sodium chloride or common salt by electrical currents flowing to the cables. Under these conditions caustic soda is produced at the sheath which is cathodic or negative to earth; hence the terms "cathodic" or "negative" corrosion. The salt usually comes from that used in the winter to thaw out street car switches, although in one case it has been traced to the drippage from salt-ice mixtures of ice-cream delivery trucks. In still another case, a power cable, negative to earth, suffered alkaline attack as the result of the electrolysis of alkali salts concentrated at a low point in the cable run by heat dissipation of the cable. Finally it should be mentioned that the use of calcium chloride on streets for melting snow or laying dust would lead undoubtedly to its coming in contact with the underground cable plant and being converted into corrosive free lime in areas negative to earth.

It has been known since the Middle Ages that lead is corroded by acetic acid. In the presence of the carbon dioxide of the atmosphere, the corrosion product is the pigment, white lead. The attack manifests itself by the formation of a white encasement around the globules of moisture on the sheath; at first a mottled effect is produced which in time develops into a heavy white encrustation of the carbonate or basic carbonate of lead. The early use of wood conduit was attended with occasional cases of acetic acid corrosion and it was found that the wood tar creosote used as the preservative contained this acid. Since that time coal tar creosotes have been specified for the preservation of wood conduit. The conduit most widely used in this country is yellow pine. Properly creosoted this product has not been known in Bell System experience to cause corrosion except when used under such unusual circumstances as close proximity with steam pipes or exposed on viaducts over railroad yards to the heat of locomotive stacks. In these cases acetic acid was liberated as a product of the slow decomposition of the wood. A recent instance of acetic acid attack in creosoted conduit manufactured from southern yellow pine has been reported and attributed to acid liberated by the destructive decomposition of the wood by the Kansas sun.[40]

The most serious corrosion of cables by acetic acid on record is that which occurred on the Pacific Coast in creosoted Douglas fir conduit a few years ago.[41] Following the initial satisfactory use of this product for subsidiary cables it was employed extensively for main communication subways. With the expansion of the cable plant into this newly constructed duct system several cases of acetic acid corrosion occurred—most of them within the first 15 months in conduit of recent installation. Analysis of the atmosphere within the cable compartments revealed the presence of corrosive concentrations of acetic acid. In the investigation made of this trouble it was concluded that the high native acidity of Douglas fir, together with the drastic treatment required to impregnate it with creosote, offered a reasonable explanation for the corrosiveness of the conduit.[42] The corrosive action was effectively stopped by neutralizing the acid with ammonia gas supplied to the affected conduit in a 2 per cent mixture with air.

The corrosiveness of air laden with acetic acid vapors lies in the persistence of effective non-polarized corrosion cells of constant voltage. The acid furnishes an abundant and reasonably constant source of replaceable hydrogen ions and the continued precipitation of lead as carbonate by the action of carbon dioxide maintains a low concentration of lead ions. Oxygen acts as a cathodic depolarizer. Since the precipitation of lead carbonate or basic carbonate occurs at an appreciable, although very small, distance from the seat of activity on the metal surface, it offers little or no hindrance to the corrosion action.

Phenols and other acidic constituents of coal tar pitches have been reported to be corrosive to cable sheathing when in direct contact in the form of protective coatings.[43] There is no evidence either from experience with creosoted conduit or from laboratory tests that phenolic vapors from creosote are appreciably corrosive to sheath.

So much for the corrosive media of the environment of the underground cable plant. Of the protective agents, none is more important than soluble silicates. It is well known that lead is markedly corroded in distilled water, and by waters low in hardness and in total solids. Saturation of distilled water with calcium silicate (soluble to the extent of about 100 parts per million), or with silicic acid derived from a suspension of silica flour, will prevent corrosion of lead. The corrosiveness of certain natural waters has been greatly reduced by the addition of only 10 parts of sodium silicate (expressed as silicic acid) per million.[44] Analysis of a large number of samples of waters from cable manholes and subways has shown silicate contents of from 2 to 25 parts per million. In concrete conduit values up to 143 parts per million have been found. It is of interest in this connection to note that although silicates appear to protect lead to some extent in all ground waters, their effectiveness is greatest in the range of alkalinity corresponding to values of pH between 9 and 11, where pH equals the logarithm of the reciprocal of hydrogen-ion concentration. The resistance of underground cables to corrosion appears to depend chiefly upon the film-forming action of silicates. The minimum concentrations required to give protection depend upon the nature and concentrations of the corroding agents which are also present.

The effectiveness of silicates in passivating lead lies in the extremely low solubility of lead silicate. Consequently silicate ions are precipitated as lead silicate in close contact with the sheath at the anodic areas of the corrosion cells. As the more anodic regions become polarized in this fashion other areas tend to function as anodes but with the same result until the surface of the sheath becomes entirely covered with an insoluble coating of lead silicate which is impervious to the corrosive elements of the environment.

Chromates and phosphates stand next to silicates in ability to passivate lead, but do not occur in the electrolytes in contact with underground cables. Sulfates, however, are a common constituent of these environments and in laboratory studies have been shown to be as effective as phosphates.[45] The passivating effect of sulfates is directly proportional to concentration, 2500 parts per million reducing the rate of corrosion of distilled water about 50 per cent.[46] Electrolytes from the cable plant seldom contain as much as 10 per cent of this amount of sulfate and so the specific contribution of sulfates alone is not large; however, added to that of various other film-formers it is of importance.

Carbonates exert a marked retarding influence on the corrosion of lead. The water which comes in contact with underground cables always contains carbonate ions derived either from soluble carbonates from the soil or from carbon dioxide of the soil atmosphere. Numerous analyses of the air in cable ducts has shown it to run from 0.1 per cent to 10 per cent of carbon dioxide, usually averaging about 1.5 per cent or 0.015 atmospheres pressure. Pressures of carbon dioxide within this range reduce the rate of corrosion of lead in distilled water about 50 per cent. It is claimed that high pressures of carbon dioxide, e.g., 6 atmospheres, increases the solvent action of water on lead.[47] Carbonate equilibria calculations of the system lead carbonate-carbon dioxide-water show that the film of corrosion products which forms on lead in aerated distilled water is a hydrated oxide of lead when the partial pressure of carbon dioxide is less than 10^{-14} atmospheres. Above this value for carbon dioxide and up to a pressure of about 10 atmospheres, the film should consist of lead carbonate. Basic carbonate, if a true solid phase, should also be found within this range. The bicarbonate of lead would appear to be stable at still higher carbon dioxide pressures. It is of interest that there is a minimum in the calculated solubility curve for lead carbonate in the region of 10^{-6} atmospheres of carbon dioxide. Increasing solubility at pressures greater than this is due to the increasing concentration of bicarbonate ions. This means that the effectiveness of soil carbonates in passivating cable sheathing is somewhat reduced by the higher carbon dioxide pressures which obtain underground. It is still, however, one of the most important of corrosion inhibitors.

Mention has already been made of the protective influence under certain circumstances of silt or clay deposits on the surface of the sheath. There are in the underground electrolyte many other substances mainly organic in nature and often colloidal which aid in the preservation of cable sheathing. Whereas the anions, such as silicates, sulfates, and carbonates, induce passivity by a process of anodic polarization of corrosion cells, the inhibitive mechanism of soil colloids and of the organic materials in soil electrolytes is usually one involving cathodic polarization of these cells.

Stray Current Corrosion

The most common kind of cable sheath corrosion, the most destructive and best recognized, is that which occurs when electrical currents flow from the sheath to ground. In this case the portion of cable of higher potential than earth has the general characteristics of an anode, while the cathode is some extraneous structure. The potentials between anode and cathode may be and generally are greater than those which are possible for the electrolytic corrosion cells which have been described at length in this paper. The size of the currents which may flow for a given potential will of course depend upon the resistance of the path, i.e., upon the electrolytic resistance of the soil solution in contact with the cable. The size of the anodic area will depend upon the area of the sheath in contact with the electrolyte. The nature of the corrosive attack accordingly will depend upon this area and the rate of current flow or, in other words, the current density. In appearance the corroded area may be a clean cut pit or pits, or it may be roughly etched. When the potential is greater than about 2 volts, a brown colored anodic oxidation product, lead peroxide, may be formed. A simple test for this—the blue coloration which develops when a small amount of it is dissolved in a 5 per cent solution of tetramethyldiaminodiphenylmethane containing dilute acetic acid—is a certain indicator of anodic action. A negative result with this test, which is the more common experience, does not, however, exclude the possibility that the attack was anodic in character; the potential to earth may have been too small or the peroxide may have been actually formed but may have been consumed by local action following removal of the positive sheath potential.

Occasionally lead chloride, a white salt, may be formed in the corroded areas under anodic conditions. Thus, the finding of a relatively greater concentration of chloride in the corrosion product than in the surrounding environment is trustworthy evidence of anodic corrosion.

The corrosion efficiency of stray current anodic corrosion, i.e., the per cent of the current involved in dissolving lead, will often be appreciably less than 100 per cent. The complementary anodic reaction occurring at voltages greater than approximately 2 volts is the evolution of oxygen. For example, in an extract of a black alkali soil containing high concentrations of sulfates, tests showed that less than 1 per cent of the current was consumed in the dissolution of lead. Under the conditions generally prevailing, however, it is likely that the corrosion efficiency is reasonably high and that the amount of corrosion will be nearly proportional to the amount of current which flows from the sheath to ground.

Cathodic or negative corrosion of cable sheathing, which occurs when current flows from earth to the sheath, has been described already under the discussion of alkaline corrosion. A not uncommon indication of negative conditions is an encrustation of calcium carbonate on the cable. In this case the sheathing is generally not corroded. It seems likely that the alkali produced by electrolysis of lime salts is carbonated as formed and before reaching sufficiently high concentration to initiate corrosion and that calcium carbonate so formed crystallizes on the surface of the sheathing.

Instances have been observed in which cable sheathing appeared to have corroded from the inside surface.[48] It is believed that the action in these cases was preceded by the occurrence of cracks or fissures in the sheath which admitted moisture and provided electrolytic paths by means of which current flowed from the sheathing to the copper conductors within.

Destruction of cable sheathing by stray electrical currents derived from large-scale galvanic cells has been experienced. In this case, which at first was rather mysterious, it was found that contact of iron pipes with beds of buried cinders set up large iron-carbon couples with potentials of approximately 0.7 volt. The soil at this location was unusually low in resistance and the wood conduit in which the cables were housed was water-logged with the result that the cables picked up current in regions near the iron structures and lost it at other points where the cable passed through the general neighborhood of the cinder beds. The electrical condition of the cables, determined by pulling through an adjacent duct a modified calomel reference electrode,[49] showed that the potential of the cable with respect to earth varied sharply from point to point and often reversed itself more than once in a section between two manholes. Removal of corroded cables always confirmed the duct survey as to the location of anodic regions. The trouble was corrected by removal of the cinder beds.

SUMMARY

In summarization it may be stated that corrosion is not a primary factor affecting the life of aerial cables. The tendency of lead to crack as a result of repeated stressing has been minimized by alloying with one per cent of antimony, and aerial cables sheathed with this alloy have shown satisfactory resistance to embrittlement of this character. When cable sheathing materials are buried in direct contact with soils, serious corrosion develops as a result of differential aeration cell action, and appears to have little or no relation to chemical composition of the metallic material. In addition to corrosion cells which originate in some inhomogeneity of the environment, such as the partial exclusion of air, corrosion of cable sheathing may occur by means of galvanic cells arising from the presence of metallic impurities or contact with a more noble metal such as copper. The electrolytic operation of these corrosion cells is influenced by the conductance of the surrounding electrolyte and the chemical nature of its components. Such constituents as oxygen, nitrates, alkalies, organic acids and chlorides (in low concentrations) facilitate the operation of these cells, thereby increasing the rate of corrosion, whereas silicates, sulfates, carbonates, colloids and certain organic compounds of the soil waters exert a protective action which may retard or prevent corrosion. Finally mention is made of the characteristics of the most common kind of corrosion, that due to stray electrical currents. This may occur as anodic action when current flows from the cable to earth, or it may occur as cathodic action when the current flows in the reverse direction if there be sufficient concentrations of alkali or lime salts in the surrounding electrolyte.

From the description of the occurrence and general characteristics of cable sheath corrosion in the present paper it may be concluded that although there are many conditions under which cables may corrode, the actual incidence of corrosion is small owing to the maintenance of non-corrosive chemical and electrical environments in the cable plant.

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Reduction of Airplane Noise and Vibration*

By C. J. SPAIN, D. P. LOYE and E. W. TEMPLIN†

THE three principal sources of airplane noise are the engine, the propeller, and air turbulence. Because of the impossibility of generating each kind of noise separately from the others, it has been necessary to develop what are in effect means for separating them and studying each one independently as they vary with speed of ship, speed of engine, and horsepower. In brief, the method that was used employs a series of tests under various flight conditions, the resulting data making it possible to solve a set of simultaneous equations. The paper gives numerous curves showing the variation with engine speed of the noise from these three sources.

Fundamental to any consideration of airplane noise are the characteristics of the ear itself. For the most part, physiology does not cooperate with the acoustical engineer when he sets out to increase the comfort of air travel. In fact, it has been necessary to develop several specialized measuring devices in addition to the familiar type of noise meter. Among these may be mentioned particularly a frequency analyzer which permits of selecting either a 20-cycle or a 200-cycle band out of any portion of the noise spectrum from 40 to 11,000 cycles per second. With the 200-cycle band filter the general shape of the noise characteristic is measured, while with the 20-cycle filter the frequency components of engine, propeller and other noise are identified and measured.

It is also desirable to be able to explore surfaces as to the extent to which they radiate noise. A microphone attachment has therefore been developed which quickly measures the characteristics of various interior surfaces. As a result, it has been found possible to improve the efficiency of distribution of the sound absorbing material, increasing its weight in certain locations and reducing it in others, thereby both lowering the noise level in the cabin and decreasing the total weight of acoustic treatment.

In order to measure the noise reduction provided by the cabin walls, another device known as a high-speed automatic level recorder has

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been developed. It is in effect a rectifying and recording oscillograph whose stylus is capable of traveling at various speeds, the highest being such as to indicate in one second a difference of level of 840 db.

To reduce airplane noise within the passengers' and pilot's compartments, it is necessary to provide sound absorbing material as well as sound insulation. If there were no absorption within the cabin, the sound reduction would be zero, no matter how efficient the insulation, as the insulation would in this case only serve to delay the building up of the sound inside to the same intensity as outside. Laboratory equipment suitable for the study of absorbing materials and the measurement of their coefficients is therefore a very necessary adjunct.

Finally, mechanical vibration of audible rates to which various parts of a ship respond must be carefully studied. For this purpose, a so-called vibrometer has been perfected. With it, data are obtainable indicating the extent to which noise is transmitted into the cabin through the fuselage structure as compared to that coming through the air.

Abstracts of Technical Articles from Bell System Sources

The Renaissance of Physics.[1] KARL K. DARROW. Intended for the general public, this book is chiefly a story of some of the great discoveries and some of the grand general principles achieved or confirmed in physics since the century began. The title is an allusion to this period, for, to quote from the beginning of the book: "ever since the turn of the century physics has been enjoying a veritable renaissance, fairly to be likened with that splendid flowering of the arts and humane letters four hundred years ago to which the name of Renaissance was first applied. In this contemporary age when the artists in so many fields are overshadowed by the work of masters long since dead, the physicist has had the glorious good fortune of sharing in a spirit, an ambition, a sense of novelty and limitless opportunity, such as (we are told) inspired the Elizabethans."

The chapter headings run: *Physics and the Physicist—Intimations of Electricity—Release of Electrons from Matter—Through Measuring to Knowing—Magnets and Moving Charges—The Atom Visible—Light in the Semblance of Waves—Mystery of Waves and Corpuscles—Structure of the Atom—Technique of Transmutation—Victory over the Elements—Unity of Nature.*

There are forty-five illustrations, many of them half-tones of apparatus, spectra of various kinds, and processes of transmutation. No previous knowledge of physics is required of the reader, and the use of mathematics is confined to a few formulae of the simplest algebraical type. Much of the content of the book figured in the course of Lowell Lectures delivered by the author in Boston during the autumn of 1935.

Gutta-Percha—Effect of Vulcanization of its X-Ray Diagram.[2] C. S. FULLER. The finding of previous investigators that gutta-percha and balata have identical x-ray patterns is verified. Experiments on the x-ray behavior of vulcanized and unvulcanized gutta-percha show that vulcanization (to the extent carried out here) has no effect in changing the lattice plane spacings of either the alpha or beta crystal modifications. Vulcanization does appear to increase the degree of orientation of the crystallites present in these substances as produced by stretching

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[1] Published by Macmillan Company, New York, N. Y., September, 1936.

[2] *Indus. and Engg. Chem.*, August, 1936.

and to that extent allows a more accurate calculation of the identity periods of the crystalline forms to be made.

A partial transformation of the beta to the alpha form of gutta-percha results by stretching at 80° C., although the exact conditions under which this occurs have not been determined.

The identity period in the fiber direction of the beta modification is 4.77 ± 0.03 Å., or double this value, and the alpha modification presents an anomaly in that two identity periods are in best agreement with the data. These are 9.00 ± 0.05 and 8.70 ± 0.13 Å. In the case of the beta modification three possible orthorhombic unit cells which are in agreement with the observed lattice plane spacings are given.

Fields Caused by Remote Thunderstorms.[3] K. E. GOULD. The object of the studies described in this paper was to verify the supposition that certain types of short-duration longitudinal voltages appearing in communication circuits are caused by remote thunderstorms. By means of simultaneous directional measurements made in the frequency range below 40 kilocycles at two points as much as 900 miles apart, thunderstorms at distances of several hundred miles from one or both of these points have been located with a degree of accuracy great enough to permit conclusive correlation of the storm locations indicated by the directional measurements with the locations of recorded thunderstorms. Methods, equipment, and results are discussed.

Improved Types of Transmission Measuring Systems and Methods of Measurement.[4] W. H. HARDEN. The quantitative measurement of the electrical efficiency of telephone circuits as one of the important checks of the ability of these circuits to satisfactorily transmit speech has become an increasingly important maintenance function during the past twenty years. The function of transmission measuring equipment is not only to provide a convenient tool for quickly checking the electrical efficiency of telephone circuits, but also to serve as an aid in locating the cause of trouble when it is found to exist. It is the purpose of this paper to review briefly the progress which has been made in transmission testing technique and to describe some recent advances in the art which greatly facilitate this important part of telephone maintenance work. The discussion of these advances in the art will, we believe, be of interest to the railroads in connection with the operation and maintenance of their private telephone systems.

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[3] *Elec. Engg.*, June, 1936.

[4] *Proc. Assoc. Amer. Railroads—Telegraph and Telephone Section*, June, 1935.

Some Improvements in Toll Circuit Design and Transmission.[5] GLEN IRELAND. Progress did not crash, along with the stock market, in 1929. Subsequent years have seen astonishing advances in many important businesses of the country as regards scientific developments, improved methods and better service. This is particularly true in the allied fields of transportation and communication where the service has been made more and more convenient, comfortable and accessible. Mr. Ireland's work lies in the field of communication and more specifically has to do with toll circuit design and transmission. In this paper he tells something of the progress in this field; first with respect to some new toll circuit instrumentalities that may be of direct interest in the work of the railroads, and secondly about some important and fundamental improvements, which are of general interest as indicating the trends in the art.

The general practices followed in connection with the design and installation of toll cables in the Bell System were described before the Telegraph and Telephone Section of the Association of American Railroads several years ago. There have been several specific changes in practices and some improved instrumentalities made available in this field which it is believed will be of interest to the railroads.

Calculated and Experimental Photoelectric Emission from Thin Films of Potassium.[6] HERBERT E. IVES and H. B. BRIGGS. Several years ago one of the writers proposed a theory of the photoelectric emission from thin films of alkali metals on supports of other metals, not photoelectrically active in the regions of the spectrum under observation. According to this theory the photoelectric emission is proportional to the rate of energy absorption by the thin film of alkali metal. The magnitude of the photoelectric current depends on the energy density immediately above the supporting metal, which is established from a knowledge of the optical constants of that metal, and upon the specific absorption of the alkali metal film. For its verification, the theory demands a knowledge of the optical constants of both supporting and alkali metals throughout the whole region of the spectrum where observations can be made. While optical constants have been determined for platinum, which is the metal most commonly used for a support for these thin films, no optical constants for the alkali metals have been available except in the visible region. In this region, a very satisfactory confirmation of the theory was obtained, particularly in respect to the variation of emission with the angle of incidence for the two principal planes of polarization (vectorial effect). One of the most characteristic phenomena of photoelectric

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[5] *Proc. Assoc. Amer. Railroads—Telegraph and Telephone Section*, June, 1935.

[6] *Jour. Opt. Soc. Amer.*, June, 1936.

emission from thin films, namely, the occurrence of a pronounced maximum of emission in the spectrum, could not be compared with the predictions of this theory because these maxima in the case of the alkali metals lie in the ultra-violet. The theory of photoelectric emission from thin films has consequently had to stand unconfirmed in its entirety until such time as the optical constants of the alkali metals became available. In a separate paper the writers describe an experimental determination of the optical constants of potassium. In the present paper these constants are applied to the photoelectric theory, and the results are compared with experiment.

The Optical Constants of Potassium.[7] HERBERT E. IVES and H. B. BRIGGS. The importance of a knowledge of the optical constants of the alkali metals is emphasized by numerous recent theories of the metallic state and the optical properties of metals in general. In these theoretical treatments the alkali metals, because of their extraordinary properties, in particular their spectral region of transparency, have figured largely. There has, however, existed a serious gap in our experimental knowledge, in that optical constants have been entirely lacking for the region of extreme interest, namely, the ultra-violet. Without such knowledge theories must stand unchecked. Sufficient warrant for undertaking an experimental determination of the optical constants of the alkali metals, of which this study of potassium is the first, is therefore found on this ground alone. In addition, the writers have a special interest in these constants in connection with their work on the photoelectric effect. A theory of the photoelectric emission from thin films of alkali metals, proposed some years ago, which has been very successful in explaining the phenomena in the visible region of the spectrum, has urgently demanded optical data for its test in the ultra-violet region, where the most extreme and characteristic peculiarities of photoelectric emission are found.

Design and Equipment of a Fifty-Kilowatt Broadcast Station for WOR.[8] J. R. POPPELE, F. W. CUNNINGHAM, and A. W. KISHPAUGH. With its novel directional antenna, WOR produces a maximum field strength toward both New York and Philadelphia while limiting radiation in the direction of the ocean and sparsely populated areas. Radiation distribution measurements are given.

The layout of the station and the unique arrangements for lighting, heating, and ventilation of the building are described.

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[7] *Jour. Opt. Soc. Amer.*, June, 1936.
[8] *Proc. I.R.E.*, August, 1936.

A serious attempt has been made to design and operate the equipment for a performance consistent with advanced ideas of high fidelity. Measurements from microphone to antenna of distortion, noise, and frequency response are presented.

Dial Switching of Connecticut Toll Calls.[9] W. F. Robb, G. M. McPhee, and A. M. Millard. The special application of step-by-step dial switching equipment to the handling of short distance toll telephone traffic was introduced in Connecticut in 1929, and has been extended gradually until at present approximately 46,000 toll messages per day, comprising 70 per cent of the traffic between exchanges in this area, are dispatched over the 1,367 circuits of the dial switching network. The resulting service improvements and savings in operating efforts are discussed in this paper, and a brief description of the transmission and equipment characteristics of the system is given.

[9] *Elec. Engg.*, July, 1936.

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