ELECTRICAL COMMUNICATION

A Record of Progress in the Telephone, Telegraph and Radio Art

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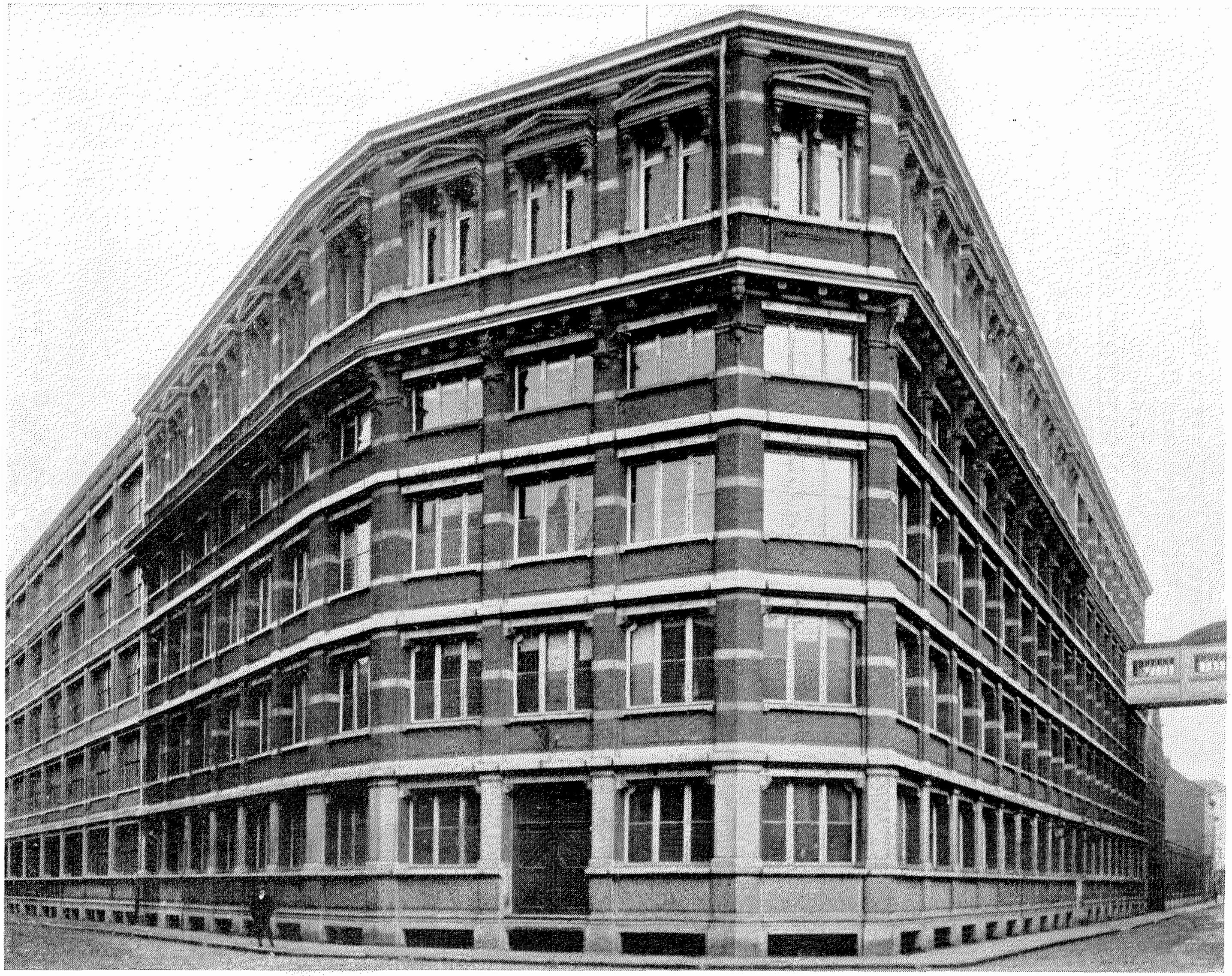


Antwerp Factory of the Bell Telephone Manufacturing Company

FOREWORD

By C. G. DuBOIS

President, International Western Electric Company

IT has been often remarked, particularly since the end of the great war, that the world is daily being brought closer together through better communication. There probably is no one thing which will do so much toward preventing future wars as the improvement and extension of communications between the various countries of the world, allowing a freer exchange of ideas and a clearer knowledge of the desires and aspirations of the peoples and governments.

The Western Electric Company has been closely associated in the development of the art of communication for more than fifty years, and particularly with the telephone art since its invention. The telephone probably has reached its greatest development in the United States, and through association with the Bell Telephone System, the Western Electric Company has been closely connected with the development and improvements in the art of speech transmission. It has always been a satisfaction to those connected with the telephone service provided by the Bell System that improvements have been made in advance of public demand, and it is very largely due to the extensive research and development work carried on in the laboratories of the American Telephone and Telegraph Company and the Western Electric Company that this has been possible of accomplishment.

With the hope of contributing to a closer association amongst the nations and peoples of the world through further improvements in communication, the International Western Electric Company inaugurates in this issue the publication of ELECTRICAL COMMUNICATION, a magazine which will be devoted to relating developments and improvements in the art of communication in all countries and to a discussion of the problems affecting telephone engineers. We hope that the publication may achieve its purpose and that it will be of interest and assistance to our friends throughout the world.

Recent Developments in Electrical Communication

By J. L. McQUARRIE

Assistant Chief Engineer, International Western Electric Company, Incorporated

WHEN it was announced in 1876 that Alexander Graham Bell had invented a device for conversing by means of electricity, there were very few persons who regarded the invention as anything but a toy, yet in less than fifty years, the telephone has become established as an essential feature of our daily lives and its blessings have spread to far corners of the earth. In the United States alone there are more than 13,000,000 telephones which serve to carry 35,000,000 messages daily.

It is indeed fascinating to speak by wire with friends and business associates located within the same community, but with what a feeling of amazement does one engage in a long distance conversation and wonder at the marvelous possibilities of the telephone. Ever since the early days the engineers of the Bell System have reached out to greater and greater distances for telephone communication, until, in the year 1915, conversation was carried on between New York and San Francisco, a distance of 3,400 miles. This was accomplished by means of wires strung on poles over the vast stretches of prairie and mountainous country which lie between the central and western sections of the United States.

The facilities for efficient long distance communication provided by improved circuits resulted in an increased demand for service, requiring the installation of additional wires so that the maximum capacity of the pole lines was soon reached. Appreciating the limitations of open wire construction for congested communication routes early consideration was given to the possible use of lead covered cables for the purpose.

Cables had been used for comparatively short lines within city boundaries, but they were not suitable for long distance communications. Improvements in design permitting of the use of cables over long distances are among the most noteworthy in the development of the telephone art. It is now possible to communicate through cables over distances as great as those bridged in the past by overhead wires; in fact, a cable is now being installed for long distance service between New York and Chicago, nearly 1,000 miles in length.

The attenuation of voice currents through submarine cables is greater than in the case of land cables, but even this obstacle has been surmounted. Three such cables (the longest in the world) were laid between the United States and Cuba in 1921, thus providing a telephone link between the cities of these two countries. An interesting feature of the design is that although each cable contains but a single path for a telephone circuit, the telephone path also provides two superimposed duplexed telegraph circuits.

With its field of application as yet undetermined, but possessing important commercial possibilities, considerable study has been given to the development of radio telephony and in 1915 spoken words were successfully transmitted by radio from Washington to Paris and Honolulu, the Paris message being the first telephone communication to bridge the Atlantic Ocean. During the past year radio telephony has been applied to the commercial system in the form of a radio toll circuit between the coast of California and Catalina Island, a distance of about 30 miles. This circuit transmits in both directions without the necessity of switching from the talking to the listening condition, and is equipped with regular wire line signaling facilities; it is arranged for connection with the land line systems so that persons at Catalina may converse directly with any subscriber on the mainland.

Another notable demonstration of the interconnection of land lines and radio stations occurred recently when telephone communication was established between subscribers' stations in the United States and a transatlantic steamship located 300 miles from shore.

A novel application of radio telephony is the distribution of music and speech from central or "broadcasting" stations in such a manner that homes equipped with comparatively simple and inexpensive apparatus may receive lectures, music, weather reports, market quotations and other useful information and entertainment.

A most interesting exhibition of long distance communication occurred in 1921, when commercial conversation was carried on between Havana, Cuba and Catalina Island, in the Pacific Ocean, a total distance of 5730 miles; the circuit comprised 5600 miles of land lines, 100 miles of submarine cable and 30 miles of radio.

Multiplex telephony has been the dream of inventors for years and it has finally been achieved. A system has been devised and placed in commercial service which provides five commercial telephone channels over one pair of wires, and through the application of the principles of this system to telegraphy, ten duplexed telegraph channels may be secured over a single circuit.

One of the most recent developments is that of the loud speaking telephone used with marked success in connection with public addressing, both in and out of doors. On one occasion an assembly of 125,000 people, in an area of six acres, were able to hear the speaker without difficulty. By association with the commercial telephone service, speech may be transmitted to assemblages at points far distant from that at which the address is being delivered. At the recent memorial services at the National Cemetery at Arlington, Virginia, the address of the President of the United States was distinctly heard by an audience of 100,000 people at Arlington, 30,000 at New York and 20,000 at San Francisco. Loud speaking telephones are also being used in connection with radio receiving sets, thereby materially increasing the popularity of the "broadcasting" service.

Automatic telephone equipments, so arranged that stations may call one another without the intervention of an operator, have been in use for some time, but they have not been suitable for service in the larger metropolitan areas. The intricate traffic problems of these localities required a new type of system, which has been perfected and is now being installed in the larger cities.

This brief survey of the more important developments in the art in the United States illustrates the nature of the work which is being done in the laboratories of the Bell System, operated by the Western Electric Company at New York. In these laboratories numbers of scientists and engineers are constantly engaged in studying the various problems of telephony, telegraphy and radio, and perfecting apparatus to serve the requirements. Future issues of this publication will contain articles dealing with these improvements, as well as a description of the largest and most completely equipped laboratory in the world engaged in the development of apparatus for electrical communication.

Telephone Repeaters

By BANCROFT GHERARDI

Vice-President and Chief Engineer, American Telephone and Telegraph Company

(In the following article the author describes the various types of telephone repeaters which have been employed and their operating characteristics. The application of the telephone repeater to the telephone plant will be discussed in the next issue of ELECTRICAL COMMUNICATION. —EDITOR.)

PART I—DESCRIPTION AND OPERATION OF REPEATER

MANY people think of the telephone repeater as a simple concrete device, a thing to be held in one's hand, brought about by some one act of invention or of engineering. As you read this article I think you will see that the development of the telephone repeater has constituted an art in itself, that it has required the work of an enormous number of scientists, inventors, engineers and manufacturing experts to produce it, and of skilled maintenance and operating men to use it in the most effective manner. The telephone repeater is in no sense a device that was, or could have been, invented by an individual working in isolation.

The purpose of the telephone repeater is to strengthen a feeble telephone message after it has gone a certain distance over line wires, or over a cable, and has become so reduced in energy that if it were not strengthened the result at the other end of the line would be feeble

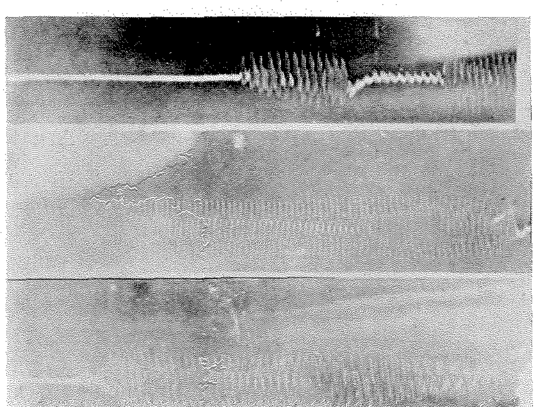


FIGURE 1

and unsatisfactory transmission. Before the telephone repeater was invented the problem of transmitting telephone speech over long distances was analogous to that of shooting a ball out of a cannon to a long distance, and getting all of the necessary impetus to it at the start. By means of the telephone repeater, it is possible to send a message a certain distance and then give it another push, and still another push, so as to finally get it through to its destination.

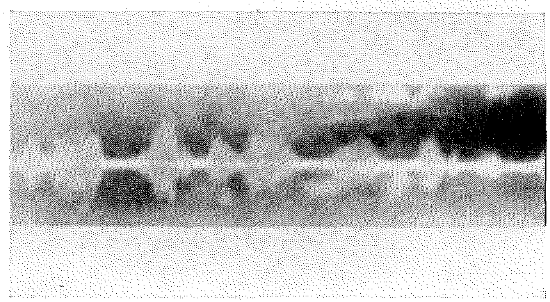


FIGURE 2

It is of course necessary in connection with the telephone repeater to have the device so operate that it preserves the characteristics of the very complicated electrical wave which carries the shape of the human voice, and which makes possible its reproduction in the receiver at the distant end. The photographs shown in Figures 1 and 2 help one to appreciate the severity of this requirement. Figure 1 is an actual photograph of the variations in the electrical current when the word "America" is spoken into a standard transmitter. It is split up into three parts simply to get it into the illustration. It starts across the top, then reads across the middle and then across the bottom.

Figure 2 is a second illustration, showing a simple phrase read from a newspaper article. One can see the rapid variations and how they change in character from instant to instant. One thing which cannot be seen in a photograph like that is the characteristics of the individual oscillations, because the waves are so much compressed that the differences in the shape of those oscillations do not show. Each one of them has characteristics of its own and it is necessary to preserve those characteristics in order that the speech at the distant end may be intelligible.

Figure 3 is a photograph of a recent model of the type of telephone repeater first used successfully for commercial service. That telephone repeater works essentially on the principle of a sensitive telephone receiver coupled with a specially designed telephone transmitter, and using a common diaphragm for the two. The current flows through the receiver element; by means of the receiver it agitates the diaphragm, which is common to both the transmitter and the receiver, and the transmitter, being of the usual battery type, sends out a much stronger current than the one which operates the receiver, and one of the same general shape. This type of repeater, however, does not preserve the wave shape with the same degree of faithfulness as does the repeater element to be described next, and in some other respects is not as good. For the information of those who have never seen one of these repeaters, the total height of the repeater shown in this figure is from four to five inches. At the right of the figure is shown the repeater element in its socket, with its little radiator which performs the same function as the radiator on an automobile.

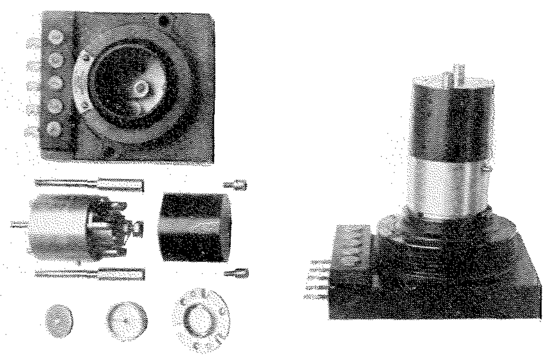


FIGURE 3

Figure 4 shows the repeater ordinarily known as the vacuum-tube repeater. This repeater element is the outgrowth of a device developed by Dr. DeForest for use in wireless work, and known as the audion. The audion was successful as a receiving device for wireless work and, while it did not present the characteristics necessary for the telephone repeater, it was ascertained that it could be developed into a satisfactory repeater element. The tube which is shown in the figure represents the outgrowth of that work. The tube is a glass vessel, a little like an electric light bulb, with the very highest vacuum that can be created inside of it. In the middle of the bulb, and not easy to see, is a filament which is heated when the element is in operation. On either side is a grid, and on the outside of the grids, a pair of plates.

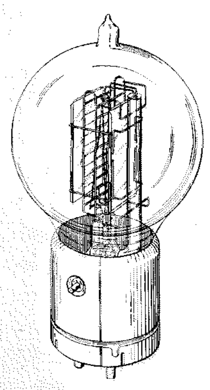


FIGURE 4

By reference to Figure 5 an idea can be obtained of the way in which the tubes operate. In the middle of the figure is diagrammatically shown the filament, as well as the battery which sends current through that filament whenever the repeater is to be used and raises it to a dull red heat.

Next are diagrammatically shown a pair of grids, which are merely wire screens as indicated in the photograph of Figure 4. They are connected together. Outside of that are two plates, also connected together. The device could work perfectly well with a single plate, but one can get more out of a single tube by having a plate on both sides of the filament.

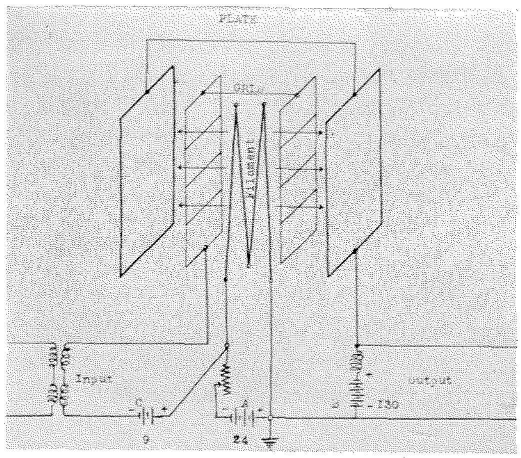


FIGURE 5

What happens in a tube like that when it is operating is this: When the filament is heated to a dull red heat there is sent out from it a continuous stream of particles of negative electricity which, under the impulse of the electromotive force of a battery in the output circuit (not shown in the picture), flows through the grids and to the plates. The tube has this property, and this is the property by virtue of which it amplifies, that any change of the electrical potential of the grids immediately changes the amount of electric current which flows from the filament to the two plates. If then the potential of the grids be varied, they act just like valves, opening and letting more electricity through, or shutting and keeping the electricity out. It is purely electrical action, but analogous to the result of moving the slats of a window blind.

The telephone current which is to be amplified is therefore applied between the grids and the filament. This current varies the potential of the grids and these variations of potential make relatively enormous changes in the amount of current which flows from the filament to the plates. The result is the flow of an enormously amplified current in the output circuit similar in shape to the current which has come in on the controlling circuit. A tube of the kind used for standard telephone work, such as the one illustrated, is capable of amplifying the energy received by it about 400-fold, which, you see, is a very large ratio. If it is desired to amplify more than 400-fold, it is perfectly practicable to do so by simply connecting a second tube in series with the first one; that is, one can connect the output circuit into another tube as an input circuit, and with such a combination can get an amplification of 400 times 400, or 160,000. This can be continued to give enormous amplifications. Some of the most marvellous work done in war times in connection with picking up wireless messages from great distances was by means of tubes connected in this way, in what we call a 7-stage amplifier, and a 7-stage amplifier gives an almost inconceivable amplification, millions and millions of times.

The arrangement which has been described so far is a one-way device, that is, a device which would not amplify the telephone current in both directions. In fact, two-way working, which is an essential feature of telephone operation, must be obtained by some additional arrangements; it is not characteristic of the element itself, it is characteristic of the circuit in which the element is used.

Figure 6 shows one of the simplest forms of a two-way circuit. A repeater element, in this case of the mechanical type, is represented diagrammatically. The input circuit is connected in series in the line. The output circuit, which is represented as a little transmitter, is shown bridged across the line.

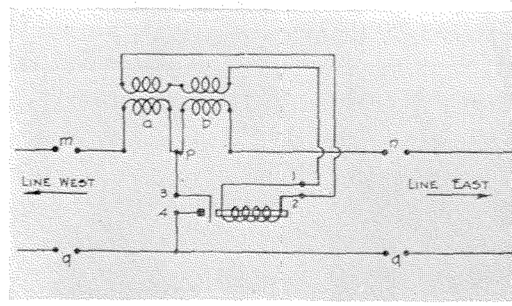


FIGURE 6

Consider now what happens when someone is speaking on the line. Let us suppose someone is speaking from the western end. The telephone current flows through the line and the series coil, and a considerable part of the energy of the telephone current is transferred by the coil to the input circuit of the repeater. In the repeater it is amplified and appears in the output circuit. From the output circuit it splits equally in the two directions, half of it going back, and serving no useful purpose as far as conversation is concerned, the other half going forward and representing the amplified speech which the repeater has produced. It has been stated previously that energy which went back served no useful purpose for conversation. However, without it the circuit would not work, for this reason: If the energy did not split equally in two directions from the output circuit, the output current would affect unequally the two halves of the input coil, which are in opposition to each other, and energy would be transferred over into the input circuit. This reaction of the output on the input produces what is called a "singing" circuit, because it will sustain a singing tone which drowns out the speech.

You will note that the circuit is perfectly symmetrical. Exactly the same thing will happen if someone talks from the eastern end of the line and so the amplification is accomplished in both directions. So you see that the simple one-way piece of apparatus is so connected to the lines by means of the circuit which is employed with it that a two-way working piece of apparatus is created.

For successful two-way working, however, there is one more condition which must obtain and which has not yet been named. I have spoken of the current as dividing equally in the two directions from the output circuit, so as to have a neutral effect on the input coil, and not come back into the receiving element. Now, no matter how well the input coil may be constructed—it may be constructed so that the two halves of it are almost perfectly precise—equal division between the two halves of the coil cannot be obtained unless the lines going west and the lines going east have the same electrical characteristics; in other words, unless they are balanced against each other. If one line is different in its electrical characteristics from the other, then, notwithstanding the equality of the two parts of the coil, there will be an unequal division of the current, and there will be singing.

The matter of balance is one of the questions of the greatest difficulty to deal with in connection with the telephone repeater problem. I may say that the matter of the study of balance, or of methods of obtaining balance, has perhaps received as much study as any other phase of the telephone repeater problem. Years of time and hundreds of thousands of dollars' worth of effort were put into it in order to obtain satisfactory solutions. It is simple enough to describe in general terms, but it is neither simple to determine the requirements, nor to determine how to accomplish it in the plant after the requirements are known.

The circuit shown in Figure 7 is a little more complicated, but it has outstanding advantages for many situations. If half of this circuit is cut off, there will remain the circuit shown in Figure 6; that is, a simple circuit in which the line in one direction is balanced against the line in the other direction. What has been done here is to employ two repeaters, one to repeat one way and one to repeat the other way, and to connect them up in such a way that each line is balanced against an artificial line. That is to say, by putting in two artificial lines where we had none before, putting in two repeaters where we only had one before, and putting in two coils where we only had one before, we have eliminated the condition that the lines must be balanced against each other, and substituted for that a condition in which each of the lines must be balanced against an artificial line. Now, it may not appear at first that we have simplified our problem, but we have, notwithstanding the fact that we are employing more elements than we did before. We have simplified it in several respects.

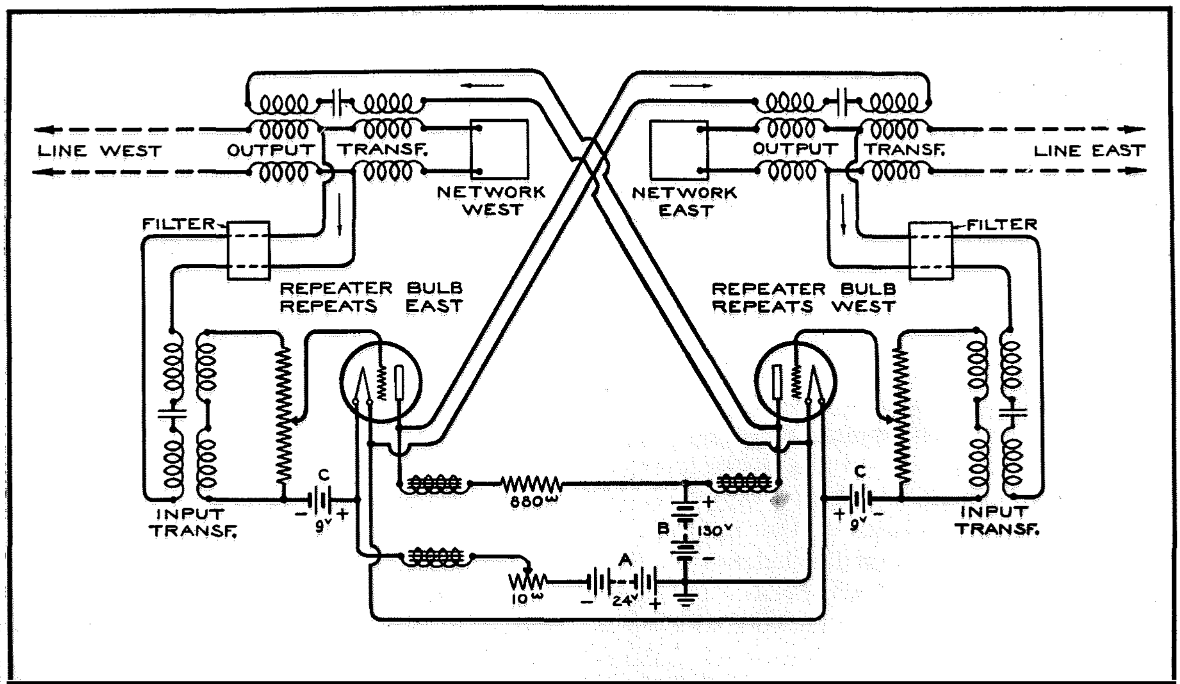


FIGURE 7

In the first place, suppose that one line is a loaded line and the other line a non-loaded line, it would not be possible to balance them against each other, because there would be two things that are inherently electrically different. But one balancing line can be put into the circuit to go with the loaded line and another to go with the non-loaded line, and meet the conditions of the problem. A perfect balance is never possible, but under a good many conditions it is possible to get a good balance, and it is very valuable to have a circuit arrangement by which operation can continue when something happens on one of the lines to disturb the balance.

The two circuits which have been shown are the principal ones which have been of practical use.

Figure 8 is an interesting diagram which has to do with the characteristics of a loaded telephone line. If the line represented by the dia-

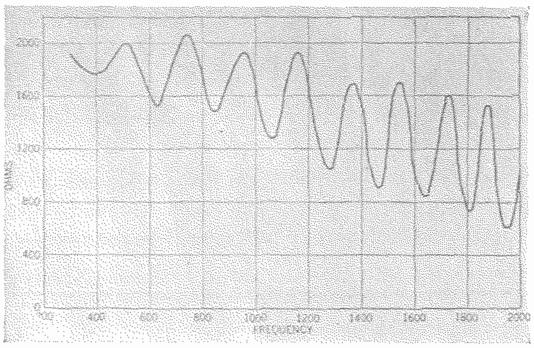


FIGURE 8

gram were a perfectly uniform line, the wavy line of impedance shown in the diagram would be a smooth curve. As a matter of fact, the line had certain irregularities in it and it is practically impossible to balance a line by means of an artificial line when it has characteristics of that kind. It can be done theoretically, but it is not a practical working proposition.

Figure 9 is the same line, showing the extent to which it has been possible to reduce the irregularities, which you see are vastly less than they were before. The diagram shows the corresponding characteristic of the network, or artificial line, that was used to balance the line; there is a variation of a few per cent. The figure shows also a diagram of the network which produced this characteristic when used as a balancing network.

Before describing repeater installations, there

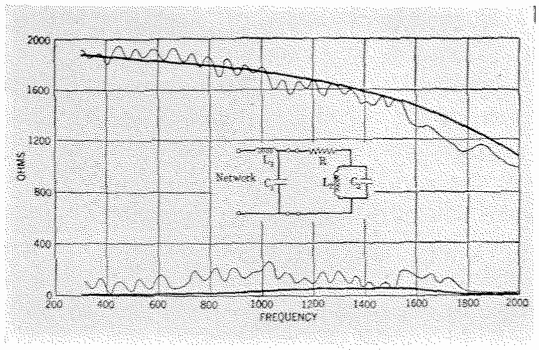


FIGURE 9

is one more way that repeaters can be used that merits description. It is a very interesting and important development which has followed our earlier repeater work, and is known as the 4-wire circuit. Its chief application is in the case of long cables and it is an arrangement which does away with the necessity for balance except at the ends of the circuit. The circuit is indicated in Figure 10. At each end is the same kind of a coil that is used in the other repeater circuits. Telephone currents from one end go through one coil and then pass through a succession of repeaters in what is merely a one-way circuit. They come out through another coil, and by means of the balancing artificial line, are prevented from going back on the other one-way circuit at the other end. All the amplification desired can be obtained in a succession of repeaters located at intervals along each one-way circuit without having to be concerned with the balance except at the two ends of the circuit,

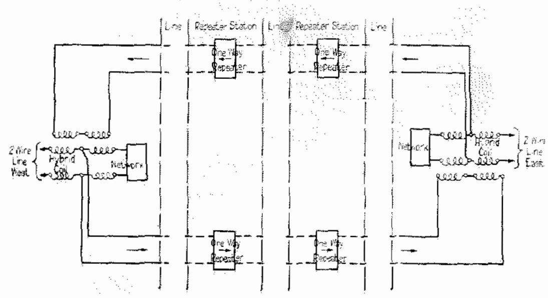


FIGURE 10

a very much simpler condition to meet than having to be concerned with balance and line characteristics at every point where a repeater is inserted. In a later issue of ELECTRICAL COMMUNICATION there will be described the application of that arrangement, and the advantages of it will be then more clearly apparent.

The Dynamical Theory of Amplifying and Oscillating Systems

By H. W. NICHOLS, Ph.D.

Department of Physical Research, Western Electric Company

An ordinary-scale dynamical system whose state is completely specified by n Lagrangian coordinates $x_1 \ldots x_n$ obeys the system of differential equations

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{x}_k} - \frac{\partial L}{\partial x_k} + \frac{\partial F}{\partial \dot{x}_k} = E_k \quad k = 1 \ldots n \quad (1)$$

in which $L = T - V$ is the difference between the kinetic and potential energies, expressed as functions of the coordinates and velocities, and F is the Dissipation Function, equal to half the rate at which energy is thrown from the system into molecular motions, *i.e.*, into degrees of freedom which would be specified by finer scale coordinates than those of interest in the problem in hand. T and F are homogeneous quadratic functions of the velocities, the coefficients being functions of the coordinates and containing parameters representing qualities of materials, such as mass, inductance, elasticity, dielectric constant, and resistance which are not functions of the coordinates.

From the derivation of (1) it follows that the principle of energy is satisfied, that is, the rate of change of energy of the system is accounted for by the dissipation and the activity of the impressed forces. There are, however, many physical systems in which a state of oscillation or motion is maintained against dissipation and with no impressed forces of the type of the motion, the energy being derived from a reservoir or source which is ignored for the purposes of the problem. Examples are "amplifiers" in which more power of the type of the impressed force is liberated than is represented by the activity of that force, and "oscillation generators" which maintain themselves in electrical or mechanical oscillation (sustained or with positive or negative damping) by transformation of energy from the reservoir. The purpose of this paper is to show what are the general conditions under which such transformation and liberation of energy can take place and to develop the equations of such systems.

Suppose a dynamical-electrical system is in a state represented by the equations (1) in which all mass or inductance parameters l, resistance parameters r, and elasticity or stiffness parameters s are constant; then impressed forces explicitly shown account for energy supply to the system. In order to produce disturbances whose energy does not come from impressed forces of similar type acting upon the coordinates it is necessary, therefore, to vary one of the parameters above and modulate, in accordance with that variation, that state of the system which would exist with invariable parameters. These parameters cannot be fixed completely by analytic functions of the Lagrangian coordinates, for if so, a new Lagrangian system would result in which no energy transformations of this kind could take place. Hence, the necessary condition that energy may be transformed from the sources supplying energy in the undisturbed state of the system, rather than from impressed forces acting upon the coordinates, is that some parameter not in the group $(x_1 \ldots x_n)$ shall be varied.

In most cases of interest equations (1), when expanded, result in linear differential equations of the form:

$$\begin{array}{llll} S_{11}\,x_1 & - S_{12}\,x_2 & - S_{13}\,x_3 \cdots & = E_1 \\ - S_{21}\,x_1 & + S_{22}\,x_2 & - S_{23}\,x_3 \cdots & = E_2 \\ \cdots & & & \\ & & + S_{nn}\,x_n & = E_n \end{array} \quad (2)$$

in which S_{jk} is an operator equal to

$$l_{jk}\,p^2 + r_{jk}\,p + s_{jk};\ p = \frac{d}{dt}$$

and l, r, s are not functions of the x's. They are inductance (or inertia), resistance and stiffness appearing in T, F and V respectively.

Now suppose that l_{11}, r_{11} and s_{11} are functions of a parameter $q(t)$ and put

$$S_{11} = S_o - \delta S$$

in which S_o is the value of S_{11} for the invariable system $q = O$. Then from (1)

$$-\delta S = \delta l\,p^2 + \left(\delta r + \frac{d\delta l}{dt}\right) p + \delta s.$$

Also let $x_k = X_k + z_k$ where

$$X_k = \frac{\Sigma D_{kj} E_j}{D}$$

is the solution for the invariable system $q = o$, D being the operational determinant of (2) and D_{kj} the minor of S_{kj}. Substituting this in (2) and adding, for completeness, forces e_k of z-type, we get, to first order terms:

$$\begin{aligned} S_{11} z_1 \quad - S_{12} z_2 \quad - S_{13} z_3 - - - &= e_1 + \delta S X_1 \\ - S_{21} z_1 \quad + S_{22} z_2 \quad - S_{23} z_3 - - - &= e_2 \\ \cdots\cdots\cdots\cdots & \\ - - - - - - - - - - \quad + S_{nn} z_n &= e_n \end{aligned} \qquad (3)$$

This shows that the effect of considering as a complete dynamical system only the varied state, and ignoring the energy of the sources E, is to make the system equivalent to one in which the driving force is located in the variable element and is treated as an impressed force.

The form of the operators S is important. It is proved in text books on dynamics that the most general form of the determinant D is

$$\begin{vmatrix} S_{11} & -(A_{12} + B_{12} p) & -(A_{13} + B_{13} p) - - - \\ -(A_{21} + B_{21} p) & S_{22} & -(A_{23} + B_{23} p) - - - \\ & & S_{nn} \end{vmatrix} \qquad (4)$$

in which $A_{jk} = A_{kj}$ and $B_{jk} = - B_{kj}$, B being a constant, *i.e.*, not an operator. The latter terms arise from departures from a state of motion and when they are zero we have $S_{jk} = S_{kj}$, the determinant is symmetrical and the reciprocal theorem holds. The B-terms do not appear in the energy equation, for, upon multiplying the *kth* equation by $\dot{z}_k$ and adding, they cancel.

It has now been shown that energy can be supplied to (or drawn from) the system by variations in certain elements and that the energy so supplied does not depend upon impressed forces acting upon the coordinates z, but comes from an ignored source. The next step is to include the dynamical system which produces the special variation δS. To do this, suppose δS depends upon $z_1 \ldots z_n$, $z_{n+1} \ldots z_{n+m}$ through a linear differential equation:

$$\delta S = \sum_{1}^{n+m} G_{1_k}(p) z_k \qquad (5)$$

where $z_{n+1} \ldots z_{n+m}$ are additional coordinates specifying a mechanism belonging only to δS. This mechanism obeys linear differential equations:

$$\begin{aligned} \underset{n+1}{S_{n+1}} z_{n+1} \quad - \underset{n+2}{S_{n+1}} z_{n+2} - - - - &= e_{n+1} \\ \cdots\cdots\cdots\cdots & \end{aligned} \qquad (6)$$

Put now

$$\Sigma G_{1k}(p) z_k X_1 = \Sigma Q_{1k} z_k$$

and substitute in (4), adding also the equations (5) to form the equations of the complete system:

$$\begin{aligned} (S_{11} - Q_{11}) z_1 \quad - S_{12} + Q_{12}) z_2 - - - - - & \\ - Q_{1,n+1} z_{n+1} - - &= e_1 \\ - S_{21} z_1 \quad + S_{22} z_2 \quad - \quad O \qquad &= e_2 \\ \cdots\cdots\cdots \quad O \qquad & \\ O \qquad O \qquad \underset{n+1}{S_{n+1}} z_{n+1} - - &= e_{n+1} \\ \cdots\cdots\cdots\cdots & \\ O \qquad O \qquad \ldots \underset{n+m}{S_{n+m}} z_{n+m} &= e_{n+m} \end{aligned} \qquad (7)$$

Finally, solve the last m equations for $z_{n+1} - - - z_{n+m}$ and substitute in the first n equations, putting

$$\sum_k Q_{n+k} z_{n+k} = f_1.$$

The result is

$$\begin{aligned} (S_{11} - Q_{11}) z_1 \quad - (S_{12} + Q_{12}) z_2 - \quad - - - & \\ - (S_{1n} + Q_{1n}) z_n &= e_1 + f_1 \\ - S_{21} z_1 \quad + S_{22} z_2 - \quad - - - - - - &= e_2 \\ \cdots\cdots\cdots\cdots & \\ - S_{n1} z_1 - - - - - - - - + S_{nn} z_n &= e_n \end{aligned} \qquad (8)$$

These are the equations of a dynamical-electrical system to which energy is supplied from an ignored source by means of the variation discussed above. They differ from those of the invariable system $\delta S = O$ because of the Q-terms, whose significance will now be discussed.

The simplest case is that in which $Q_{11} \ldots Q_{1n}$ are zero so that the only term which depends upon the variation is f_1. This is the impressed force which arises from those acting upon the coordinates $z_{n+1} - - - z_{n+m}$ controlling δS. Since the energy liberated in the system $z_1 - - - z_n$ is not, in this case, dependent upon the energy required to control δS, it follows that amplification may be produced at the expense of the ignored sources $E_1 --- E_n$. The simplest example of a system of this type is a telephone microphone in which the single variable ($\dot{z}_1$) is the variation in current through the microphone while $z_{n+1} --- z_{n+m}$ are the coordinates specifying the state of the dynamical system comprising the diaphragm, a column of air and the speaker's vocal apparatus. Evidently the variation $X_1\delta S$ may bear any relation to the impressed sound waves and hence the power liberated, $X_1\delta S\dot{z}_1$, may be larger than that in the sound waves. In systems of this first class there is no reaction back from $z_1 --- z_n$ to $z_{n+1} --- z_{n+m}$, that is, the energy flow is unilateral.

A second class is made up of those systems for which Q_{11} is the only term containing δS. Writing $Q_{11} = a_{11} p^2 + b_{11} p + c_{11}$ it is clear that the variation δS has resulted in changing the "stiffness" S_{11} to

$$S_{11} - Q_{11} = (l_{11} - a_{11}) p^2 + (r_{11} - b_{11}) p + (s_{11} - c_{11})$$

Hence $-b_{11}$ is called a "negative resistance." Such a term can arise only when (1) there is an ignored source of energy and (2) when some element of the system is varied as discussed above.

Since here $D = \Delta - Q_{11} \Delta_{11}$, where Δ is the value of D for $\delta S = O$, an impressed e_1 produces the effect

$$z_1 = \frac{\Delta_{11}}{\Delta - Q_{11} \Delta_{11}} e_1$$

which may be larger or smaller than that occurring in the corresponding invariable system for which $Q_{11} = O$. Amplification may therefore take place. The power supplied by the ignored source is $b\dot{z}_1^2$.

A third type of system is found by making one of the Q's with unlike subscripts different from zero, all the others being zero. For example, let Q_{12} be different from zero, so that the differential equations are

$$\begin{aligned} S_{11} z_1 \quad & - (S_{12} + Q_{12}) z_2 \quad - S_{13} z_3 --- = e_1 \\ - S_{21} z_1 \quad & + S_{22} z_2 \qquad - S_{23} z_3 --- = e_2 \end{aligned} \quad (9)$$

$$\cdots\cdots\cdots\cdots\cdots\cdots\cdots$$

in which the S's are still of the form (4). Hence in addition to the activity of the impressed forces, $\Sigma e_k z_k$, which, with $Q_{12} = O$, would account for the rate of change of energy and the dissipation of the system, there appears the activity $Q_{12} z_2 \dot{z}_1$, or $\frac{Q_{12}}{p} \dot{z}_1 \dot{z}_2$. The power represented by this is drawn from the ignored source. $\frac{Q_{12}}{p}$ is called a "mutual impedance" and since $Q_{21} = O$, this mutual impedance is ***unilateral.***

The meaning of this will become more apparent upon considering how the reciprocal theorem is modified by the presence of terms such as Q_{12}. Thus considering two impressed forces e_1 and e_2 we have:

$$z_1 \text{ (due to } e_2) = \frac{D_{21}}{D} e_2$$

$$z_2 \text{ (due to } e_1) = \frac{D_{12}}{D} e_1.$$

In the case of oscillations about equilibrium, and with no ignored sources, $D_{12} = D_{21}$ so that

$$\frac{z_1}{e_2} = \frac{z_2}{e_1}$$

which is the reciprocal theorem. In this case, however,

$$D_{12} = \Delta_{12}$$

$$D_{21} = \Delta_{21} - Q_{12}\Delta_{21}^{12}$$

and the effects of an impressed force are different in opposite directions through the system because of the Q-term. For example, let $\dot{z}_1$ and $\dot{z}_2$ be currents and the corresponding e's electromotive forces. Then the mutual impedances,

$$\frac{e_1}{\dot{z}_2} = \frac{D}{pD_{12}} \text{ and } \frac{e_2}{\dot{z}_1} = \frac{D}{pD_{21}}$$

are different in the directions (1-2) and (2-1). If $\Delta_{21} = \Delta_{12} = O$, the two parts of the system are *conjugate* for $Q_{12} = O$ and the action between the two is entirely in one direction. This is the condition usually desired in telephone repeater operation.

A fourth case of great interest is that in which there are no impressed forces of any kind, so that the right hand members of equations (8) are all zero. In this case the system executes free oscillations. This problem has been studied very thoroughly for the usual case in which there are no Q-terms, the result being as follows:

Each coordinate z_k undergoes a variation which is the resultant of n damped oscillations:

$$z_k = \Sigma A_{kr} \epsilon^{p_r t}$$

in which p_r is a root of $\Delta(p) = O$ and A_{kr} is a constant depending upon the initial conditions. Both are, in general, complex numbers and occur in pairs so that z_k is real. p_r is equal to $i\omega_r + \delta_r$ where $\frac{\omega_r}{2\pi}$ is the frequency of a component oscillation (it may be zero) and δ_r is the damping of that component. For the case $\delta S = O$, *δ_r is always negative, i.e.*, all component oscillations decrease with the time. This is a mathematical consequence of the form of the determinant Δ. The more general determinant, D, which is obtained when δS is not zero, permits a much wider range of values of p_r, since there is no necessary relation between the Q terms and the dynamical system $z_1 - - - z_n$. This allows, for example, the fixing of δ_r at some positive value, or at zero, so that the oscillation of the system may increase with time, or be sustained. It may also be fixed at any negative value. Suppose it is required to determine under what conditions the system will execute *sustained* oscillations, for which $p = i\omega$. Substitution of this in $D = O$ will result in the equations:

$$F(\omega, \text{system constants}) + iG(\omega, \text{system constants}) = O$$

which, solved, simultaneously, will give certain values of ω which can exist for certain corresponding values of the constants of the system. A similar method applies when the damping is to have any assigned value. When the damping or the frequency is fixed beforehand and the system constants adjusted to produce such oscillations, the behavior of the system is different from that of an invariable one in two respects: the oscillations do not necessarily decrease with time and there are not necessarily (or usually) n component oscillations of each coordinate.

Examples of dynamical and electrical systems which function as amplifiers and oscillation generators are worked out in two papers in the *Physical Review*, August, 1917, and June, 1919.

To summarize, it has been shown that sufficient conditions for the production of "negative resistance" or "negative impedance" phenomena, the various types of amplification known, and for the operation of devices executing sustained oscillations are that there shall be a basic state of the system which is specified by variables whose values are not of interest in the problem and consequently are ignored ($X_1 \ldots, E_1 \ldots$), that this state shall be modulated to produce variations of the type ($z_1 \ldots z_n$) considered in the problem, and that this modulation shall be accomplished by changes in physical quantities of the nature of mass or inductance, resistance, elasticity or dielectric constant, whose dynamical structures are not included in the Lagrangian and Dissipation functions of the problem. The essential feature is the ignoring of certain sets of variables: when the *complete* dynamical structure of the system is taken into account there can be no addition of energy to the system in the manner here considered. In the same way, a complete dynamical specification of a system would include molecular and electronic coordinates so that, as is shown in the dynamical theory of heat, the apparent loss of energy from the system by dissipation would be accounted for by energy acquired by degrees of freedom which were ignored in the ordinary-scale problem.

A New Type of High Power Vacuum Tube

By W. WILSON, D.Sc.

Department of Physical Research, Western Electric Company

(The type of vacuum tube described in the present article is likely to become one of the most remarkable devices of modern electrical science. Vacuum tubes capable of handling small amounts of power have been extensively used during the past few years as telephone repeaters and as oscillators, modulators, detectors and amplifiers in radio transmission and other fields. All vacuum tubes heretofore used have depended upon thermal radiation from the plates to dissipate the electrical energy which the device necessarily absorbs during its operation. With present known methods of construction a fairly definite upper limit can be set for the power which a radiation cooled tube can handle; as the author points out, this limit gives a tube capable of delivering about 1 to 2 k. w. when used as an oscillator.

Contrasted with this, one of the water-cooled vacuum tubes described herewith, although scarcely two feet in length and weighing only ten pounds, is capable of delivering 100 k. w. of high frequency energy. Another tube of similar construction, but somewhat smaller in size, and capable of delivering about 10 k. w., is also described. It is expected that these water-cooled tubes will find an immediate application in radio telephony and telegraphy, and without doubt they will shortly be put to other important uses.

Although the principle of operation of the water-cooled tube in this article is identical from an electrical point of view with that of the small tubes which are now so very familiar, their construction has only been made possible by a new and striking development in the art of sealing metal to glass. In the case of the 100 k. w. tube the seal between the cylindrical copper anode and glass transmitter is 3.5 inches in diameter.

The remarkable character of these copper-in-glass seals is evidenced by the fact that they do not depend upon a substantial equality between the coefficient of expansion of the metal and glass. To Mr. W. G. Houskeeper, of the Bell System Research Laboratory at the Western Electric Company, goes the credit for developing the copper-in-glass seals. As the article brings out, Mr. Houskeeper has also invented means for sealing heavy copper wire and strip through glass in such a way that the best vacua can be maintained under wide changes of temperature.—EDITOR.)

THE development of wireless telephony and the use of continuous wave transmission in wireless telegraphy have led to the general adoption of the vacuum tube as the generator of high frequency currents in low power installations.

The ordinary form of vacuum tube is, however, ill suited for the handling of large amounts of power, and at the large wireless stations where the plant is rated in hundreds of kilowatts either the arc or the high frequency alternator is used.

The undoubted advantages to be derived from the use of vacuum tubes, especially in the field of wireless telephony where the output power must be modulated to conform to the intricate vibration pattern of the voice, has led to a demand for tubes capable of handling amounts of power comparable with those in use at the largest stations.

That the development of such tubes was of great importance was recognized by the engineers of the Bell Telephone System in the early days of the vacuum tube art. The experiments at Arlington, Virginia, in which speech was first transmitted across the Atlantic to Paris and across the Pacific to Honolulu, required the use of nearly 300 of the most powerful tubes then available, each capable of handling about 25 watts, and the difficulties encountered in operating so many tubes in parallel gave added impetus to the development of high power units.

It is the object of the present paper to deal with the various steps in the development of high power tubes as carried out in the Bell System research laboratories at the Western Electric Company.

The usual type of vacuum tube consists of an evacuated glass vessel in which are enclosed three elements, the filament, the plate, and the grid. When the tube is in operation an electron current flows between the filament which is heated by an auxiliary source of power and the plate, the magnitude of this current being controlled by the grid.

The passage of the current through a thermionic tube is accompanied by the dissipation in the plate of an amount of power which is comparable to the power delivered to the output circuit and which manifests itself in the form of heat. This causes the temperature of the plate in the usual type of tube to rise until the rate of loss of heat by radiation is equal to the power dissipated. Some of the heat liberated by the plate is absorbed by the walls of the containing vessel which consequently rise in temperature. These factors, together with a consideration of the size of plate that can be conveniently suspended inside a glass bulb and the size of glass bulb that can be conveniently worked, set a limit of about 1 to 2 k. w. for the power that can be dissipated in the plate of a commercial vacuum tube of this type. The plates are generally constructed of molybdenum or some other refractory metal and the containing vessel made of hard glass.

The use of quartz as the containing vessel offers certain advantages which tend to raise the power limit somewhat and this material has been used for power tube purposes in England. It is apparent then that in the development of vacuum tubes capable of handling large amounts of power means other than radiation must be used for removing the heat dissipated at the plate, and development of tubes along these lines was undertaken by Dr. E. R. Stoekle and Dr. O. E. Buckley.

Dr. Stoekle had already worked for some years on the problem of removing the heat dissipated at the anode of a thermionic tube by making the anode a part of the outside wall of the vessel and thus making it possible to convey the heat directly away from it by means of circulating water. This was clearly the right principle but as is obvious to those who are familiar with these devices, great difficulties presented themselves in the mechanical construction of large tubes in which vacuum tight joints must be made and maintained between glass and large masses of metal. The importance of the problem, however, was such that Stoekle and Buckley pushed on in the face of difficulties to the construction of tubes which could handle kilowatts where previous tubes could only handle watts.

A step in the direction of overcoming these difficulties was made by Messrs. Schwerin and Weinhart, who were working with Dr. Buckley on the problem, and who suggested that the anode might be made in the form of a tube or thimble of platinum sealed into a glass vessel and kept cool by passing water through it.

This suggestion led to the development of a tube which, although not the one finally adopted, is discussed in some detail since it was the first one to be pushed to such a point as to give promise of economical commercial manufacture.

The tube is shown in Fig. 1. The anode consists of a platinum cylinder A, 7″ long and .625″ wide, which is sealed into the center of the glass cylinder B. The end of the platinum cylinder remote from the seal is closed. The anode is surrounded by the grid C and by the filament D, which are supported by the glass arbors E. The current for the filament is led into the tube through the platinum thimbles F.

The anode is kept cool by means of a supply of water passing into the anode through the tube G and leaving by the tube H.

A number of tubes having this general type of construction were made up and it was found possible to dissipate as much as 15 k. w. in the anode.

As soon as the pressure of work more directly connected with the necessities of the war would permit, Mr. W. G. Houskeeper and Dr. M. J. Kelly undertook the further improvement of the water-cooled tube, the former assuming the task of developing the mechanical structure, and the latter that of determining the electrical design and the process of tube exhaust.

Mr. Houskeeper adopted into the construction of the tube a remarkable type of vacuum seal which he had previously developed. These seals are made between glass and metal and can be made in any desired size. They are capable of

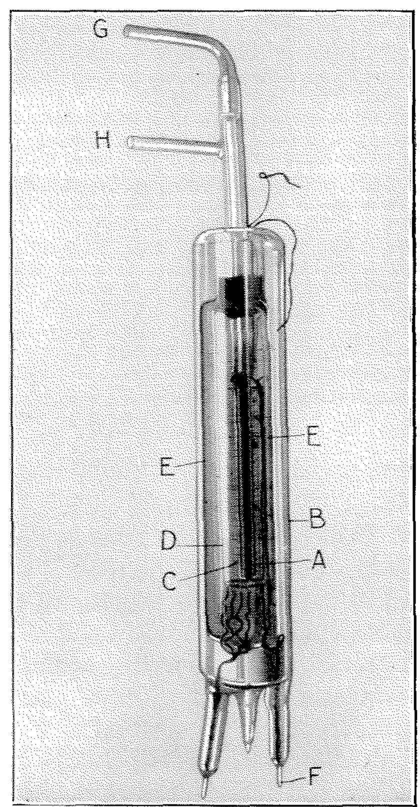


FIGURE 1

withstanding repeated heating and cooling over wide ranges of temperature, from that of liquid air to 350° C, without cracking and without impairment of their vacuum holding properties.

It is no exaggeration to say that the invention of these seals has made possible the construction of vacuum tubes, capable of handling in single units, powers of any magnitude which may be called for in wireless telegraph and telephone transmission.

The underlying principle connected with the making of this seal consists in obtaining an intimate connection between the glass and metal, either by chemical combination or by mere wetting, and in so proportioning the glass and metal portions of the seal that the stresses produced when the seal is heated or cooled will not be great enough to rupture either the glass or the junction between the glass and metal.

The three principal types of seals developed by Mr. Houskeeper are known as the ribbon seal, the disc seal and the tube seal.

If a copper ribbon is directly sealed through glass it is found that the glass and copper adhere along the flat faces of the seal but that ruptures occur along the edges as shown in Fig. 2 (a). This is due to the fact that as the seal cools after

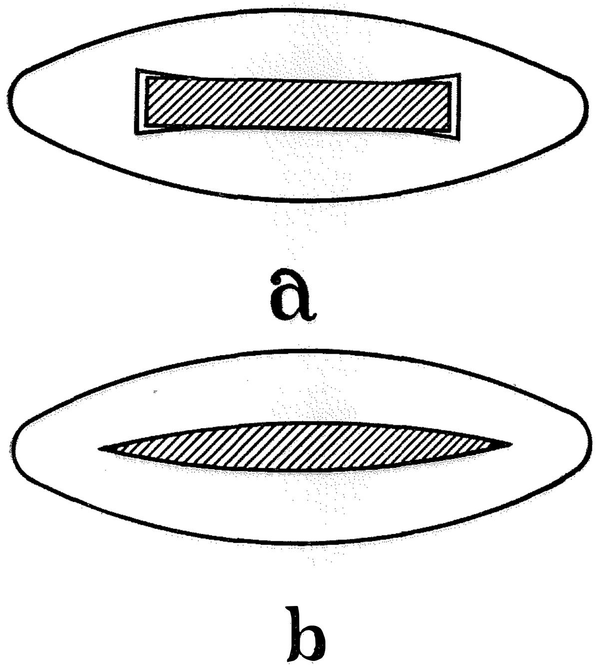


FIGURE 2

being made, the glass in contact with metal is capable of resisting the shearing and tensile stresses that occur along the faces, while the glass wrapping round the edges of the ribbon is called upon to withstand much greater tensile stresses and gives way. If the edges of the ribbon are sharpened as shown in Fig. 2 (b), a tight seal results, the reason being that the forces of adhesion between the glass and copper acting along the flat contact faces are sufficient

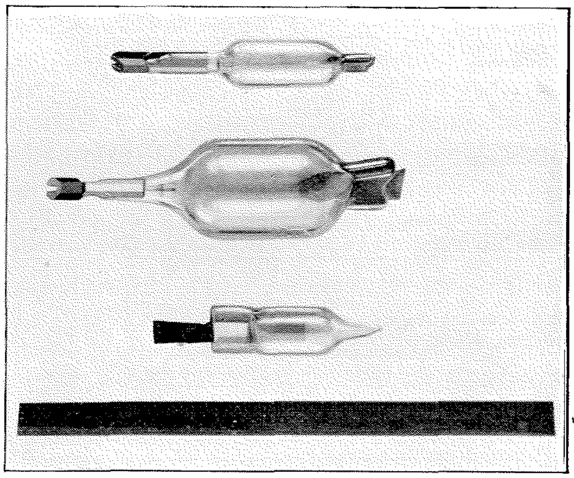


FIGURE 3

to stretch the thin copper at the edge and prevent its drawing away when cooled. There is a definite relation between the elastic properties of the metal and glass and the angle of edge that can be used for a successful seal.

By proper shaping of the metal ribbon, seals have been successfully made up to very large sizes. Some of these are shown in Fig. 3, the largest in the photograph being about 1″ in width, and capable of successfully conducting a current of 150 to 200 amperes.

The principles involved in the making of the disc seal are the same as those involved in making the ribbon seal. If a metal disc is sealed wholly into glass the edges must be sharpened or the glass and copper break away from each other as in the case of the ribbon seal.

In the general use to which these seals are put there is no necessity for having the glass surround the circumference of the copper disc and the necessity for sharpening the edge is obviated by allowing the glass to adhere to the flat portion of the disc only, care being taken to prevent its flowing around the edge. It is necessary to have a ring of glass on both sides of the seal in order to equalize the bending stresses which would otherwise tend to break the glass and copper away from each other. Successful disc seals have been made with copper up to $\frac{1}{10}$″ thick. There is, of course, a certain maximum thickness that can be used for a seal of a given diameter and it is preferable to keep well below this limit.

The seals shown in Fig. 4 close the ends of glass tubes to the other ends of which are sealed

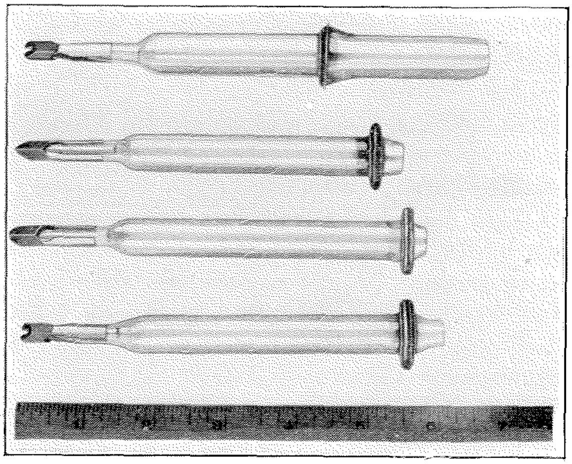


FIGURE 4

pilot lamps for the purpose of testing the vacuum. Tubes sealed in this way have been kept a number of years without any impairment of the vacuum.

The third type of seal and the most important in connection with the present problem is the tube seal shown in Fig. 5. This furnishes the means of joining metal and glass tubes end to end and is used in the water-cooled tube to attach the anode to the glass cylinder which serves to insulate the other tube elements. As in the case of the disc seal, it can be made either with the edge of the metal not in contact with the glass, as shown at A, or with the metal sharpened to a fine edge which is in contact with the glass. The glass may be situated either inside or outside of the metal, see B and C.

The first thermionic tubes in which these seals were embodied were made of copper and

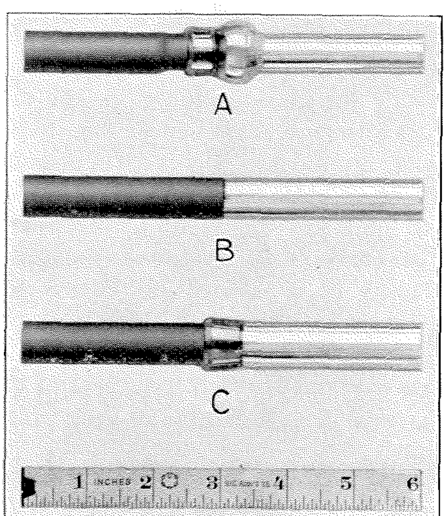


FIGURE 5

were designed to operate at 10,000 volts and to give about 5 k. w. output.

A photograph of one of these tubes is shown in Fig. 6; and the filament grid assembly is shown in Fig. 7.

The anode consists of a copper tube 1.5″ in diameter and 7.5″ long. A copper disc is welded to one end forming a vacuum-tight joint. The other end which is turned down to a knife edge is fused directly to a glass tube.

The filament grid assembly consists of two lavite discs D and E, spaced 5″ apart by a seamless steel tube. The grid F is made in the form

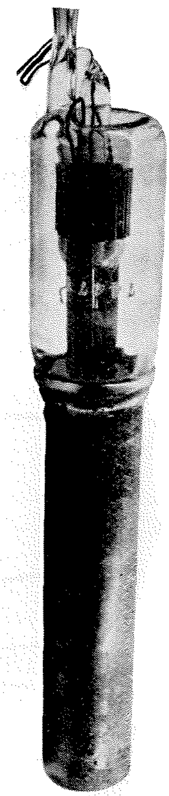


FIGURE 6

of a helix, and is held in position by allowing the ends of the longitudinal wires, to which the turns of the helix are welded, to pass through holes in the lavite blocks D and E. The filament G is mounted between hooks fastened to the lavite blocks and is kept taut by the springs H. The grid lead is shown at J, and the filament leads at K, K. In this tube platinum seals are used for the lead wires. The use of the springs H make it necessary to supply the filament with current from the opposite end of the assembly and this is done by passing the current through the steel support tube and returning it through a lead passing through this tube and insulated from it by a quartz tube.

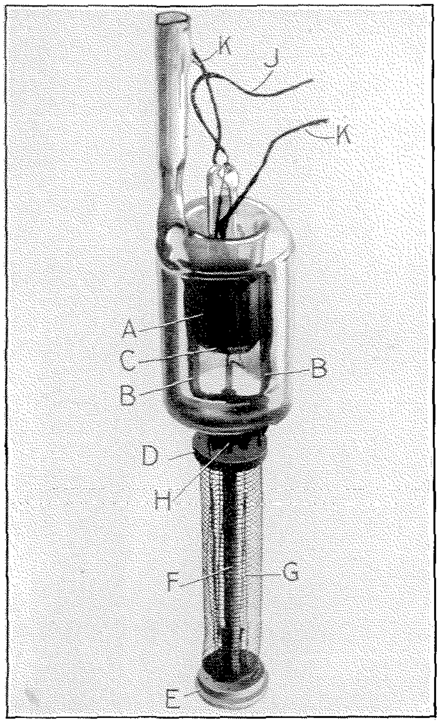


FIGURE 7

The whole assembly is carried by two supports B B. These supports are welded to a corrugated nickel collar A which grips the glass stem C.

The pumping of these tubes at first presented considerable difficulty, chiefly on account of the large amount of occluded gas contained by the metal parts. This caused the time of pumping of the tube to be very long and a dangerous warping of the internal structure developed owing to the fact that during exhaust the tube elements are maintained at a much higher temperature than they are subjected to during normal operation. The trouble was overcome by heating the various parts of the tube to as high a temperature as possible in a vacuum furnace, prior to the final assembly, and thus getting rid of a large amount of the occluded gases. The anode was preheated before the glass seal was made and the whole filament grid assembly was preheated just before it was mounted on the glass stem. The preheating of the parts brought about an enormous reduction in the time required for pumping and gave a much more uniform product.

Although successful from the standpoint of operation, this tube had several undesirable features that it was thought well to eliminate. In the first place the welding of the end into the tube was not particularly desirable, and in general any troubles that occurred due to leaks in the metal could be traced to this point. Further, in the assembly of the tube there were a very large number of welds to be made which constituted points of weakness at the high temperature necessary for the evacuation of the tubes. It was, therefore, decided to go to a type of tube in which the anode would be drawn in one piece and in which as many welds as possible would be eliminated in the assembly of the internal elements. At the same time it was considered desirable to go to a somewhat larger type of structure in which high tension insulation could be more easily provided and a larger tube was, therefore, designed capable of delivering 10 k. w. to an antenna at a plate voltage of 10,000 volts.

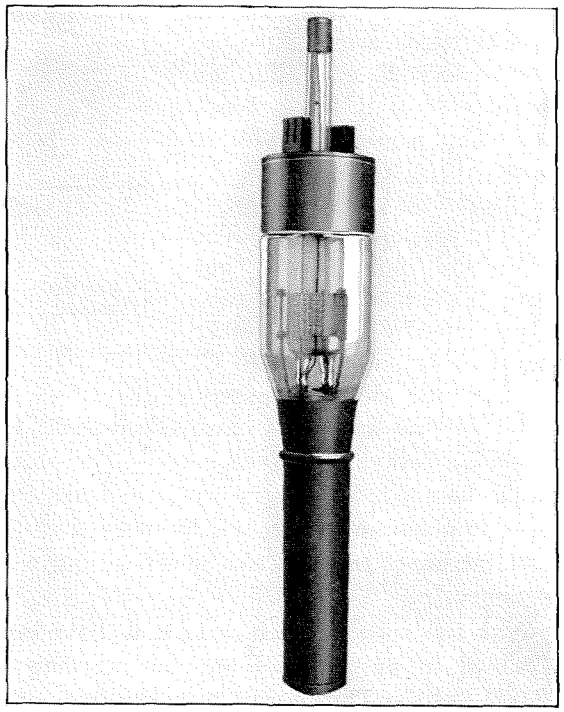


FIGURE 8

The final form adopted for this tube is shown in Figs. 8 and 9.

The anode A is drawn from a piece of sheet copper and is 9″ long and 2″ in diameter.

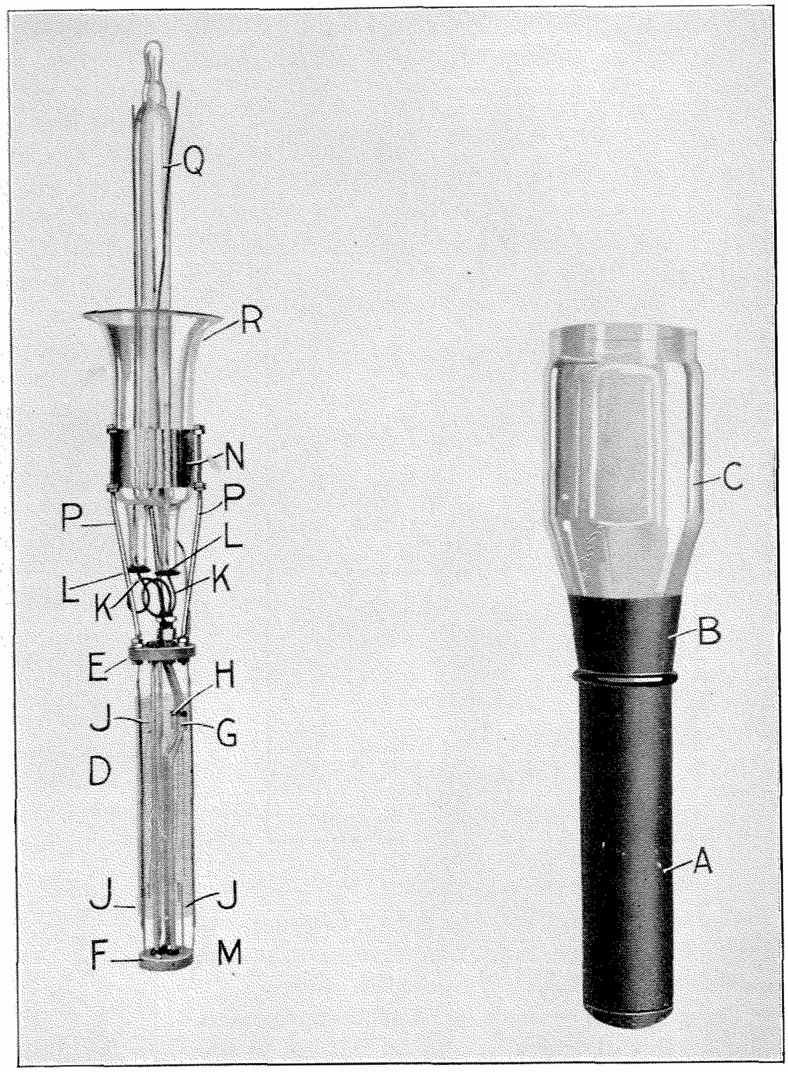


FIGURE 9

The copper flare B is turned down to a sharp edge and a glass bulb C sealed thereto. The grid and plate assembly is shown at D. The structure is supported by four molybdenum rods, which are threaded and secured by means of nuts to the lavite pieces E and F. The filament is made of 19.5″ of .025 pure tungsten wire purchased from the General Electric Company and is formed and secured to two of the molybdenum rods at G and H. The power consumed in it during operation is .75 k. w. It is guided by the hooks J. The filament leads are shown at K, K and are led through the glass by the copper disc seals L, L. The grid is a molybdenum helix and is supported by the molybdenum rods M which are fixed to the lavite block E and slide on the outside of the lavite block F. The whole structure is mounted on the flare R by means of the nickel collar N and the support rods P. The grid lead is brought out through the tube Q. The tube is completed by sealing together the flare R and the bulb C. In this tube all welds except those in the collar N are eliminated, the assembly being bolted together. The drawing of the anode does away with the leaks that were troublesome in the older tubes and the manufacture of the tube can be carried out with certainty.

With this tube as much as 12 k. w. have been obtained in an artificial antenna working at 12,000 volts. This power was obtained at a frequency of 600,000 cycles corresponding to 500 meters wave length. The difficulties of obtaining this amount of power at this frequency using a number of smaller tubes in parallel, are obvious to anyone who is acquainted with the problem. On a D. C. test the anode was found to be capable of dissipating 26 k. w. when cooled with water.

The success which had attended the development of a tube of this high power capacity indicated the possibility of constructing still larger tubes and it was decided to proceed with the development of a tube capable of delivering at least 100 k. w. into an antenna.

The development proceeded with a few minor alterations along the lines of the smaller tube, nominally rated at 10 k. w. and the 100 k. w. tube as now developed is shown in Figs. 10 and 11. The anode which is made of a piece of seamless copper tubing closed by a copper disc welded into the end, is 14″ long and 3.5″ in diameter. The filament is of tungsten and is

.060″ in diameter and 63.5″ long. The current required to heat it is 91 amperes and the power consumed in it 6 k. w. The filament leads are

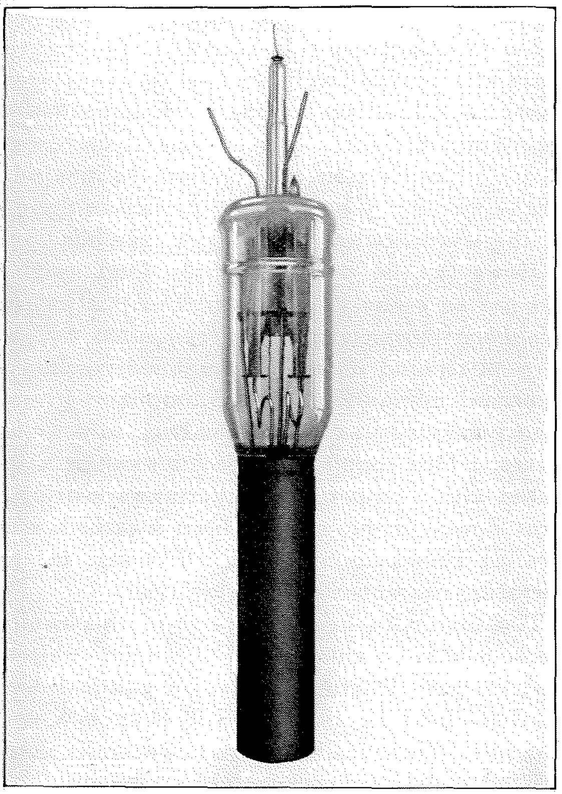


FIGURE 10

of copper rod one-eighth of an inch in diameter and are sealed through 1″ copper disc seals. The grid is of molybdenum and is wound around three molybdenum supports.

The handling of the parts of this tube during manufacture presents a task of no mean magnitude and numerous fixtures have been devised to assist in the glass working. It has been found necessary for instance to suspend the anode in gimbels during the making of the tube seal owing to its great weight, and special devices have been made to hold the filament grid assembly in place while it is being sealed in, otherwise the strains produced by its weight cause cracking of the seal.

The significance of this development in the radio art cannot be overestimated. It makes available tubes in units so large that only a very few would be necessary to operate even the largest radio stations now extant, with all the attendant flexibility of operation which accompanies the use of the vacuum tube.

From the standpoint of wireless telephony the development of these high power tubes gives us the possibility of using very much greater amounts of power than have ever been readily available before. The filaments in these tubes have been made so large that the electron emission from them will easily take care of the high peak currents accompanying the transmission of modulated power.

The 100 k. w. tube by no means represents the largest tube made possible by the present development. There is no doubt that if the de-

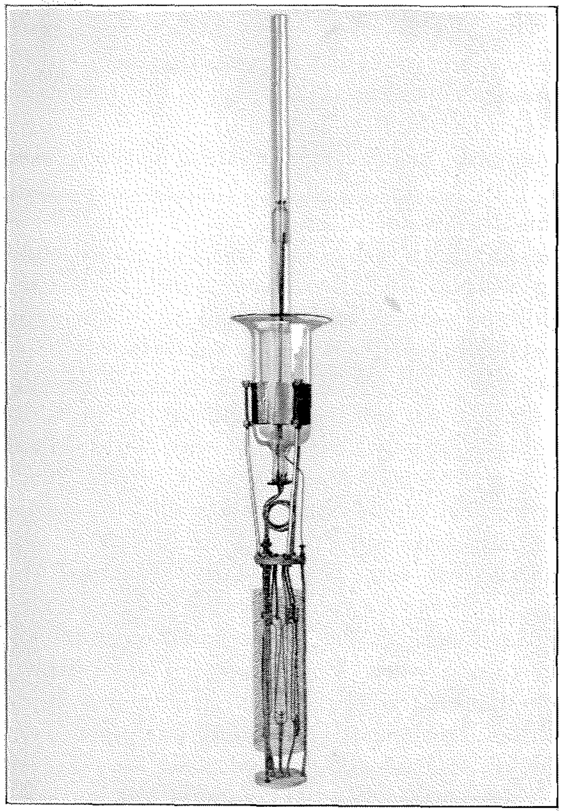


FIGURE 11

mand should occur for tubes capable of handling much larger amounts of power they could be constructed along these same lines.

A Unique Demonstration of the Public Address System

WEDNESDAY, June 14, 1922, marked an event not only of unusual interest to the employees of the Hawthorne Works of the Western Electric Company, but one which may well be regarded as a milestone in the progress of the science of speech transmission.

When the president of a huge industrial concern, seated in his office in one city, addresses simultaneously 27,000 members of his organization who are gathered in another city half-way across the continent, and yet is heard as distinctly as if face to face with each individual, it is truly epoch-making.

This was accomplished for the first time in history when H. B. Thayer, President of the American Telephone and Telegraph Company, C. G. DuBois, President of the Western Electric Company, and F. B. Jewett, a Vice-President of the Western Electric Company, speaking from the executive offices on the 26th floor of the American Telephone and Telegraph Building at No. 195 Broadway, New York City, addressed an enthusiastic audience comprising practically the entire manufacturing force at the Hawthorne Works in Chicago. This same gathering, an interesting photograph of which is shown on pages 24 and 25, was also addressed by J. C. Nowell, a Vice-President of the Pacific States Telephone and Telegraph Company, speaking from San Francisco, California.

This feat was made possible by apparatus developed during recent years by the engineers of the American Telephone and Telegraph and Western Electric Companies. The apparatus comprises extremely sensitive microphone transmitters, electrical amplifying equipment employing vacuum tubes, and loud speaking receivers of special design mounted on horns for directing the sound. Thus amplified, the voices of the speakers, transmitted 1,000 miles over the regular long-distance telephone circuits, could be heard by every one of the huge audience as distinctly as by persons standing beside them in the New York office.

In reviewing the history of loud speaker development, it will be apparent that all attempts prior to the coming of the distortionless amplifier were doomed to failure. It was only when such an amplifier became available that the transmitter employed in the loud speaker system could be chosen on the basis of distortionless reproduction, rather than on the basis of efficiency of conversion of sound waves into telephone current. The amplifier has made the use of the distortionless transmitter possible.

However, the problem of the loud speaker did not lie entirely in the amplifier. After the telephone current had been generated by the transmitter and its energy amplified possibly a thousand million-fold by the amplifier, it was then necessary to reconvert it back into sound waves. This required a special receiver associated with a proper type of horn representing a joint development, since a horn attached to a receiver brings about a marked change in the operating characteristics of the latter.

The first notable applications of this equipment, which is known as the Public Address System, were in connection with political conventions held in 1920 at San Francisco and Chicago. These installations, however, were restricted to enclosed areas and were wholly local in character, the speakers being in the same auditorium with the audience. Next came the use of the equipment for an out-of-doors area at the inauguration of President Harding on March 4, 1921, when an audience of 125,000 thronged about the National Capitol at Washington heard with perfect distinctness the President's inaugural address.

As illustrative of the utility and effectiveness of the Public Address System, when used in conjunction with the long distance telephone plant, may be noted the Armistice Day Exercises on November 11, 1921, when President Harding delivered his oration over the body of the Unknown American Soldier at Arlington Cemetery. On that occasion his words were made audible to an audience of 100,000 gathered in and about the cemetery and at the same time, the oration, music and other speeches were transmitted to New York and San Francisco over the long distance wires of the American Telephone and Telegraph Company, and, by means of other public address systems, were made audible to other audiences totalling over 50,000 persons, 15,000 persons in Madison Square Garden in New York, as many more in the park adjoining the latter, and 20,000 in and about the Civic Auditorium in San Francisco. The audiences in New York, San Francisco and Arlington Cemetery joined in singing the National Anthem during the ceremony.

The Hawthorne demonstration, while serving to indicate a new field for the use of the loud speaking telephone equipment in connection with long distance communication lines, also served to show dramatically to the 27,000 employees the utility and excellence of apparatus that they themselves had produced.

By virtue of the fact that Public Address Systems may be used under greatly varying conditions, such as are encountered in banquet halls, auditoriums, open-air meetings, railway terminals or amusement parks, the design and manufacturing requirements are extremely exacting. Every part must function so that there may be no distortion, and all of the delicate sound inflections be retained through the various transformations and amplifications which the electrical energy undergoes. This may be noted when considering that with maximum settings the energy delivered to the loud speaking receivers in the horns may be made 18¾ billion times that received over the long distance telephone wires. The area over which the system is required to operate must be carefully studied, for if the installation is out of doors, the sound waves may encounter the walls of buildings; or, if in an auditorium, in addition to reaching the ears of the audience, they strike the walls and floors and are reflected or absorbed, dependent on the material and shape of the obstruction.

FIGURE 1—Microphone

The Public Address System comprises essentially one or more sensitive microphones (Figure 1), mounted in a suitable housing with special supports to insure freedom from mechanical vibration, which might impair the quality of the sounds to be transmitted; current supply apparatus; voice current amplifiers, for increasing the magnitude of the voice currents (Figure 2); one or more loud speaking projectors

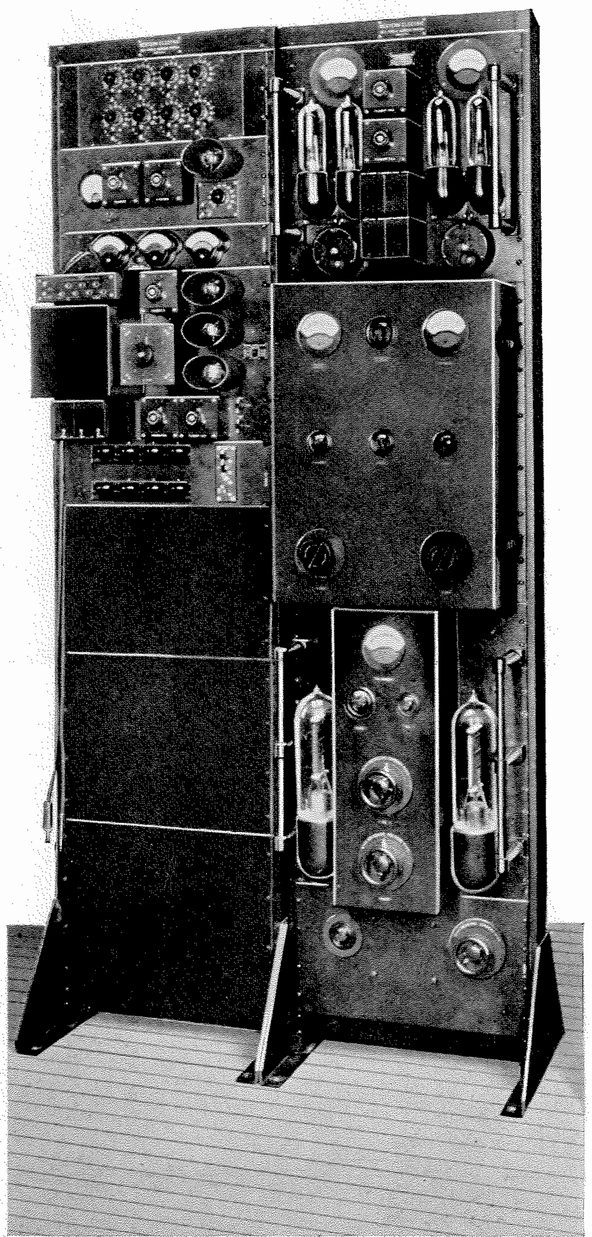
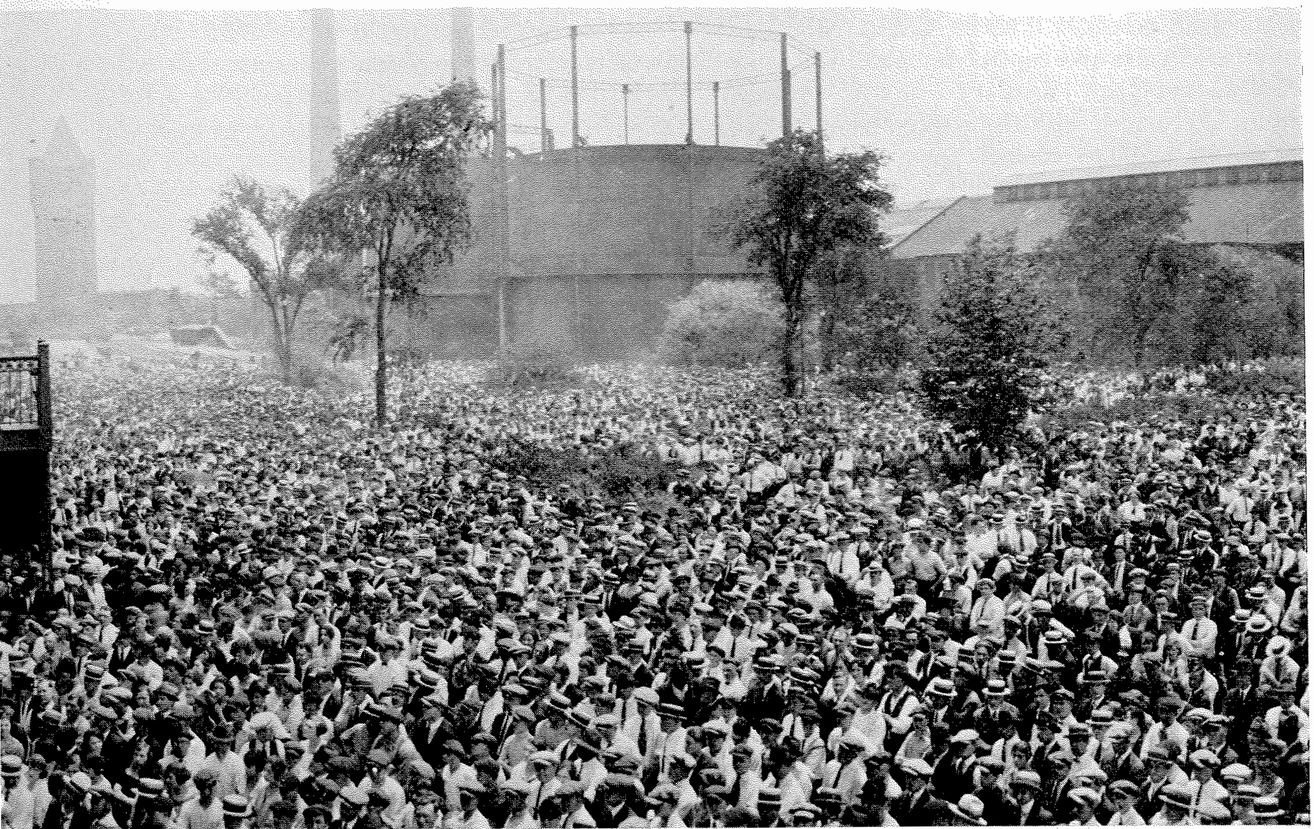


FIGURE 2—Current Supply and Amplifier Equipment for No. 1 Public Address System

The 27,000 Employees at the Hawthorne Wo

The upper and lower illustrations when plac

hered Together to Hear Their Chief in New York



to end form a complete picture of the gathering with their associated horns (Figure 3); and suitable circuits and control devices. The voice current amplifiers are of two types; the first, which is provided with three stages of amplification and suitable control apparatus, receives and amplifies the weak voice currents obtained from the microphone circuit; the second, which is of the single-stage type, receives the input current direct from the first amplifier. The vacuum tubes associated with this second amplifier are connected in the differential, or, as it is sometimes called, "push-pull" principle. This form of connection makes it possible for the amplifier to deliver a comparatively large amount of power at voice frequencies without distorting the complex wave form of the voice currents. The loud speaking projectors are of the balanced armature type providing great sensitiveness and the ability to handle comparatively large amounts of voice current energy without distortion. The projector horns are of several types, designed to suit the particular installations for which they are required.

Suitable control apparatus is provided to permit of regulating the volume of sound emitted by the loud speaking telephone projectors, for if the sound is amplified much above that normally employed by a person speaking or singing, it will seem unnatural and displeasing and may be thought distorted, simply because the hearer is not accustomed to that volume of speech. The reproduction may, however, be so accurate as to be indistinguishable from the original when the volume is weakened by distance to that of the normal voice. When properly adjusted, the sounds heard seem perfectly natural and comment has frequently been made that the loud speaking system is not working, the greatest surprise being manifested in these instances by temporarily disconnecting the projectors.

To what extent this equipment may be used in future it would be idle to forecast, but the work which has already been done indicates that this development has proven a real contribution to the art of communication.

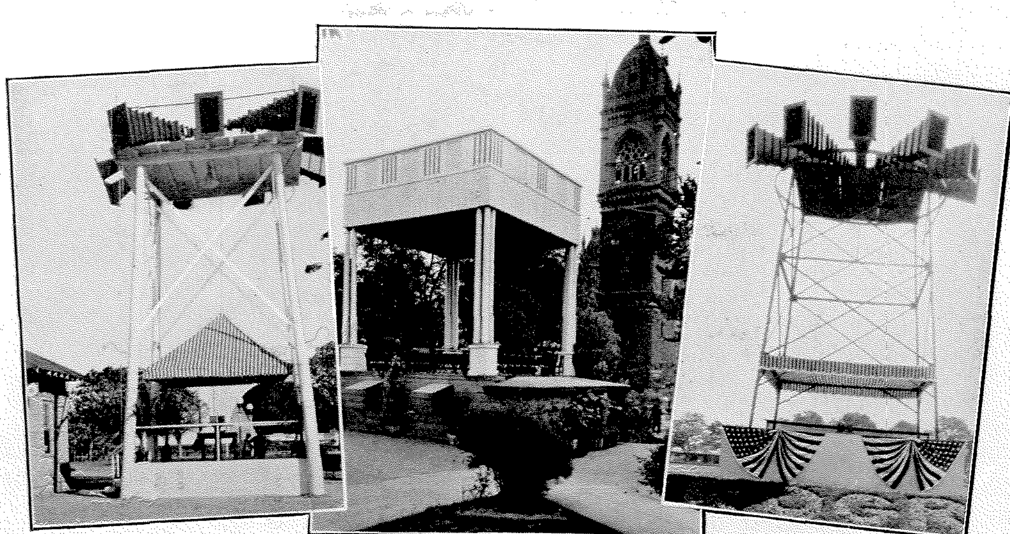


FIGURE 3—Types of Superstructures

(Left) Projectors on wooden superstructure; control room at left
(Center) Projectors concealed by grille work; control room below stand
(Right) Projectors on steel superstructure; control room below stand

Some Notes on Statistics With Special Reference to the Telephone Business

By S. L. ANDREW

Chief Statistician, American Telephone and Telegraph Company

The Origin of Statistics

In the popular mind statistics is frequently looked upon as a science of recent development which deals with uninteresting figures at its best and with involved mathematical concepts at its worst. Yet the use of crude statistical methods runs back as far as recorded history; and probably the evolution of no subject is more closely interwoven with the needs and development of peoples than is that of statistics. The history of statistics through the past ages is no mere catalog of successive steps in the development of a scientific basis of recording facts, but rather is a story of persistent efforts to obtain a working knowledge of the fundamental elements in the lives of nations—first, with respect to their population and material resources and, later, with respect to their economic and social relationships also. From the earliest records of organized social and political communities, the enumeration and compilation of statistical data has played an integral and vital part in their existence. The apportionment of taxes and the organization of armies were practically impossible without some degree of statistical information concerning the resources in materials and man power of the tribe or nation. One of the earliest known statistical compilations took place about 3050 B.C. and concerned the collection of data regarding the population and wealth of Egypt in order to make arrangements for the construction of the pyramids. Both secular and sacred history are filled with instances of the taking of censuses of population in order to determine the fighting strength of nations and as a basis for levying taxes. Until the 17th or the 18th century, however, practically the sole use of such censuses was to aid the government in its administrative work or in its military aspirations.

The Beginning of Modern Statistical Methods

Modern statistics developed from two apparently independent schools of research, one in Germany which became prominent about the middle of the 18th century and the other in England which originated about a century earlier. Statistics as first used in Germany applied to lectures or books upon descriptive political science and was considered as a science of populations, similar to what is now known as demography. Etymologically, "statistics" means the science of states, and not until the development of the English school of political arithmetic was statistics looked upon as primarily a study of numerical data.

Interest in statistical compilations was aroused in England during the middle of the 17th century after the disastrous visitations of the plague had caused the publication of weekly reports of the burials, and later the christenings, in London. In 1622 Captain John Graunt of London published his "Observations on the Bills of Mortality" which contained the results of his observation and measurement of the births and deaths in London and is one of the first recorded analytical studies of a strictly statistical nature. This field of study was at that time called "Political Arithmetic," but by the early part of the 19th century it had largely absorbed the descriptive political science school in Germany, from which it took over the term "statistics."

The first journal of the Royal Statistical Society, which was founded in London in 1834, defined statistics as "the ascertaining and bringing together of those facts which are calculated to illustrate the condition and prospects of society." Further expansion in the scope and meaning of statistics took place at this period, and from the name of a science or art of state-description by numerical methods the word was transferred to those figures with which it operated. When this occurred, the term soon lost its peculiar application to data concerning the state and was used in referring to any collection of numerical data, covering psychology, biology and other sciences, as well as political economy.

Thus statistics in modern usage has come to mean primarily a method or tool by means of which numerical data in any field may be analyzed and interpreted. In its development statistics has, of course, borrowed very largely from the older science of mathematics. Using processes largely mathematical in character, the student of statistical methods formulates the rules of procedure for handling groups of data, and the specialists in various fields of knowledge apply these rules to their own particular problems.

The Application of Statistics to Business

But while statistics has had a long and distinguished career in the service of public administration and private scientific research, it is true that the application of statistical methods of analysis to business data is a development of recent origin. This is because business administration itself has only recently taken on the aspects of a distinct science, with the process of evolution from small individual enterprises to large corporate organizations which has been coincident with the growth and improvement of transportation and communication. Moreover, the use of statistical methods in business has been facilitated by the recent progress in the invention and manufacture of mechanical labor-saving devices which have made it possible to undertake much statistical work which was formerly prohibitive from the standpoint of both cost and time. The increase in legislation affecting business has also served to stimulate the expansion of statistical work in industry. So long as business was conducted by small units, each with a limited market, there was a tendency to regard statistical work as an unnecessary luxury; but with the development of business as a science, statistical analysis is destined to play the same vital part in business administration as it has in the progress of other sciences. Indeed, the progress made in business statistics in the last few years has been so pronounced that "statistical control" is rapidly becoming an actuality in many lines.

Business Statistics Defined

To make clear the scope and character of that branch of statistics which has come to be called business statistics, it is perhaps advisable to attempt briefly to define "statistics" as it commonly applies to business administration.

The man in the street looks upon statistics as the systematic collection, classification and tabulation of numerical facts, and his idea of a statistician is a man who knows how many males of foreign parentage, between the ages of twenty and thirty, are employed in mining occupations in the State of Nevada. The more scientific person probably thinks of statistics as a method mathematical in its operation, in which numerical data are analyzed through complex calculations of averages, units and the like.

The business statistician himself, however, thinks of his work as the collecting, classifying and interpreting of ascertained facts—including facts not subject to numerical statement—primarily with the aim of disclosing some further and hitherto unascertained facts. He thinks of his duties as those of assembling and selecting data, analyzing and combining them, and presenting and explaining them in such a way that they tell much more than they do in their primary, unrelated form. The opportunity for work of this character obviously pervades all branches of any business organization. Moreover, the field for such statistical work is not confined merely to the analysis and interpretation of internal operating and financial data, but includes the study of general business and economic conditions and the influence of these conditions upon the individual business.

The Development of Telephone Accounting

In considering the progress already made in the field of statistical analysis of business operations, it should be remembered that accounting work is to a large extent the basis of statistics and that the introduction of scientific accounting methods is itself a comparatively recent development. This applies to the telephone business as well as to other lines of industry.

While the telephone was invented forty-five years ago, only for the past fifteen years or so has the telephone been a widespread public service. During this period the first work was naturally the erection of an adequate accounting system to show the financial condition of the business. It was necessary to set up refined methods for the separation of capital and income, the proper treatment of depreciation, etc. Practically all available time was devoted to the development of uniform accounts and standard reports, correct plant and maintenance accounting, suitable records of departmental expenditures and forms of accounts for general publication. Along with all this, careful plans have been worked out for extending the use of accounts by administrative officers, placing in the hands of responsible officials accounts practically arranged as working tools for everyday use. In the Bell System most of this work has been accomplished during the past fifteen years, a period within which the number of company-owned telephone stations has increased from two millions to nine millions.

The Field for Statistical Analysis of Internal Telephone Data

Under such circumstances it would be surprising if the work of statistical analysis had progressed to the same degree as the accounting work. Development of the business has gone on faster than development of the necessary statistical personnel. Thus, at the present time, the Bell System is in possession of an admirable accounting system and a comprehensive set of primary records—operating as well as financial—but has not advanced so far in the development and application of methods of statistical analysis. The magnitude of the business has made necessary such a voluminous mass of records and reports that many useful facts as to past conditions now lie buried, while significant elements of current operations are frequently subordinated. It seems apparent, therefore, that we have reached the point where there is not so pressing a need to extend and sensitize the accounting system as a whole as there is need to proceed further with the scanning, sifting and interpreting of results now shown by the accounts and operating records, and the presentation of the significant facts, trends, ratios and units through appropriate graphical and other statistical forms. Even as close cooperation has been established between the Accounting Department and other Departments in the working up of accounting data, in like measure close cooperation can profitably be established between the Departments in the work of statistical analysis. It is a matter of general concern that all accounts are under proper check so that figures finally lodged in the balance sheet are absolutely correct according to the accounting instructions; should not equal care be taken that all accounts and operating records are subjected to suitable and adequate statistical analysis not merely as to the correctness of the figures, but as to the significance and interpretation of the figures? While the accounts show very definitely *what* has happened, statistical work is designed to show, from an analysis of operating as well as accounting data, exactly *where* it has happened, *why* it has happened, and *who* or *what* is responsible.

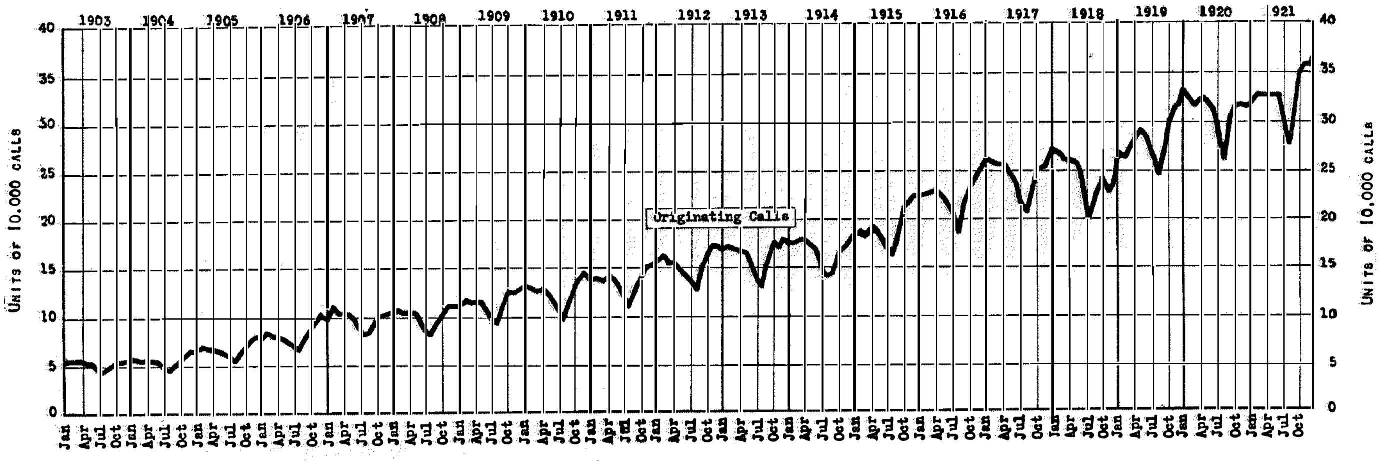
The Influence of External Forces

As already indicated, the field of business statistics is by no means limited to the analysis of internal financial and operating records. One of the fundamental characteristics of present-day industrial organization is the instability of business activity. This instability is manifested in individual businesses and in business as a whole. Business may be improving or it may be growing worse, but it is never static. Because they directly or indirectly affect profits, these fluctuations in business activity are of paramount interest to the business man; and their accurate measurement and analysis through the application of scientific statistical methods is consequently a matter of prime importance. This applies to the telephone as well as to other business, even though the telephone business is one of relative stability as compared with business in general.

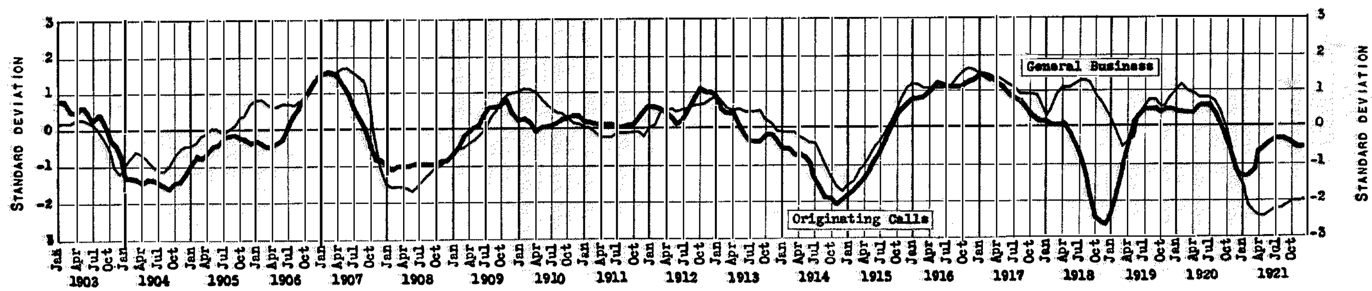
Perhaps the most common form of analysis of business data is the comparison of crude data for a current month with corresponding figures either for the preceding month or for the same month of the preceding year, or for both. However, direct comparisons of business data either as between different months or periods of the same year, or as between the same month or periods of different years, are in most cases liable to give rise to more or less misleading conclusions, because of the presence in the crude data of the effect of two influences: namely, seasonal variation (which affects the accuracy of the comparison in the first case) and normal growth or long-time trend (which affects the accuracy of the comparison in the second case).

As an illustration of this point, take an example applicable to the telephone business. Suppose, for instance, that the number of originating local calls in a certain exchange area during the month of August is reported as 3%

AVERAGE DAILY ORIGINATING CALLS IN AN EXCHANGE
(ACTUAL FIGURES)



COMPARISONS OF ORIGINATING CALLS AND GENERAL BUSINESS WITH ESTIMATED NORMALS
(LONG-TERM TREND AND SEASONAL VARIATIONS HAVE BEEN ELIMINATED)



less than the number in the preceding month of July, but 5% greater than the number in the month of August of the preceding year. This comparison of August with the preceding July does not necessarily indicate unfavorable traffic conditions or results in August; indeed, since local traffic in that month is usually less than that in July as a result of the effect of normal seasonal influences, the fact that the decrease in August as compared with July is only 3% may even indicate an improvement in conditions. In the comparison of August with the same month of the preceding year, the element of seasonal variation is largely eliminated but no allowance is made for the element of normal growth. Thus, the fact that local traffic is 5% greater than in the same month of the preceding year does not necessarily indicate that the volume of traffic is as great as it ought to be. If the normal annual growth in local traffic in the exchange area in question happened to be in excess of 5%, the traffic results in the current August would be unfavorable rather than favorable.

The Statistical Measurement of External Forces

Therefore, in dealing with business data in which the influences of long-time trend and seasonal variation are present, accurate conclusions can generally be reached only if the effects of these influences are eliminated.

In recent years, however, a statistical method has been developed whereby the effect of these influences can be removed, the method being one which has been carefully tested both in the analysis of general business data and in the analysis of statistics of the telephone business. The accompanying chart shows the result of the application of the method to local traffic in a certain telephone exchange area.

After the effects of seasonal variation and long-time trend have been eliminated from any series of business data, the corrected figures will usually be characterized by a broad wave-like movement similar in general form, though of different amplitude, to the cyclical swings of business activity through its alternate periods of prosperity and depression. In the case of telephone data, the comparison of figures analyzed by this method (where applicable) with external indices of general business, similarly analyzed, will permit proper conclusions to be drawn as to whether the current movements reflected by the telephone figures are reasonable and satisfactory in the light of general business conditions, or whether they indicate the existence of some abnormal condition which warrants examination from an administrative standpoint. The establishment of a consistent relationship, or correlation, between two or more analyzed series of telephone figures will also prove serviceable for administrative purposes, since the development of inconsistencies in these relationships will also generally indicate the presence of some condition warranting administrative investigation.

Statistical Aid in Forecasts

Not only is accurate analysis of past and present performance serviceable for administrative purposes and necessary for proper conclusions as to the real trend of current movements, but the measurement of the elements of long-time growth and seasonal variation by the statistical method above mentioned affords, it is believed, an improved basis for forecasts, especially forecasts in which it is necessary to allow for the effect of general business conditions. The normal trend of long-time growth may be projected into the future and, where forecasts by months are desired, the projected annual trend may be translated into monthly figures in accordance with the normal seasonal variation. Such a projection, if limited to a period not more than five years in advance, should prove in the case of most series of telephone statistics to provide a substantially accurate forecast of future trends in so far as these elements are concerned. If, furthermore, a fairly consistent relationship can be shown to have existed in the past between a given telephone series and some index of outside business conditions, a still more accurate forecast can be provided by modifying the figures indicated by the projected normal to allow for the influence of the probable future course of business conditions.

Rehabilitation of the Antwerp Factory

By J. S. WRIGHT

Managing Director, Bell Telephone Manufacturing Company, Antwerp

SUBJECTED to all the disturbances which could be expected to result from its location in a territory held by a hostile invading force, with manufacture abandoned for a period of over four years, its personnel disbanded, records lost or destroyed, stock of piece parts and raw material depleted, laboratory equipment, machinery and furniture scattered throughout other countries, our Antwerp factory's return to normal operating conditions did not, in 1918, appear as the most promising of possibilities. In slightly more than three years, however, a period during which the world has undergone the most violent of business upheavals, the factory has regained its pre-war position as one of the largest and most progressive of the telephone manufacturing establishments of Europe.

On November 14, 1918, starting with but little more than an empty factory building, and that not in the best of repair, a force of fifty of our pre-war workmen was organized. They began to clean and repair the factory, taking proper care of the war material which had been left by the invaders and inventorying such of our property as remained, so that by June, 1919, there were 750 people employed and at the end of that year 1,500.

Machines to the amount of fifty per cent. of the pre-war capacity of the plant had previously been ordered from America and began to arrive in January, 1919. The task of installing them began immediately, but it proved to be a difficult one because of our inability to obtain shafting, belting and other material in anything like the quantities required. Entirely new sources of supply had to be sought out and on account of the tremendous world demand, deliveries were slow and the quality of the needed equipment unsatisfactory.

Immediately after the return of the Belgian Government to Brussels in November, 1918, a special commission was organized, called the "Service Belge de Restitution Industrielle," whose business it was to trace and assist in the return of all material requisitioned by the Germans. Offices of the Commission were established at Brussels, Wiesbaden and Berlin. The German records were taken over by the Commission and as soon as a demand was made by any Belgian concern for the return of requisitioned material, these records were examined and an attempt was made to locate and return the material to its rightful owners. Delegates of the Commission also visited the principal German factories and wherever machinery was found which was undoubtedly of Belgian ownership, it was immediately returned to Belgium without waiting for its rightful owner to demand it. As soon as it arrived in Belgium all firms that had made claims for requisitioned machinery were notified, and upon the production of satisfactory evidence of ownership, they were allowed to take immediate possession of their property.

The Belgian Commission was efficient to a very high degree and as it worked in conjunction with the French Commission, we were also able to get back machinery, motors, etc., which had been installed in the German zone of occupation in France. Of 550 machines which had been requisitioned we received back 466, the remainder being either destroyed or found unserviceable.

Steam turbines are not generally considered as "mobile" equipment, yet witness the transcontinental journeyings of our principal prime mover. Transported from Antwerp to the midst of a forest one hundred miles east of Warsaw, where it had been used in connection with a wood alcohol plant, it was personally conducted to its former location by an old employee of the factory, the transfer having been effected but two weeks in advance of the invasion of the forest by the Bolshevik Army.

Among the first steps undertaken was the organization of a force of installers to put in working order the telephone exchanges in Belgium, most of which were in an exceedingly unserviceable condition.

Immediately after the armistice a Jobbing Department was organized to handle emergency orders and to give us the satisfaction that comes from the knowledge that one is producing something. The output of this little shop amounted to only Frs. 1500 during January, 1919, but by the end of that year we were turning out work at the rate of Frs. 150,000 per month. As fast as machines were installed they were put in operation and steadily our production continued to increase until in December, 1921, it reached a figure of Frs. 2,700,000 per month.

During this period the machine tools which remained were inspected and it was found that there was hardly a piece of apparatus of our manufacture for which the tools were complete. Building up our force was one of our chief problems, and this question of toolmakers was one of its most difficult phases. Only a few were to be found in the country on account of emigration or army service, and it became necessary for us, with what skilled men we could find, to train apprentices for this work.

By no means the least of our problems was that of straightening out our books. The official records of the Company were left in Antwerp and during the war no entries were made. Temporary books were kept in London and The Hague, but neither set was complete on account of the difficulty, and oftentimes the impossibility of communicating with Antwerp. Only one of our pre-war bookkeepers, and he the youngest of our staff, returned after the armistice. The head of our Voucher Department was still in the Army so that the problem was to complete the records and unravel the knots that had accumulated during the four years that Antwerp had been occupied. This work involved a summary of more than 4,000 items which had not been included in the accounts before our cash and bank accounts agreed with the funds on hand. Unaudited pre-war purchases had to be checked and accounts receivable investigated, so that it was not until June, 1919, that we were able to close our books for the war period, and it was not until the end of that year that we felt entitled to boast that the plant was again running normally.

It had been a long, hard struggle against continual difficulties, and there were times when those of us who were watching the situation most closely could see little or no progress. Without the able assistance rendered by our Allied Companies in America and abroad our task would have been insurmountable. Our very valuable association with these Companies, however, has made it possible to place our factory on a pre-war producing basis, as well as to undertake the manufacture of the new types of apparatus developed during the period of the war and thereafter.

A visitor at Antwerp today can see little or no signs of the intense bombardment to which the city was subjected for forty-eight hours in 1914, and the people whom he meets do not talk of the war. We have taken our inspiration from the city and the visitor to our works today takes away with him the picture of a fine modern plant, with 2,800 loyal, industrious employees, all of whom are contributing to the development, manufacture and distribution of our products for the upbuilding and the improvement of telephone facilities in many of the principal countries of Europe. To our people the war is a memory. Their faces are turned toward the future.

Analysis of the Energy Distribution in Speech[1]

By I. B. CRANDALL, Ph.D., and D. MACKENZIE, Ph.D.

Department of Physical Research, Western Electric Company

SYNOPSIS: *The frequency distribution of energy in speech* has been determined for six speakers, four men and two women, for a 50-syllable sentence of connected speech, and also for a list of 50 disconnected syllables. The speech was received by a condenser transmitter whose voltage output, amplified 3,000 fold, was impressed on the grids of twin single stage amplifiers. The unmodified output of one of these amplifiers was measured by a thermocouple and was a known function of the total energy received by the transmitter, corrections being made for the slight variation with frequency of the response of the circuit. The output of the other amplifier was limited by a series resonant circuit to a narrow band of frequencies, the energy in this band being measured by a second thermocouple. The damping of the resonant circuit was so chosen that sufficient resolving power and sufficient energy sensitiveness were obtained over the range from 75 to 5,000 cycles per second; and 23 frequency settings were made to cover this range. For each syllable simultaneous readings were recorded on the two thermocouples at each frequency setting. The consecutive syllables were pronounced deliberately by each speaker, maintaining as nearly as possible the normal modulation of the voice. Corrections were applied to offset the unavoidable variations in total energy incidental to repetition of a given syllable. 13,800 observations were made for all speakers. *The energy distribution curves* obtained are essentially the same for connected as for disconnected speech, and indicate that differences between individuals are more important than variations due to the particular test material chosen. A composite curve drawn from the individual curves shows a great concentration of speech energy in the low frequencies, a result which would not be expected from data previously published by others. The actual results contain a factor due to standing waves between the speaker's mouth and the transmitter, a complication always present in telephoning; this could not be eliminated.

The rate of energy output in speech for the normally modulated voice, was determined from the readings for total energy and was found to be about 125 ergs per second.

IN the study of speech and its reproduction by mechanical apparatus it is necessary to consider its composition from several different points of view. We desire first of all to know the actual frequency distribution of the total energy in speech, as well as the separate distributions for each individual sound. We also desire to know the apparent distribution of energy, that is, the distribution as perceived by the ear. Finally, we wish to know the importance of each frequency, that is, the contribution to "articulation" or "quality" in the exact reproduction of speech which can be traced to the energy of each elementary band of frequencies in the speech range. In all three cases certain frequency functions are used to represent these distributions. The advantage of considering these different frequency distribution functions separately has already been indicated by one of the present writers.[2]

In our judgment the most important of these data of speech study is the *actual energy distribution*, considering speech as "a continuous flow of distributed energy," in accordance with the ideas expressed in the earlier paper. The present paper offers a determination of this fundamental factor.

To determine the energy distribution in speech to a high degree of accuracy it would be desirable to analyze a certain amount of connected speech and take a time average of the energy distribution of the whole. This is not feasible at the present time, but a very close approach to this result has been made. The method consists in analyzing the speech waves as impressed on a condenser transmitter, using a tuned circuit to transmit narrow frequency bands of energy and pronouncing the separate syllables of the connected speech so slowly that the kick of a direct current galvanometer connected to an A. C. thermocouple can be separately read for each syllable. Using a suitable calibration for the whole apparatus, the magnitude of this kick can be interpreted in terms of the time integral of the energy at a particular frequency setting for each syllable. A mean of the readings for all the syllables in the "speech" at any frequency setting gives the relative energy at that frequency.

The present method is a modification of an earlier method in which approximate analyses of speech sounds were made, using a condenser transmitter, tuned circuit, an amplifying-rectifying circuit, and ballistic galvanometer. The method is, however, much improved as we now have very accurately calibrated condenser transmitters of better design, and a great deal of care has been taken to calibrate the successive

[1] Reprinted from *The Physical Review*, N.S., Vol. XIX. No. 3, March, 1922.

[2] "The Composition of Speech," *Phys. Rev.*, X, p. 74, 1917.

elements of the train of apparatus, and increase the resolving power.

Experimental Procedure

Sound waves emitted from the mouth of the speaker are allowed to fall upon the diaphragm of a condenser transmitter, connected in the conventional manner to the input of a three-stage amplifier. The output of this is impressed upon the input circuits of twin single stage amplifiers, potentiometers being interposed to permit regulation of the grid voltages of the twin amplifier tubes.

The output circuits of the fourth stage consist of the high windings of two step down ironclad transformers. These step down transformers have a voltage ratio of 11:1 and are designed to work between impedances of 6,000 and 50 ohms. The low impedance winding of one of these transformers operates into a thermocouple heater of, roughly, 40 ohms resistance. The low side of the other transformer operates through a tuned circuit into a similar thermocouple heater.

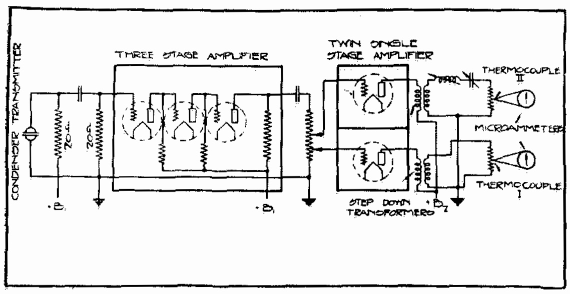


Fig. 1—Circuit Used for the Analysis of Speech. (The Usual Details of the Three-Stage Amplifier Are Not Shown)

The diagram of Fig. 1 exhibits the essential features of the electrical circuits just described.

When the diaphragm of the condenser transmitter is set in vibration by speech a current made up of a range of frequencies flows in the heater of thermocouple I., while the heater of thermocouple II. is traversed only by such a band of frequencies as the resonant circuit allows. Fig. 2 shows a number of typical resonance curves obtained in the course of calibrating this apparatus. These curves are such that the tuned circuit functions as a filter transmitter only a narrow region of frequencies. One side of the twin amplifier transmits the entire electrical response of the system; the other side suppresses all save a band of frequencies, the center of this band being shifted by resetting the condenser and inductometer.

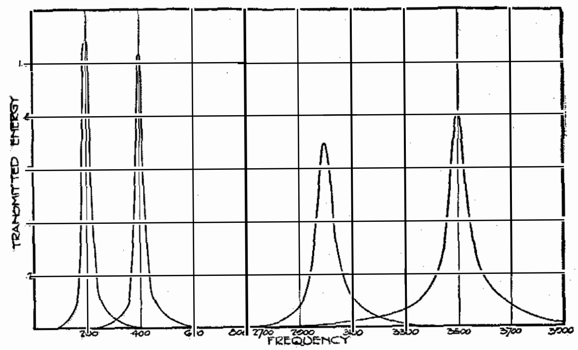


Fig. 2—Resonance Curves Showing the Resolving Power of Apparatus

Having chosen for analysis a piece of connected discourse, the speaker utters the successive syllables separately but as nearly as may be with the same inflection and volume as if the syllables were continuously spoken. Two observers record the readings of microammeters in the couple circuits of the thermocouples. One of these instruments gives a deflection corresponding to the total energy of the syllable uttered; the deflection of the other instrument corresponds to the energy of the syllable lying within the limits of transmission of the tuned circuit.

Preliminary experiments were carried out to determine the relation between momentary deflection read on the microammeter, and the current momentarily flowing in the thermocouple heater. Currents of different values were caused to flow for intervals of time varying from 0.2 second to 1.2 seconds, and the deflections were found nearly proportional to the product of current squared and time interval; this proportionality was most nearly exact when the current was weak and the time intervals short. For all cases likely to be duplicated in the speech analysis work the error might be taken as about 5 per cent, a quantity small in comparison with the inevitable uncertainties due to other causes.

Quite low damping is attained in the resonant circuit. The values of inductance used ranged from 0.20 to 0.66 henry and the total resistance of the circuit—transformer winding, inductometer coil, thermocouple heater—is of the order of 100 ohms. The damping thus ranges from 75 to 250.

The circuit is calibrated in the following manner:

A switch is so introduced that it is possible to include in series with the thermocouple the resonant circuit, or replace it by a non-inductive resistance whose value is approximately that of the A. C. resistance of the inductometer winding. With the tuned circuit excluded, an alternating current of suitable magnitude is caused to flow in the thermocouple heater; the tuned circuit is then substituted and the new value of the current observed, the input voltage remaining constant. The ratio of current squared "tuned circuit in" to current squared "tuned circuit out" is plotted against frequency, yielding a curve for energy transmission.

Twenty-three bands in all were considered adequate for the analysis of energy distribution in speech; the centers of these were at 75, 100, 200, 300 cycles, 400 to 3,200 cycles by steps of 200; 3,500, 4,000, 4,500, 5,000 cycles per second. Beyond 5,000 cycles per second, the energy is so low as to be impossible of measurement with the apparatus used. A Weston Type 322 microammeter recorded the couple current for the tuned circuit side of the twin single stage amplifier. With this instrument and the thermocouple used, 0.2 microampere in the couple circuit corresponds to one-quarter of a milliampere in the heater, and this is the lowest readable deflection of the Weston instrument.

Reduction of Observations

Three corrections have to be made, the first being the correction for varying volume.

Simultaneous observations are made, at each setting of the tuned circuit, of the filtered and the unfiltered energy of each syllable. It is not possible to utter a given syllable with the same intensity and at the same distance from the transmitter for every one of twenty-three times. Accordingly, the "unfiltered" readings are averaged and each of the filtered readings for each syllable reduced from the value actually observed to the value that would have been read had the volume and distance been such as to give the average "unfiltered" reading. This procedure is quite legitimate if it be granted possible to maintain a definite composition of the syllable in question throughout the changes of the tuned circuit setting.

A second correction was made for the varying area of tuned circuit curves.

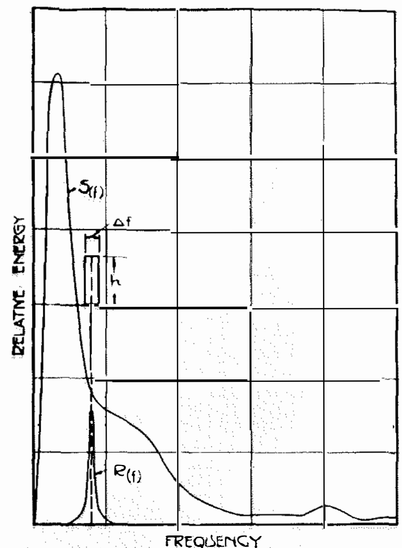


Fig. 3—Illustrating Correction of Observations, Necessary Because of Variation in Resolving Power with Frequency Setting

In Fig. 3 let $S(f)$ be the speech spectrum determined by ideal methods; "R" the transmission curve of the tuned circuit, set for a resonant frequency f. An ideal transmission curve would be a rectangle when plotted in this figure, of height "h" and transmission range Δf.

The true amount of energy $S(f)$ associated with frequency f, and the experimentally determined value which we may call $(\overline{S}f)$ are connected by the relation

$$h\overline{S}(f)\Delta f = \int_f^{f+\Delta f} S(f)R(f)df$$

and if we make

$$h\Delta f = \int_f^{+\Delta f} R(f)df$$

we may take for all practical purposes $S(f) = \overline{S}(f)$, considering the narrowness of the transmission range. We must therefore find the factor $h\Delta f$, proportional to the area of each tuned circuit curve and divide the energy received through the filtered side by $h\Delta f$, in order to obtain $S(f)$. This treatment may be gone through for each syllable individually, but it is more convenient to sum the tuned circuit readings for all the syllables used, corrected one at a time for varying volume, and then apply the curve area correction to this sum.

A third correction was made for the varying frequency-sensitivity of the whole apparatus. Thus far we have discussed only the electrical energy in the output circuit of the fourth stage. It remains to show in what way this is related to the mechanical energy of the diaphragm, and this in turn to the incident sound energy.

The calibration of the circuit as a whole was made by introducing a small resistance carrying alternating current in series with the condenser transmitter, thus introducing a known potential drop in the undisturbed input mesh of the circuit.

An amplification curve is appended (*A*, Fig. 4) which gives to an arbitrary scale the ratio of volts output to volts input as a function of frequency, for the system as actually operated. The calibration of the condenser transmitter shown in Fig. 4, Curve *C*, gives the open circuit voltage of the transmitter per unit pressure on the diaphragm as a function of frequency. The product of these curves is the volts output per unit alternating pressure on the diaphragm, and the square of this product, curve *E* is proportional to the electrical energy output per unit sound energy incident on the diaphragm, if we assume that the sound energy is proportional to the square of the alternating pressure. This point, however, requires some further discussion, which will be given later on.

It is plain from curve *E* that the response of the system is a maximum of frequencies in the neighborhood of 2,250 cycles. If, now, the observations already corrected for varying volume and for area of resonance curves, are subjected to further correction for the exaggeration of these frequencies, it is possible to draw a curve which shall exhibit the mean square of the excess pressure on the diaphragm, as a function of frequency in the voice exciting the vibration. We obtain this corrected curve by dividing the results, after the first and second corrections above have been made, by the ordinates of curve *E*.

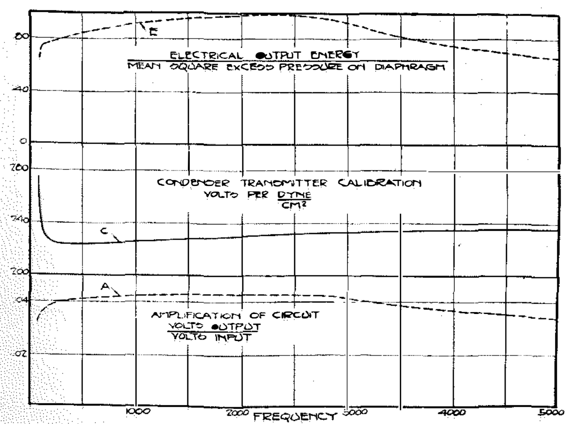


Fig. 4—Energy-Frequency Characteristics of the Apparatus

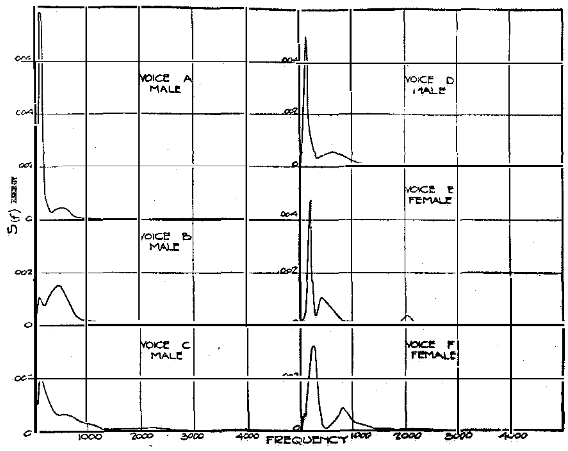


Fig. 5—Analysis of Individual Voices

Observations

In order to investigate the possibilities of this method it was decided to work with a rather short piece of connected speech, and to use a limited number of observers, on account of the large number of observations which are required for each separate syllable. With six speakers (four men and two women) each pronouncing the test sentence of fifty syllables for each of the twenty-three frequency settings, 6,900 separate observations were required. It is believed that representative results have been obtained from these observations, but if this is not the case then some method of graphical registration of the energy-time curve of speech for the different frequency settings must be applied in order to handle the vast amount of data involved in work on an appreciably larger scale.

The test sentence used was as follows:

"*Quite* four score and seven years ago our fathers brought forth on this continent, a *nice* new nation, conceived in liberty, and dedicated to the proposition that all men are created equal."

The two *italicized* words were added to the first sentence of the "Gettysburg Address" in order to bring the total up to fifty syllables, and improve the balance between the vowel sounds.

The resulting speech-energy curves are shown in Figs. 5, 6 and 7, plotted so that $\int_0^\infty S(f)\,df = 1$ in each case. In Fig. 5 the individual curves for each of the six speakers are shown on a small scale; in Fig. 6 the composite curve for the men and the composite curve for the women, drawn separately, and in Fig. 7 the composite curve for all six speakers, giving the data of curves 6*A* and 6*B* equal weight.

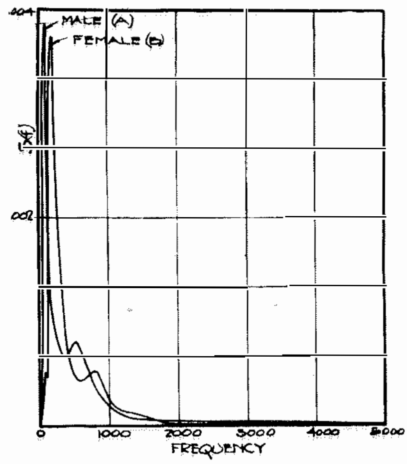


Fig. 6—Energy Distribution: Composite Curves of Male and Female Voices

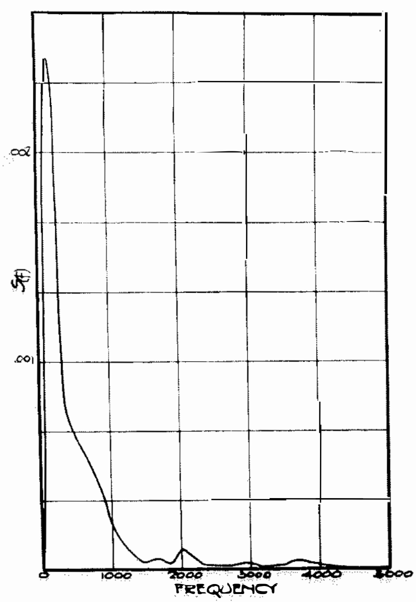


Fig. 7—Energy Distribution: Composite Curve for All Voices

These curves are very similar to a curve obtained by Dr. Fletcher of this laboratory, using block filters and based on the simple calling sentence "Now we're off on one." A general consideration of this fact and of the data shown leads us to believe that the differences between curves of this sort, made by the method described, are due rather more to differences between the voices of the individual speakers than to the particular piece of connected speech which is chosen, provided the speech is of reasonable length. The differences between the different voices are so marked that we should expect them to remain even though we used as test material a connected speech ten or fifty times as long as the sentence used.

The Energy Distribution in Speech

An interesting comparison may be made between the curves shown for the energy distribution of "continuous speech" and certain speculative curves previously constructed to indicate the energy distribution. One of these curves is shown in Fig. 8. Curve *A* was constructed by one of the writers in 1916 in an attempt to synthesize the energy curve from the energy distributions of the vowel sounds, using the vowel analyses of Dr. Dayton C. Miller. Curve *C* is the composite "continuous speech" curve of Fig. 7. The vowel sounds analyzed by

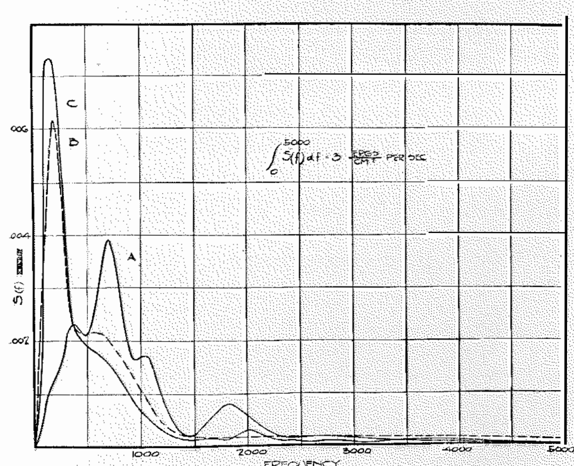


Fig. 8—Energy Distribution: *A*. Synthesized from Vowel Records of D. C. Miller (1916). *B*. Disconnected Speech Analysis of this Paper. *C*. Connected Speech Analysis of this Paper (from Fig. 7)

Miller were intoned and the vowel sounds analyzed by us were spoken, but Miller's work seemed to show that there was no essential difference between intoned and spoken vowel sounds. There is, however, a very noticeable difference between Curve *A* and Curve *C*, the energy in the fundamental tone of the speaker's voice coming out much more strongly in Curve *C*. We should expect that our improved apparatus would record the energy in the lower frequencies more correctly than the apparatus heretofore used but as we used different test material (connected speech instead of disconnected syllables or vowel sounds) it is not immediately evident which of these two factors is responsible for the differences between the *A* and the *C* curves.

In order to investigate this point more fully the testing routine for all six speakers was repeated, using instead of the fifty-syllable sentence, the fifty disconnected syllables of one of the standard articulation testing lists, as used by Dr. Fletcher in this laboratory. The results for energy distribution are shown in Fig. 9, Curve *A* being the mean energy distribution for the four male speakers, using the syllables, while Curve *B* is the mean energy distribution of the two female speakers. Curves 9*A* and 9*B* may be compared with Curves 6*A* and 6*B* which represent the sentence of continuous speech. The two sets of curves are essentially the same as shown in Fig. 8, *C* and *B* being respectively the composite curves for all speakers, using connected and disconnected speech.

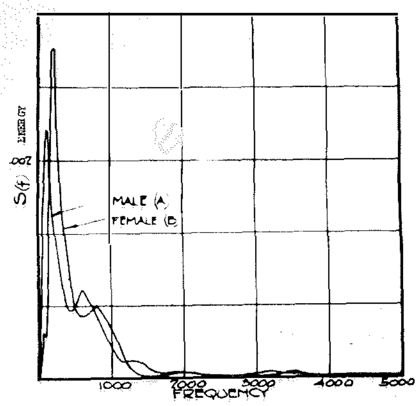


Fig. 9—Energy Distribution in Disconnected Speech

Such small differences as exist between Curves *C* and *B* of Fig. 8 may probably be due to differences in the distribution of the vowel sounds in the connected and disconnected test material. This distribution is given in the following table:

Vowel Sounds	a	ā	á	e	ē	ér	ı	ī	o	ō	ó	u	ū	ou	Total
In Sentence	6	6	3	7	3	3	7	2	2	5	3	0	2	1	50
In Syllabic List (No. 174)........	4	4	3	4	3	4	3	4	3	4	3	4	4	3	50

Key to Vowel Sounds: a, as in father (or o as in top)
ā, as in tape
á, as in tap
e, as in ten
ē, as in team
ér, as in term
i, as in tip
ī, as in time
o, as in ton
ō, as in tone
ó, as in for
u, as in pull
ū, as in rule
ou, as in house

The similarity between Curves *C* and *B* of Fig. 8 is evidence of the general reliability of the method, and leads to two rather important conclusions.

In the first place, characteristic results have been obtained for a given set of speakers, using two different types of test materials. This seems to show that the choice of test material does not require especial consideration, provided it is of sufficient length. It seems to be a matter of rather greater importance to increase the number of observers.

In the second place, it seems that for the actual energy distribution, the results previously obtained from the vowel analyses are definitely in error, in that they show relatively little energy associated with the lower voice frequencies.

Criticism of the Results

The foregoing treatment provides a curve showing the frequency distribution of the square of the excess pressure on the diaphragm.

In an undisturbed field of sound energy we have for the intensity

$$I = \frac{P^2}{2\rho a}$$

in which ρ is the mean density of the medium, a the velocity of sound in the medium and P the maximum excess pressure.

It remains for us to consider in how far the results obtained represent the frequency distribution of sound energy in speech.

Due to the fact that at frequencies where the sound wave-length is short and comparable with the diameter of the transmitter, considerable reflection takes place, and the pressure on the diaphragm is proportionately greater for these frequencies than for those which are not accompanied by strong reflection. In this

The Nature of Speech and Its Interpretation[1]

By HARVEY FLETCHER, Ph.D.

Department of Transmission Research, Western Electric Company

INTRODUCTION

VARIOUS phases of this subject have received serious study by phoneticians, otologists, and physicists. On account of its universal interest, it has received attention from men in many branches of science. In spite of the large amount of time devoted to the subject, the progress in understanding its fundamental aspects has been rather slow. At the present time the physical properties which differentiate the various fundamental speech sounds are understood in only a very fragmentary way. Some very interesting and painstaking work has been done on the physical analysis of vowel sounds, but the results to date are far from conclusive. Although several theories have been advanced to explain the way in which the ear interprets sound waves, they are still in the controversial stage.

The material which is presented here is the result of an investigation which has been carried on in the Research Laboratories of the American Telephone and Telegraph Company and Western Electric Company during the past few years.

To make a quantitative study of speech and hearing it is necessary to obtain the speech sounds at varying degrees of loudness and with definitely known amounts of distortion. The main reason why so few real results have been obtained in the investigation of speech sounds is due to the fact that it is extremely difficult to change the volume and distortion of these sounds by acoustic means. Due to recent developments in the electrical transmission of speech it is possible to produce the equivalent of these changes by electrical means. For this purpose a telephone system was constructed which reproduced speech with practically no distortion. It was arranged so that by means of distortionless attenuators the volume of reproduced speech could be varied through a very wide range, and so that by introducing various kinds of electrical apparatus the transmitted speech wave could be distorted in definitely known ways.

[1] Presented at a meeting of the Electrical Section of the Franklin Institute, held Thursday, March 30, 1922. Reprinted from the Journal of the Franklin Institute for June, 1922.

A method was developed for measuring quantitatively the ability of the ear to interpret the transmitted speech sounds under different conditions of distortion and loudness. By choosing these conditions properly, considerable information was gained concerning both speech and hearing. This indirect method of attack has a distinct advantage for engineering purposes, in that it measures directly the thing of most interest, namely, the degrading effect upon telephone conversation of introducing electrical distortion into the transmission circuit. However, the application of the results is not limited to this particular field.

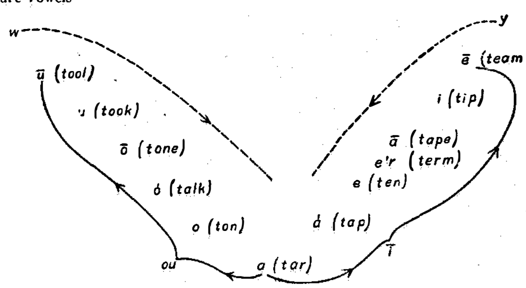
METHOD OF MEASURING THE QUALITY OF SPEECH

Briefly stated the method consists in pronouncing detached speech sounds into the transmitting end of the system and having observers write the sounds which they hear at the receiving end. The comparison of the called sounds with those observed shows the number and kinds of errors which are made. The per cent of the total sounds spoken which are correctly received is called the articulation of the system.

TABLE I.

Classification of the Speech Sounds.

Pure Vowels



Combinational and Transitional Vowels
w – y – ou – ī – h

Semi-vowels
l – r

Stop Consonants

Voiced	Unvoiced	Nasalized	Formation of Stop
b	p	m	lip against lip
d	t	n	tongue against teeth
j	ch	—	tongue against hard palate
g	k	ng	tongue against soft palate

Fricative Consonants

Voiced	Unvoiced	Formation of Air Outlet
v	f	lip to teeth
z	s	teeth to teeth
th (then)	th (thin)	tongue to teeth
zh (azure)	sh	tongue to hard palate

respect again the higher frequencies provoke the greater response in the system.

The following experiment was tried to investigate this variation. A wall six feet square, with a central hole to fit over the condenser transmitter, was brought up to make the transmitter a part of a plane wall. The clearance around the periphery of the transmitter was tightly closed, and reflection was to be expected at all frequencies. Where total reflection takes place, a given quantity of sound energy results in twice the alternating pressure on the diaphragm as when no reflection occurs. That is, the resulting electrical energy observed should be four times as great for total reflection as for no reflection. The wall was expected to cause reflection at all frequencies, and the experiment consisted in reading the electrical response, with and without the wall, the condenser transmitter being exposed to tones of frequencies from 200 to 10,000 cycles per second under definite adjustments of the supply circuit of a receiver producing this tone. When the frequency is low, little reflection takes place from the transmitter standing alone, and bringing up the wall should cause a great increase in the response of the system. At high frequencies the transmitter should reflect nearly as much alone as when part of a large wall, and the readings with and without the wall should be nearly equal. Plotting ratio of response without, to response with the wall was expected to yield a curve which could be used to make the final reduction of electrical output to incident sound energy, and so permit a more accurate determination of the spectrum of sound energy of the voice.

No consistent results were obtained after several trials and the experiment was abandoned. The failure is doubtless to be ascribed to standing waves, the character of which is very sensitive to the location in the room of the transmitter and the wall. This experiment is to be repeated under more favorable conditions when standing waves can be eliminated.

Thus, the curves finally obtained show no more than the frequency distribution of energy in speech in terms of the mechanical energy of a more or less ideal transmitter diaphragm. However, this information has its value because in any given configuration of transmitter, speaker, and room, there is a definite correspondence between the sound energy of the voice and the force acting on the diaphragm on which it falls, and in telephony at any rate it is this action on the diaphragm with which we are immediately concerned.

In conclusion we may give a determination of the total energy rate of speech, obtained as a by-product of the preceding investigation. Knowing the calibration of the system in absolute units, it is possible to determine the alternating pressure on the condenser transmitter diaphragm exposed to continuous speech from the normally modulated voice under the conditions of the experiment. Using the mean of the values obtained with 9 observers we find for the alternating pressure 11.3 dynes per sq. cm. (r.m.s.) for a distance of 2.5 cm. from mouth to diaphragm. This corresponds to an energy flow of 3.2 ergs per sq. cm. per second. Assuming that this energy flow is distributed uniformly over a hemisphere of 2.5 cm. radius, we may take 125 ergs per second as the total sound energy flow from the lips with the normally modulated voice.

In order to understand the construction of the articulation lists and also to interpret the results of this investigation, I desire to give here a brief classification of the speech sounds, which is based upon the position of the various speech organs when the sounds are being produced. It is shown in the accompanying table (Table I).

The pure vowels are arranged in the vowel triangle, which is familiar to phoneticians. Starting with the sound ū the lips are rounded and there is formed a single resonant cavity in the front part of the mouth. Passing along the left side of the triangle from ū to a the mouth is gradually opened with the tongue lowered to form the successive vowels. Going along the right side of the triangle from a to ē, the tongue is gradually raised to the front part of the mouth forming two resonant chambers in the mouth cavity. An infinite number of different shadings of these vowels may be produced by placing the mouth in the various intermediate positions, but the ones which are shown were chosen as being the most distinct.

The sounds w, y, ou, ī and h are classed as combinational and transitional vowels. As the mouth is placed in the position to say ū and then suddenly changed so as to form any other vowel in the triangle, the result obtained is signified in writing by placing the letter w before the vowel. In a similar way we get the effect usually designated by y if the position of the vowel suddenly changes from ē to any other vowel. An infinite variety of dipthongs can be formed by changing the position of the mouth necessary to form one vowel to that to form another without interrupting the voice. The most distinct and principal ones used in our language are formed by passing from the sound a to either extreme corner of the triangle and are known as ou and ī. When a vowel commences a syllable it is formed by suddenly opening the glottis, permitting the air, which has been held in the lungs, to escape into the mouth, which is formed for the proper vowel. If the glottis remains open and the vowel is started by the sudden contraction of the lungs, we have the effect which is represented in writing by placing an h before the vowel. The sounds l and r are called semi-vowels because the voice train is partially interrupted, although the sound can be continued. The stop and fricative consonants are classified in a manner which is familiar to phoneticians.

It will be noticed that the markings are not those used in the international phonetic alphabet which were entirely too complicated for practical use. Only the bar and accent stroke are used. These can be written quickly and with little chance of error.

In order to pronounce these speech sounds properly, they must be combined into syllables. For the purpose of this investigation they were combined into mono-syllables of the simple types consonant-vowel, vowel-consonant, and consonant-vowel-consonant.

To eliminate memory effects every possible combination of the sounds into these types of syllables was used unless there was a good reason for excluding it. The complete list contained 8700 syllables. For convenience of testing these syllables were divided into groups of fifty. Each group contained the same kind and number of syllable forms and an equal number of each of the fundamental vowel and consonant sounds.

TABLE II.
Speech-sound Testing List. List No. 160

	Speech-sound	Key-word		Speech-sound	Key-word
1	ha	ho(t)	26	gōb	go+b
2	hā	hay	27	shōl	shoal
3	wă	wa(g)	28	ros	rus(t)
4	wi	wi(th)	29	jod	ju(g)+d
5	vou	vow	30	bok	buck
6	ăr	air	31	zīk	z+(d)ike
7	ez	e(bb)+z	32	bīch	buy+ch
8	ūsh	you+sh	33	kīth	ki(te)+th
9	an	on	34	gīt	gui(de)+t
10	id	(l)id	35	yif	y+if
11	jouv	jow(l)+v	36	sin	sin
12	moush	mou(nd)+sh	37	tĕrm	term
13	rour	r+our	38	mĕrl	m+earl
14	zūth	z+(s)oothe	39	pĕrv	p+(n)erve
15	hūs	who+s	40	yēt	y+eat
16	chush	ch+(p)ush	41	bēl	b+eel
17	jum	j+(f)oo(t)+m	42	zef	ze(al)+f
18	thup	th+(s)oo(t)+p	43	weng	whe(n)+ng
19	fuch	foo(t)+ch	44	kev	k+ev(er)
20	wŏng	wa(ll)+ng	45	hăng	hang
21	chŏth	cha(lk)+th	46	păg	p+(r)ag
22	tŏj	ta(ll)+j	47	yās	y+ace
23	kŏg	k+aug(er)	48	dāp	d+ape
24	fōn	(tele)phone	49	yang	ya(cht)+ng
25	dōs	dose	50	lan	l+on

To illustrate the technique of articulation testing a sample list is given in Table II. In the first column the syllable is given in its phonetic form. A key-word showing how each syllable is pronounced is given in the second column. These syllables were written on cards which were shuffled each time before they were used, so that the order in which they were pronounced was entirely haphazard. One hundred and seventy-four similar lists were used in this work. In order to eliminate personal peculiarities, several callers and observers were used. In Table III are shown the results obtained by an observer when this list was transmitted over a system which eliminated all frequencies above 1250 cycles per second.

TABLE III.

TRANSMISSION BRANCH
ARTICULATION TEST RECORDING SHEET

WORD ARTICULATION 40 %

TITLE OF TEST 320311
CONDITION TESTED Low Pass Filter - 1250~
DATE 2-7-20 Attenuation = 5 napiers down OBSERVER M. A.
TEST No. 11 CALLER H. E. D.
LIST No. 160

No.	OBSERVED	CALLED	ERRORS	No.	OBSERVED	CALLED	ERRORS
1	tan	term	ér – a m – n	26	zip	thup	th – z u – i
2	zit	gīt	g – z ī – i	27	ko'd	to'j	t-k j-d
3	wa	wa'	a'-a	28	tish	chush	ch-t u-i
4	dāp	✓		29	yang	✓	
5	gōb	✓		30	zēt	zūth	ū-ē th-t
6	yis	yif	f-s	31	ref	ros	o-e s-f
7	māl	merl	e'r-ā	32	jum	✓	
8	thin	sin	s-th	33	jo'g	ko'g	k-j
9	zīp	zīk	k-p	34	jad	jod	o-a
10	jouv	✓		35	tūth	hūs	h-t s-th
11	yāt	yās	s-t	36	id	✓	
12	thou	vou	v-th	37	ha	✓	
13	bīp	bīch	ch-p	38	fōn	✓	
14	ha'ng	✓		39	ko'th	cho'th	ch-k
15	mīs	moush	ou – ī sh-s	40	rour	✓	
16	dăch	dōs	ō-ă s-ch	41	an	✓	
17	kev	✓		42	bok	✓	
18	tig	pa'g	p-t a'-i	43	yēt	✓	
19	kīs	kīth	th-s	44	o'r	a'r	a'-o' y inserted
20	hā	✓		45	yēth	ūsh	ū-ē sh-th
21	weng	✓		46	wo'ng	✓	
22	dēl	bēl	b-d	47	kōv	pérv	p-k er-ō
23	thich	fuch	f-th u-i	48	zēt	zēf	f-t
24	wif	wi	f inserted	49	lan	✓	
25	ez	✓		50	shōl	✓	

E.M.B. E.A.

The correct word is written opposite all of the syllables which were recorded incorrectly. The errors for each of the fundamental sounds were taken from this original sheet and recorded on an analysis sheet as shown in Table IV; for example, it will be noticed that p was recorded as k 24.4 per cent, as p 45 per cent, and as t 22.2 per cent of the times called. On the other hand, the sound w was only recorded incorrectly 1 per cent of the times called.

For this system the consonant articulation was 65.8 and the vowel articulation 83.4.

TABLE IV

Summary Sheet — Average Errors above 2 %
TRANSMISSION BRANCH
ARTICULATION TEST ANALYSIS SHEET

TITLE OF TEST 320311
CONDITION TESTED Low Pass Filter – 1250~ Average of
DATE 6-22-20 Attenuation = 5 napers down OBSERVERS 8
LIST Nos.
CALLERS 2
TEST Nos.

Sounds Called	No. of Times Called	a	ā	á	e	ē	ér	i	ī	o	ō	ó	u	ū	ou	% ERROR
a				10.2												13.1
ā																2.2
a		13.8			4.3				2.2			3.8				27.9
e			2.4	2.3						10.0						17.5
ē																2.9
ér		3.2	32.8	2.7	4.4					3.6	3.8					60.3
i													5.3			8.4
ī																4.2
o		4.6			24.2											31.9
ō																3.9
ó		5.4								2.2						10.2
u								26.1		4.8						34.6
ū													2.8			11.8
ou																5.4

Total number of sounds called ______ Letter Articulation 72.2
Total number of errors ______ Word Articulation 41.2
Vowel Articulation 83.4

Summary Sheet – Average Errors above 3 %
TRANSMISSION BRANCH
ARTICULATION TEST ANALYSIS SHEET

TITLE OF TEST 320311
CONDITION TESTED Low Pass Filter – 1250 Average of
DATE 6-22-20 Attenuation = 5 napers down OBSERVERS 8
LIST Nos.
CALLERS 2
TEST Nos.

SOUNDS CALLED	b	ch	d	f	g	h	j	k	l	m	n	ng	p	r	s	sh	th	t	v	w	y	z	Omissions	Insertions	% Error
b			10.3																				4.5		21.2
ch						4.9		8.7							3.2	7.3	4.3	24.7							56.6
d	7.8				11.6		3.3																		35.2
f						3.3									26.0	11.7	19.0						3.9		60.8
g			30.6				3.9																		35.6
h													4.2												13.5
j			19.3		4.0																				29.9
k													3.8					33.7							48.0
l																									3.9
m											2.9														6.8
n										31.7															35.4
ng																									3.6
p		3.0						24.4										22.2							55.0
r									10.4														5.5		18.5
s				6.2												21.5	24.4	4.2							64.9
sh				3.6											21.3		17.0								53.2
th		3.4		8.6											21.1	8.3			7.0			0.8	3.1		70.7
t		7.3				3.4		18.5					6.2												42.4
v																	10.7					15.1			32.0
w																									1.0
y														9.3											15.8
z			4.2				4.7									4.2	6.8		7.9						39.8

No. of times each sound is called ______ Letter Articulation 72.2
Total number of sounds called ______
Total number of errors ______ Word Articulation 41.2
Consonant Articulation 65.8

DESCRIPTION OF THE SYSTEM FOR REPRODUCING SPEECH SOUNDS

The telephone system used in this investigation is probably more nearly perfect than any other which has yet been built. Its essential elements are a condenser transmitter to receive the speech waves and transform them into the electrical form, an amplifier for magnifying the intensity of the electrical speech currents, an attenuator for controlling the intensity, an equalizing network, and a receiver for delivering the speech to the ear. A schematic arrangement of the circuit is shown in Fig. 1.

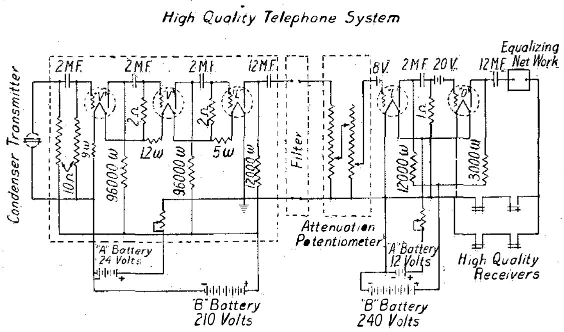


FIG. 1.—High Quality Telephone System

A detailed description of the construction and operation of the condenser transmitter has been given by Crandall and Wente and published in the *Physical Review.*[1] It is simply an air condenser, one of its plates being a flexible metal diaphragm.

A five-stage vacuum tube amplifier was used. Particular care was taken in coupling the stages together, so that the amplifier was practically free from frequency distortion.

The attenuator consisted of a potentiometer arrangement which could reduce the amplitude of the speech waves to approximately one-millionth of their maximum values.

The equalizing network was an arrangement of resistances, condensers and inductance coils having a frequency selectivity which was the complement of that of the rest of the system.

The telephone receiver was a bipolar type having a special construction which was designed to broaden the range of frequency response.

The reproducing efficiency of the system from the mouth of the speaker to the ear of the listener for each frequency is shown in Fig. 2.

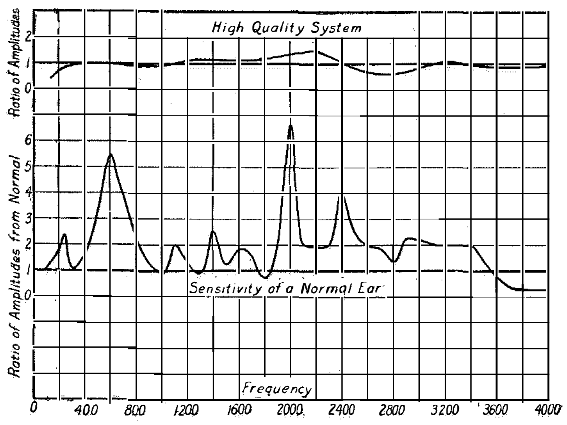


FIG. 2.

The pitch or frequency of the tone is given on the X axis. The ordinates represent amplitude ratios or the number of times the amplitude of the tone reaching the ear was greater than that which entered the transmitter. It will be seen that this high quality system has practically a uniform response for all frequencies throughout the speech range.

In order that its uniformity may be appreciated, a comparison curve is given. This curve shows the deviation in the sensitivity of a typical individual ear from the average sensitivity of a large number of ears. The ordinates represent

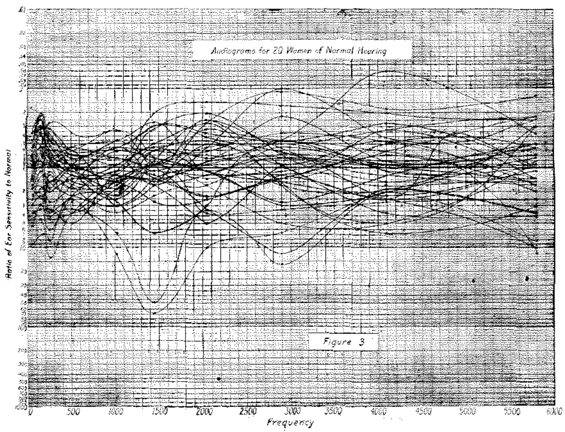


FIG. 3.

the ratio of amplitudes at the various pitches which was necessary to bring the tone to the threshold of audibility. It is evident that this deviation is much larger than the departure of the high quality circuit from uniformity.

To show that this particular individual's curve is typical, the curves for both ears of 20 women are given in Fig. 3. For convenience these curves are plotted on logarithmic paper. If an arithmetic scale is used, all of the curves below the mean are crowded together in the small space between zero and one, and all those above the mean are stretched out from one to infinity. By using a logarithmic plot a symmetrical distribution is obtained. The method of obtaining these ear sensitivity curves was fully described in a recent paper[2] given before the Natural Academy of Sciences.

It is interesting to note that they indicate that each individual has a hearing characteristic which is quite different from other in-

[1] Crandall, *Phys. Rev.*, June, 1918; Wente, *Phys. Rev.*, July, 1917.
[2] Fletcher and Wegel, *Proc. Nat. Acad. Science*, Vol. 8, No. 1, pp. 5–6, Jan., 1922.

ties. At all intensities, the sounds th, f and v are the most difficult. Z, h and s become very difficult at weak volumes. The sounds i, ou, er and ó are missed less than 10 per cent of the time, even with "very weak" intensity. At "average" volumes there are only three sounds more difficult than e while at "very weak" volumes there are 23 sounds more difficult. At very weak volumes l, which is the easiest sound at "average" volumes, is missed three times as often as e.

We will now pass to a consideration of the effect of distortion upon the articulation of the sounds.

Description of Electrical Filters Used to Produce Distortion

In order to investigate distortion we would like to be able to take the train of speech waves going from the mouth to the ear and operate upon it in various ways such as eliminating frequencies in certain regions without marring or disturbing other frequencies. For example, if all frequencies above 1000 were eliminated, it would be possible to determine what intelligibility is carried by this range of frequencies.

Fortunately one of the recent electrical inventions is admirably adapted for this purpose, namely, the electrical wave filter invented by

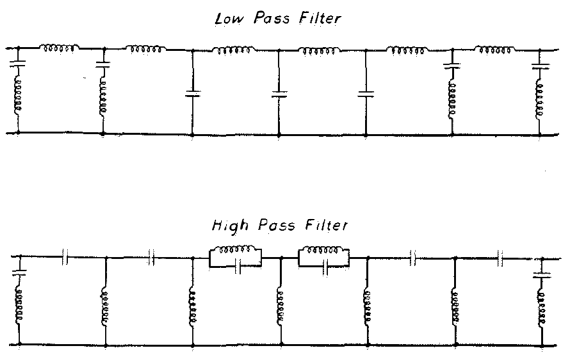


Fig. 6.

Dr. G. A. Campbell. This device was used extensively in this investigation.

The schematic circuit diagrams of the two types of filters which were used are given in Fig. 6.

This arrangement of coils and condensers produces an electrical conductor with the unusual properties that it transmits without appreciable diminution in amplitude any frequency between certain limits and reduces the amplitude of all frequencies outside these limits to less than 1/1000 of their original value. By varying the numerical values of the inductances and capacities this transmitted range can be placed at any desired position. In the arrangement which was used in the investigation these coils and condensers were housed in two boxes. The switching mechanism was arranged so that by turning a dial the condensers and coils were connected in such a way that the filter transmitted different frequency bands.

In Fig. 7 are shown the transmission properties of the low pass filter when the dial is set to transmit frequencies from 0 to 1500. It is seen that for frequencies below 1400 the amplitudes of the transmitted tones are always greater than .8 of their initial values, while for frequencies above 1500 the amplitudes are decreased to

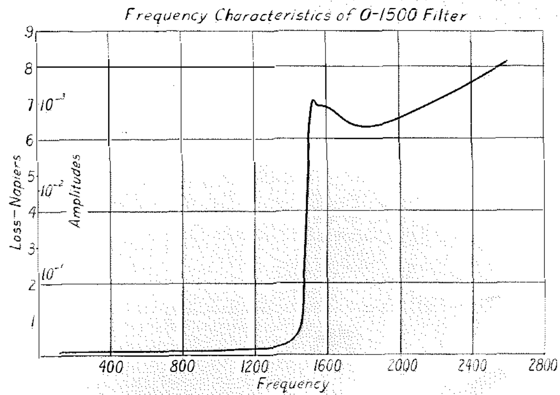


Fig. 7

less than .001 of their initial values. These electrical filters were connected into the high quality circuit between the third and fourth stages of the amplifier as indicated in Fig. 1. This combination formed a system which would pick up a complex sound wave and transmit faithfully to the ear those component frequencies in any desired region and eliminate all other frequencies.

Results of Articulation Tests with Filter Systems

Articulation tests were made with these filter systems and the results analyzed as described above. In Fig. 8 the syllable articulation results are shown in graphical form. The ordinates for the solid curves represent the per cent of the articulation syllables called into the system which were correctly recorded at the observing end. The abscissas represent the so-called "cut-off" frequency of the filter. For example, on the curve labelled "Articulation L" the point (1000, 40) means that a system which transmits only frequencies below 1000 cycles per second has a syllable articulation of 40 per cent. Similarly on the curve labelled "Articulation H" the point (1000, 86) means that a system which transmits only frequencies above 1000 cycles per second has a syllable articulation of 86 per cent. The dotted curves show the per cent of the total speech energy which is transmitted through the filter systems used in the articulation tests. These curves are derived from the results of Crandall and MacKenzie which were recently published.[3]

It will be seen that although the fundamental cord tones with their first few harmonies carry a large portion of the speech energy, they carry practically none of the speech articulation. A filter system which eliminates all frequencies below 500 cycles per second eliminates 60 per cent of the energy in speech, but only reduces the articulation 2 per cent. A system which eliminates frequencies above 1500 cycles per second eliminates only 10 per cent of the speech energy, but reduces the articulation 35 per cent. A system which eliminates all frequencies above 3000 cycles per second has as low a value for the articulation as one which eliminates all frequencies below 1000 cycles per second. This last statement may appear rather astonishing since it is contrary to the popular notion of the relative importance of various voice frequencies from an interpretation standpoint.

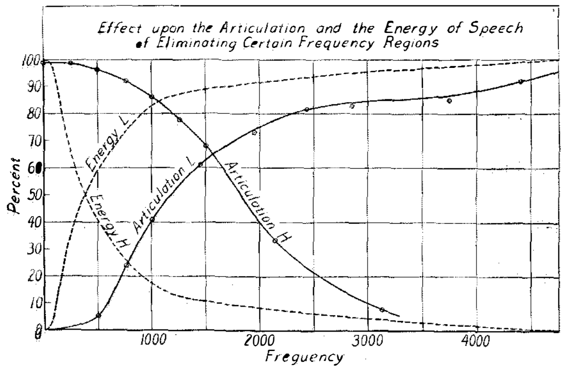


FIG. 8.

[3] See preceding paper.

The two solid curves intersect on the 1550 cycle abscissa and at 65 per cent articulation, which shows that using only frequencies above or frequencies below 1550 cycles an articulation of 65 per cent will be obtained. The two dotted curves necessarily intersect at 50 per cent.

The curves in Fig. 9 show how the articulation of some of the fundamental speech sounds was affected by eliminating certain frequency regions. The ordinate gives the number of times the sound was written correctly per 100

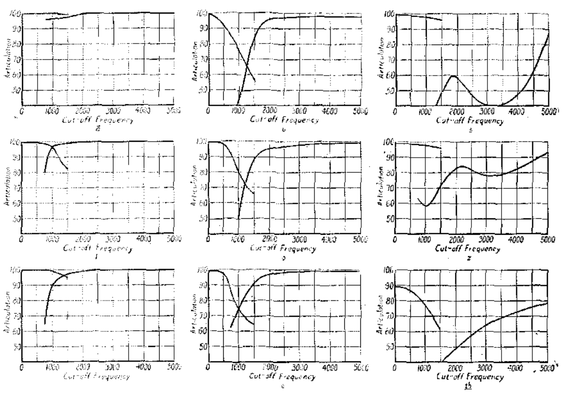


FIG. 9.

times called. As in Fig. 8 the left hand curve shows the effect of eliminating all frequencies below and the right hand curve the effect of eliminating all frequencies above the frequency specified by the abscissa.

These nine speech sounds were chosen as representing three important classes. It is seen that the long vowels ē, l and ī can be transmitted with an error of less than 3 per cent when using either half of the range of frequencies. When using either frequencies from 0 to 1700 or from 1700 to infinity, ē was interpreted correctly 98 per cent of the time. Similarly l was interpreted correctly 97 per cent of the time when using either the range from 0 to 1000 or 1000 to infinity, and ī 96 per cent of the time when using either the range from 0 to 1350 or from 1350 to infinity. The short vowels, u, o and e are seen to have important characteristics carried by frequencies below 1000. More than a 20 per cent error is made on any of these three sounds when frequencies below 1000 are eliminated. The elimination of frequencies above 2000 produces almost no effect.

The fricative consonants s, z and th are seen to be affected very differently from those in the other two classes. These sounds are very definitely affected when frequencies above 5000 are eliminated. The sounds s and z are not affected by the elimination frequencies below 1500. It is principally due to these three sounds that the syllable articulation is reduced from 98 per cent to 82 per cent when frequencies above 2500 cycles are eliminated.

Conclusion

In conclusion then we see that the intensity of undistorted speech which is received by the ear can be varied from 100 times greater to one-millionth less than the initial speech intensity without noticeably affecting its interpretation. The intensity must be reduced to one-ten-billionth of that initial speech intensity to reach the threshold of audibility for the average ear. Also it is seen that any apparatus designed to reproduce speech and preserve all of its characteristic qualities must transmit frequencies from 100 to above 5000 cycles with approximately the same efficiency. Although most of the energy in speech is carried by frequencies below 1000, the essential characteristics which determine its interpretation are carried mostly by frequencies above 1000 cycles. In ordinary conversation the sounds th, f and v are the most difficult to hear and are responsible for 50 per cent of the mistakes of interpretation. The characteristics of these sounds are carried principally by the very high frequencies.

It is evident that progress in the knowledge of speech and hearing has a great human interest. It will greatly aid the linguists, the actors, and the medical specialists. It may lead to improved devices which will alleviate the handicaps of deaf and dumb persons. Furthermore this knowledge will be of great importance to the telephone engineer, and since the telephone is so universally used, any improvement in its quality will be for the public good.

These humanitarian and utilitarian motives as well as the pure scientific interest have already attracted a number of scientists to this field. Now that new and powerful tools are available, it is expected that in the near future more will be led to pursue research along those lines.