BELL LABORATORIES RECORD

ARRIVAL OF RADIO WAVES
C. B. FELDMAN

FEEDBACK AMPLIFIERS
H. S. BLACK

SILICA SPRINGS
H. W. WEINHART

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In this Issue

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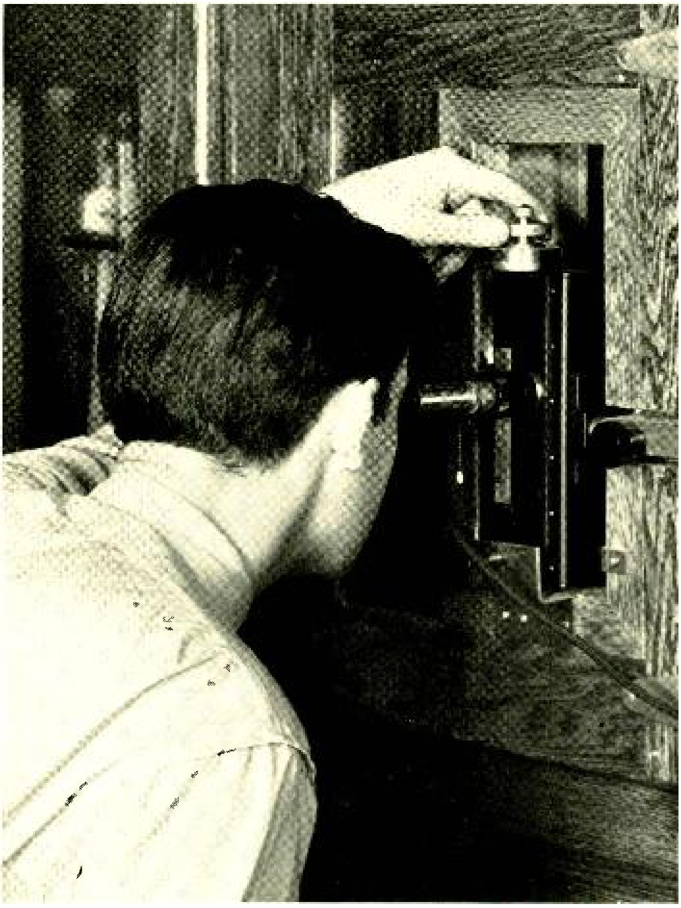

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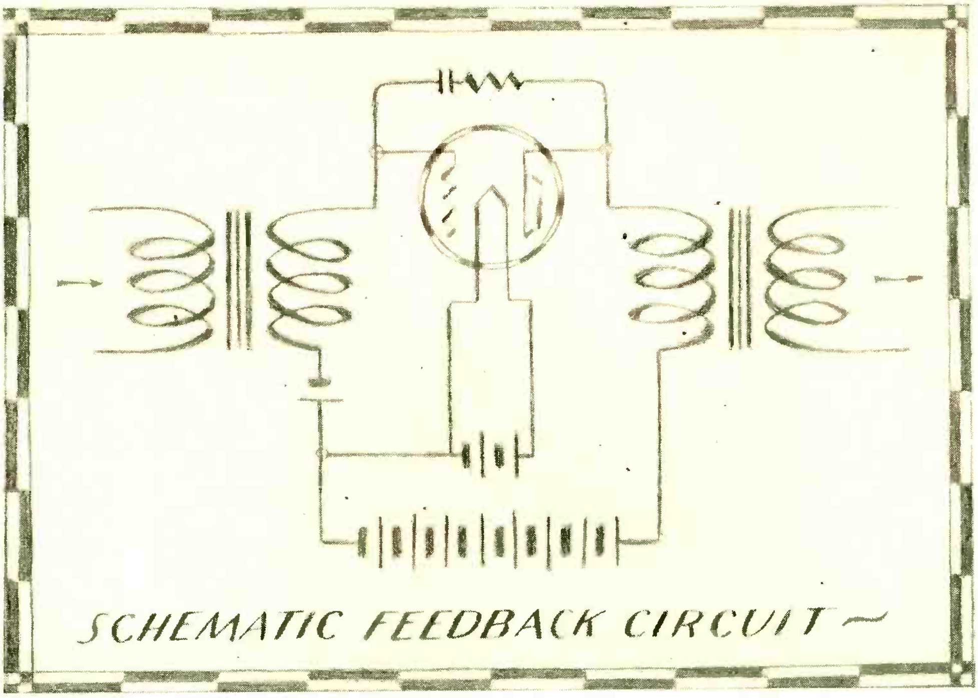


Feedback Amplifiers

By H. S. BLACK
Toll Systems Development

TELEPHONE history is full of dreams come true. Few rosier dreams could be dreamed than that of an amplifier whose overall performance is perfectly constant, and in whose output distortion constitutes only one one-hundred millionth of the total energy, although the component parts may be far from linear in their response and their gain may vary over a considerable range. But the dreamer who awakes in amazement to find that such an amplifier can be built has additional surprises in store for him. These benefits can be obtained by simply throwing away some gain, and by utilizing "feedback action".

A feedback amplifier is one in which a portion of the output is fed back to the input. The notion of doing this with various types of electrical apparatus has long been familiar; and it has been appreciated that by applying the principle to an amplifier the gain of the device might be increased or decreased, according to the amount and phase of the impulse fed back. It has commonly been supposed, however, that for stable operation there must be a net loss around the closed loop formed by the amplifier and feedback circuits. Furthermore, it has been supposed that in the case where the gain was reduced there was ordinarily no advantage to be had which would justify the loss in amplification; and that, in the case where the gain was appreciably increased, dangerous instability would result, causing at the worst sustained oscillations or "singing" around the closed loop.

It is only recently that further studies revealed the many remarkable and desirable properties that could be secured by properly employing feedback action. Increased constancy of amplification and decreased outputs of noise and harmonics—benefits previously obtainable only by further refinements in the already refined design of vacuum tubes and their power supply circuits—can now be obtained simply and cheaply by designing the amplifier with a feedback circuit whose loss is properly proportioned to the gain of the amplifying circuit. The extent of these improvements is a function of the total gain and phase shift around these two circuits: with a gain of 26 db, noise and the amplitudes of harmonics may be reduced twenty-fold, and constancy or stability of gain may be improved more than twenty-fold. With a total gain of 60 db these improvements can be made a thousand-fold.

There are many ways that feedback action may be produced. In the most general sense feedback action can be defined as the action taking place whenever a resultant vector—representing in this case a voltage or current—is the sum of two vectors one of which is under the control of the resultant. One method of applying a voltage under the control of the resulting voltage is to apply the resulting voltage back upon itself, through a suitable transmission path.

Important and fundamental conditions surrounding the design of feedback amplifiers according to this principle can be derived from some simple considerations embodied in Figure 1. At the top of that figure an amplifier without feedback is shown by an active or amplifying network with a voltage ratio, output to input, of μ. The output voltage, E, of such an amplifier is μ times the input voltage, e.

The corresponding schematic of a feedback amplifier in Figure 1 shows the active network bridged by a passive feedback circuit, whose output voltage is β times its input voltage. In the closed loop thus formed feedback action takes place, and at the input the effective grid voltage e_0 is no longer equal to e but becomes the sum of two voltages: e the applied, and $\mu\beta e_0$ the feedback voltage. From this equation, $e_0 = e + \mu\beta e_0$, the effective input voltage is found to be $e_0 = e \frac{1}{1-\mu\beta}$. Thus feedback action alters the applied impulse by the factor $\frac{1}{1-\mu\beta}$. Since the output is μ times the effective input, e_0, the output with feedback, is $\mu e_0 = \frac{\mu e}{1-\mu\beta}$.

Hence the act of connecting the feedback circuit has divided the principal effect of the applied generator or excitation by the quantity $(1-\mu\beta)$. If the magnitude of this quantity is

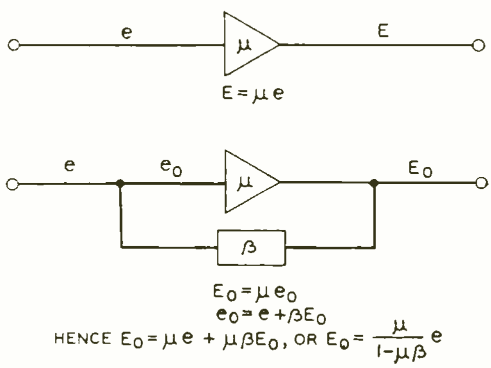


Fig. 1—In an ordinary amplifier (above) the input voltage and the applied voltage have the same value, e. In a feedback amplifier the input voltage e_0 is the sum of the applied voltage and the voltage fed back. The amplification of the amplifier is thus changed from μ to $\frac{\mu}{1-\mu\beta}$

greater than unity the output is reduced, and the feedback is called "negative feedback"; if this denominator is less than unity, "positive feedback" occurs, increasing the gain of the amplifier.

The more detailed schematics in the headpiece and Figure 2 show two types of feedback: a "voltage" feedback, and a bridge type of feedback. In the second, balanced bridges eliminate the effect of feedback upon the impedances presented by the amplifiers, and remove the influence of the circuits connected to the amplifier upon the amount of feedback.

Since μ and β are voltage or current ratios they have both magnitude and phase angle. It is interesting to note that when the magnitude of $\mu\beta$ is unity and the phase angle zero, the output $\frac{\mu e}{1-\mu\beta}$ becomes indefinitely large. This is the extreme case of instability, and would, of course, render an amplifier inoperative. In fact it is the one and only necessary condition for self-oscillation. The uniqueness of this condition, however, does not make it easy to avoid. In the theoretical case of a perfectly linear amplifier, with infinite power carrying capacity, there are several conditions under which a small disturbance may become exponentially larger with time to an indefinite extent.* In all practical cases amplifiers are non-linear, and μ and β vary with the load. Practically, therefore, whenever a linear amplifier would ultimately give an indefinitely large output, the increasing load will change μ and β in the non-linear amplifier until their product is unity with a zero phase angle at a certain frequency, and thus the practical amplifier will sing at this frequency.

For this reason it is far from simple to employ feedback. Very special control is required of phase shifts in the amplifier and feedback circuits, not only throughout the useful frequency band but for a wide range of frequencies above and below it. Unless these relations are maintained singing will occur. Experience has

H. Nyquist has given in the Bell System Technical Journal for January 1932 a simple criterion for designing an amplifier so as to insure freedom from this effect.

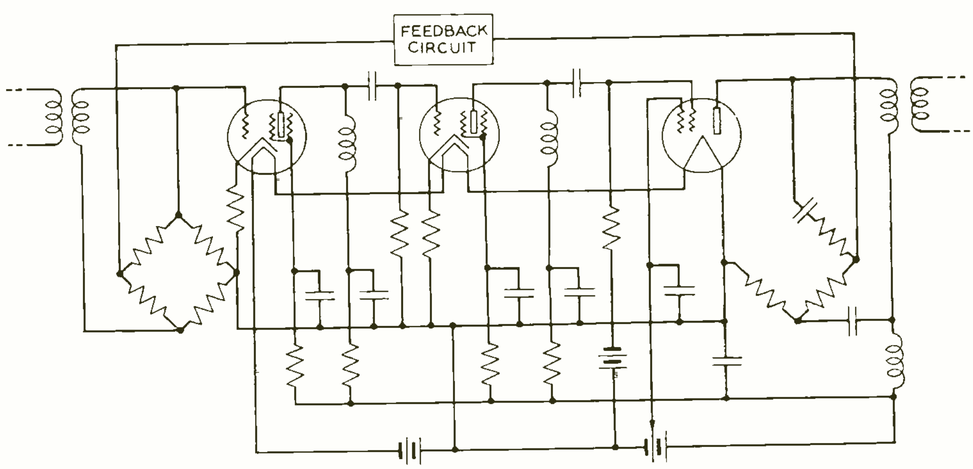


Fig. 2—Although a feedback circuit can sometimes be connected directly between the input and output leads of an amplifier, as shown in the headpiece, it is often more satisfactory to establish the connections through bridges which prevent undesired reactions of the feedback circuit on the input and output circuits

shown, however, that when proper phase relations are provided in the design of an amplifier, its performance is perfectly reliable.

Adding to an amplifier a circuit through which negative feedback will occur is an excellent method of reducing the outputs of noise and harmonics originating in the amplifier. Noise and harmonics may be considered—like the signal input—as generators applied at various points around the closed loop. At each such point, feedback action takes place, and the effective generator is $\frac{1}{1-\mu\beta}$ times the original. Since noise is independent of the signal, and the harmonics are a function of the signal level, the two must be considered separately.

The signal-to-noise ratio at the output of two similar amplifiers, one employing feedback and the other having the same gain and output level but without feedback, is a convenient measure of the effect of feedback upon the noise. In order that an amplifier with negative feedback have the same gain as the reference amplifier, there must be some extra gain in the μ–circuit of the former. If the noise is inserted in the last stage in the same manner and magnitude in the two amplifiers, the feedback amplifier will reduce the applied generator by the factor $\frac{1}{1-\mu\beta}$. Inasmuch as the extra gain is not added after the last stage, the signal-to-noise ratio in this case is improved by the factor $(1-\mu\beta)$. If the noise is assumed to be introduced in the first stage, the applied noise generator is again changed by the factor $\frac{1}{1-\mu\beta}$, but the gain after these two identical first stages is different in the two cases. In the case with feedback the amplification is $(1-\mu\beta)$ times greater—to compensate for the amount of gain thrown away—than the reference amplifier which does not have feedback. Hence the signal-to-noise ratio in this case is unchanged. It is apparent from the first case that the power supply and tube design in the last stage of a feedback amplifier may be $(1-\mu\beta)$ times noisier and meet the same requirements.

Harmonics differ from noise in varying with the signal output. To a first approximation in considering the combined output, of the desired signal and the undesired harmonics, it makes no difference how the distortion was produced: whether by a non-linear condition or by a linear device possessing many extra generators which are the sources of the distortion. In the case without feedback it is assumed that the magnitude of the distortion generator depends only upon the magnitude of the signal output. In many cases it is satisfactory to make the further assumption that this is also true with feedback. Then for a given signal output level the imaginary generators of distortion are fixed in value. When feedback is applied and the input is changed so that the signal output is restored to the value it had without feedback, the "actual" values of these distortion generators will be the same as their original values, but feedback will change their effective values to $\frac{1}{1-\mu\beta}$ times the original values. With positive feedback, this is an effective increase; with negative feedback, an effective and material decrease. Hence, for the same output, each 10 db decrease in gain at the frequency of the distortion generator will result in reducing by a factor of ten the energy in the distortion.

A closer examination of what happens to the gain of an amplifier when a feedback circuit is added to it, is repaid by the discovery of two interesting types of amplifier. Without feedback the ratio of output to input is μ; with feedback this ratio was shown to be $A = \frac{\mu}{1-\mu\beta}$. If the product $\mu\beta$ is large compared to unity—say 40 or 100 or 1000—then the amplification A approximates $-\frac{1}{\beta}$. With a given frequency characteristic in the β-circuit of such a feedback amplifier, the amplifier as a whole will have the inverse characteristic.

One of the most readily apparent and valuable uses of this sort of amplifier is as an equalizer. Equalization for the frequency distortion occasioned by many types of apparatus is usually accomplished by placing in the direct path of the signal a network having a frequency characteristic which is the inverse of that to be corrected. For many types of frequency characteristics it is difficult, and for some impossible, to construct a passive network having the exact inverse characteristic. With this type of amplifier, however, it is only necessary to place in the feedback circuit apparatus possessing the same characteristic as that to be corrected. The value of $\mu\beta$ may be increased to the extent necessary for the desired accuracy of the correction.

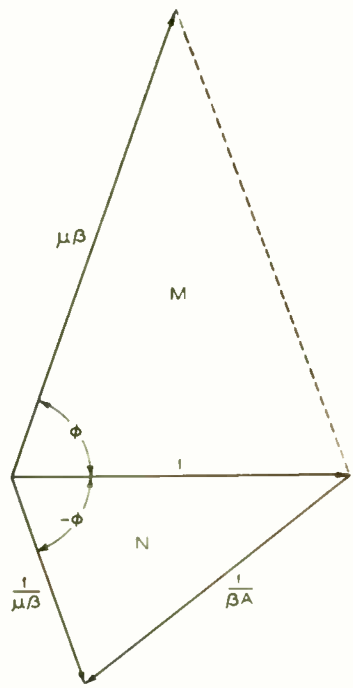


Fig. 3—When μβ is so chosen that M is an isosceles triangle (that is, when $|\mu\beta| = \frac{1}{2}\sec\Phi$), N is also an isosceles triangle and the length of $\frac{1}{\beta A}$ is the same as the length of 1. Hence the length of A is the reciprocal of the length of β, and the amplifier has a gain-frequency characteristic the same as the loss-frequency characteristic of the feedback circuit

There is another method by which the gain can be made exactly equal to $\left|\frac{1}{\beta}\right|$ without resorting to large values of $\mu\beta$, as can be seen from the vector diagram in Figure 3. Since A equals $\frac{\mu}{1-\mu\beta}$, vector $\frac{1}{A}$ equals $\frac{1-\mu\beta}{\mu}$ and vector $\frac{1}{\beta A}$ equals $\frac{1-\mu\beta}{\mu\beta}$ or $(\frac{1}{\mu\beta}-1)$. To construct $\frac{1}{\beta A}$, therefore, it is possible to begin with $\mu\beta$ (Figure 3), having the length $|\mu\beta|$ and the angle Φ, and the unit vector 1. The vector $\frac{1}{\mu\beta}$ can then be drawn with the length $\frac{1}{|\mu\beta|}$ and the angle $-\Phi$. Finally the vector $(\frac{1}{\mu\beta}-1) = \frac{1}{\beta A}$ can be obtained by drawing an arrow from the head of the unit vector to the head of $\frac{1}{\mu\beta}$ already constructed. These three vectors form triangle N; and a line between the heads of $\mu\beta$ and the unit vector completes another triangle, M. These triangles are geometrically similar, since the angles Φ and $-\Phi$ are equal in magnitude and the sides including these angles are proportional $\left[\frac{1/|\mu\beta|}{1} = \frac{1}{|\mu\beta|}\right]$. When triangles M and N are made isosceles triangles as shown in Figure 3, the length of $\frac{1}{\beta A}$ is the same as that of unity, and thus the length of A is exactly the reciprocal of the length of β. It can be seen from the figure that this condition is satisfied, and the feedback amplifier will have exactly the same gain as the loss in the β–circuit, whenever $\frac{1}{2|\mu\beta|} = \cos\Phi$.

The perfectly constant amplifier, mentioned at the beginning of the article, can be obtained in two ways similar to the two just described for the gain characteristic. It has been shown that when there is a large net gain around the closed loop $\mu\beta$ becomes large compared to unity, and A the amplification closely approximates $-\frac{1}{\beta}$. This means that the effect of μ on the overall amplification is less and less. If β is a passive network, constant with time, the effect on the amplification, caused by changing μ a small amount $\Delta\mu$, is the change $\Delta\mu$ divided by $(1-\mu\beta)$. With $\mu\beta$ equal to about 20 db, producing about a 20 db decrease in gain variations in the amplification due to a change of $\Delta\mu$ will be $\Delta\mu$ divided by 10. Similarly if the gain were increased 20 db by feedback, the variations due to a change in μ would be multiplied by 10.

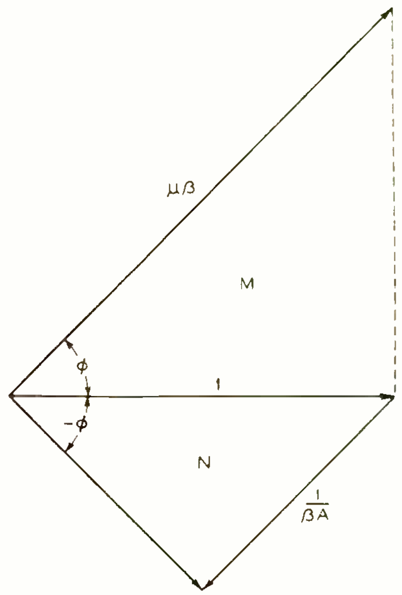


Fig. 4—When $|\mu\beta| = \sec\Phi$, M and N are right-angled triangles

In most practical cases it is not the complete vector A that is important, but merely its magnitude, the factor influencing the reading of the voltmeter or current-indicating device in the output. Moreover, it has been found that most amplifier variations are merely variations in the magnitude of μ, unaccompanied by appreciable change of phase. To take advantage of these two facts, an amplifier can be designed whose vector diagram is like that in Figures 4 and 5. These diagrams are similar to Figure 3, except that triangles M and N are made right-angled triangles. It can be seen that, for small changes in the magnitude of $\mu\beta$, the length of $\frac{1}{\beta A}$ will be practically unchanged. Furthermore, if there is a slight shift of the right sort in the phase of μ at

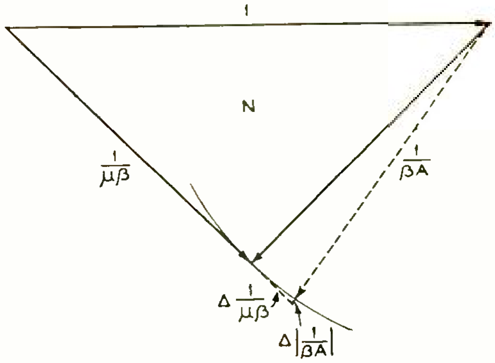


Fig. 5—An enlarged view of triangle N of Figure 4 illustrates the effect on the length of $\frac{1}{\beta A}$ of small changes in the length of μ. A small decrease in the length of μ decreases the length of $\mu\beta$ and hence increases the length of $\frac{1}{\mu\beta}$ as shown by the dotted extension. The resulting extension of $\frac{1}{\beta A}$ is only the negligible amount between the circular arc and the line of $\frac{1}{\mu\beta}$. Since β is constant, a small change in $\left|\frac{1}{\beta A}\right|$ means a correspondingly small change in $|A|$. Hence the gain of the amplifier remains substantially constant despite small changes in gain in the amplifying circuit

the same time that the magnitude changes, a considerable change in the length of $\frac{1}{\mu\beta}$ will not change the length of $\frac{1}{\beta A}$ at all.

The triangles M and N will be right-angled whenever $|\mu\, \beta| = \sec \Phi$. It is interesting to notice that this expression holds not only for negative feedback but for positive feedback as well. Hence when $\frac{1}{1-\mu\beta}$ is greater than unity and $|\mu\, \beta| = \sec \Phi$, the feedback will increase the gain of an amplifier and at the same time render it immune to small variations in μ.

The advantages already described and credited to feedback, such as noise reduction, increased linearity, desirable gain frequency characteristics and constancy of gain, are impressive in themselves. Others are also obtainable: improved phase distortion, improved gain load characteristic and better impedances. Their combined practical value is in enabling cheaper apparatus to be used to meet the same requirements, or in meeting requirements that otherwise could not practically be met.

All these apparently parodoxical but extremely valuable results have actually been observed in tests conducted by the Laboratories and many were amply demonstrated in a field trial of feedback repeater-amplifiers at Morristown, N.J. Here 70 feedback amplifiers, designed for use in cable carrier systems, were used in tandem. At full load the energy in the distortion from each amplifier was one ten millionth or less of the signal energy. The maximum change in each amplifier did not exceed .0007 db per volt of change in the plate battery, and at twenty kilocycles the change was only .00005 db per volt. Such constancy as this, hitherto unattainable, will be of the greatest assistance in improving and lowering the cost of carrier telephone systems over long cables.

FEEDBACK FOR GENERATORS

The vacuum tubes in telephone repeaters are almost all supplied with filament power from 24-volt storage batteries, "floated" across charging generators. To avoid introducing the ripple produced by these generators into the telephone circuits by way of the filaments, filters are inserted between the batteries and the filament circuits. When the currents flowing between the generator and the batteries are large, however, their fluctuating component may induce the undesired ripple in the transformers associated with the repeaters. By connecting across the charging generator a special amplifier, with its output connected to its input, which amplifies only the alternating components, excluding the direct current, it has been found possible to reduce to a hundredth the power of the ripples in the charging current. This interesting application of the feedback principles, discussed in the foregoing article, was described by F. A. Cowan of the Long Lines Department in ELECTRICAL ENGINEERING *for April, p. 590.*

A Telephone for Use in Explosive Atmospheres

By J. M. HAYWARD
Telephone Apparatus Development

A NUMBER of years ago a telephone set was developed for use in coal mines where explosive gases, such as methane or coal dust, might be present in dangerous proportions. It was designed not only to minimize the hazard of explosion but to withstand the rough usage it might encounter in narrow passages underground. More recently a need has appeared for a subscriber set for more general use in chemical factories, gas manufacturing plants, and other industrial establishments where explosive mixtures of gas may be present. The heavy mine set is unsuitable for such locations, and so the development of a new set for use in manual areas was undertaken based on experience gained from the earlier development.

Under normal use the only place where sparks are formed in a subscriber's set of the non-dial type is at the switchhook contacts. One of the chief objects of the design, therefore, is to prevent these small arcs at the switchhook from causing explosions. In addition, however, since a broken conductor, or loose contact might cause an arc, the set must be designed to prevent damage to any of the current-carrying parts, or the possible loosening of a contact. As a further precaution the set is locked so that only authorized persons may have access to it.

Either of two methods are possible for preventing arcs at the switchhook from causing explosions. The switchhook assembly could be mounted in an enclosure made absolutely gas tight—thus always insuring that no explosive gases would surround the contacts. Although this method is possible it requires a very expensive construction, and there is always the possibility that leaks may develop due to one cause or another. The other method, which was chosen for the new set, is to enclose the switchhook assembly in a small compartment,

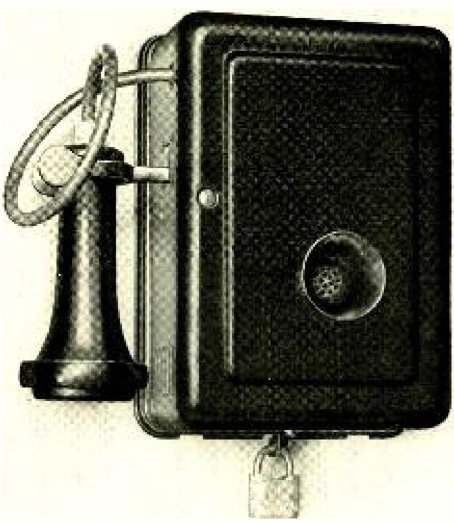


Fig. 1—The locked case, internally mounted transmitter, and heavy receiver cord are the external features that differentiate the 629A subscriber set from the usual type

strong enough to withstand the explosion of the small amount of gas that it may contain, and to provide very long leakage paths to the outside of the compartment so that the escaping gases will be cooled below the ignition point before they reach the outside.

The desired seal could have been obtained in a number of different ways. The arrangement selected as being simple but yet effective is shown in Figure 2. The switchhook is fastened to a casting that forms the top of the compartment, and is surrounded by a heavy cylindrical container, which screws on the casting by a very long fine thread. The bottom of the cylinder is securely brazed and tested under air pressure to insure tightness. A plunger with a very long and closely fitting bearing surface is employed to operate the main contact spring. Connections to the contact springs are made with leads passing through a sealing chamber above the cylinder. To insure that there are no unfilled spaces, due to the wires being grouped together, the leads are spread at the top of the chamber so that each is surrounded by a minimum of 1/32 inch of sealing compound.

The interior arrangement of the set is shown in Figure 3. A standard ringer is employed except that a metallic shield, lined with bakelite, is placed around the coils to prevent their being accidentally damaged, which might occur when adjustments are being made. The leads, at the base of the ringer, are covered with sealing compound which prevents any possibility of short circuiting, and also holds them securely in place so that the soldered connections cannot be broken. In addition the leads are tied with twine to the bracket on which the ringer is mounted so that no movement can take place to crack the compound.

To avoid having soldered connections outside of the condenser, the leads are connected to the units inside the can, and are thus held in place when the can is filled with the regular compound. The can is made of brass to decrease the likelihood of corrosion,

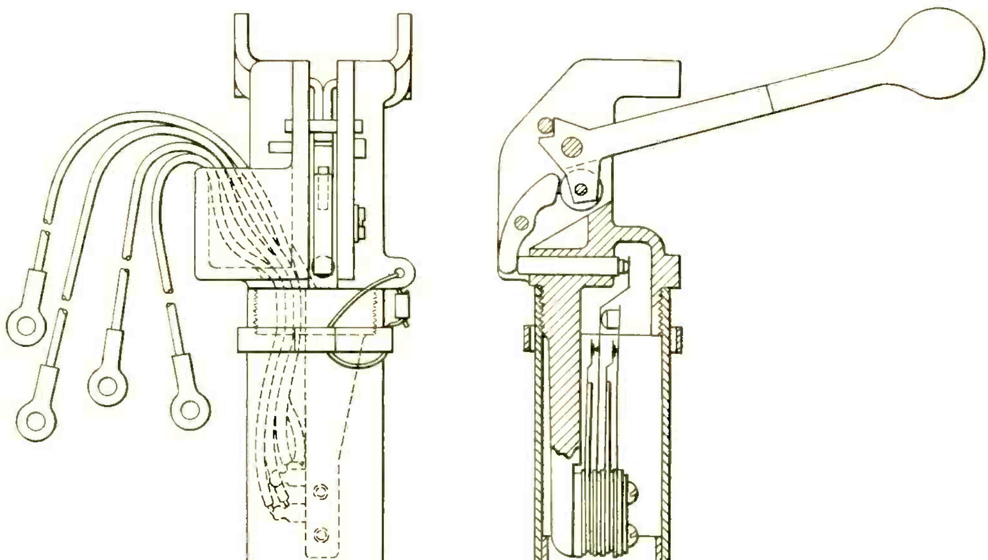


Fig. 2—Switchhook assembly and enclosing cover with the new subscriber sets

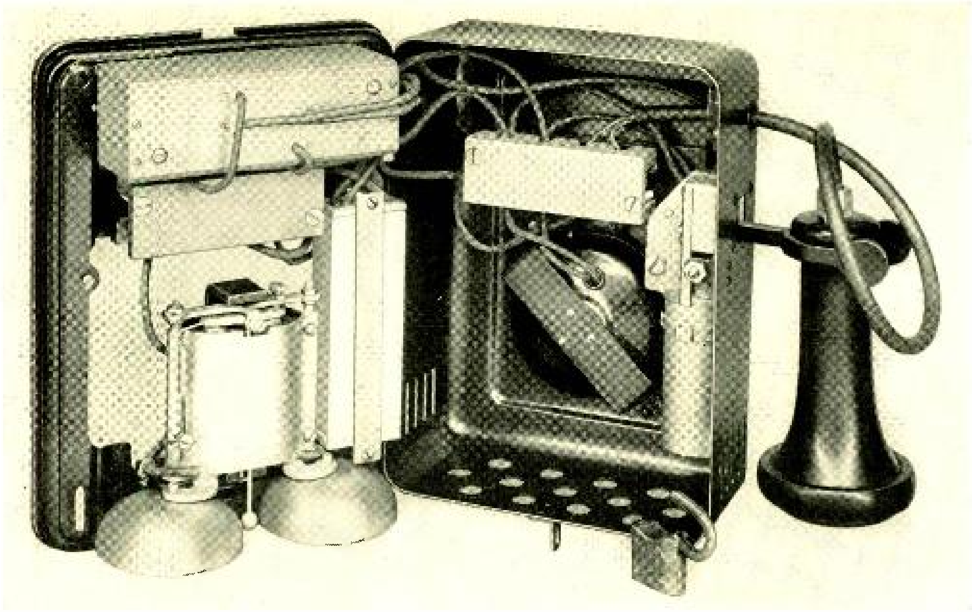


Fig. 3—No exposed or unprotected conducting parts are permitted within the set and all leads are short, and securely fastened

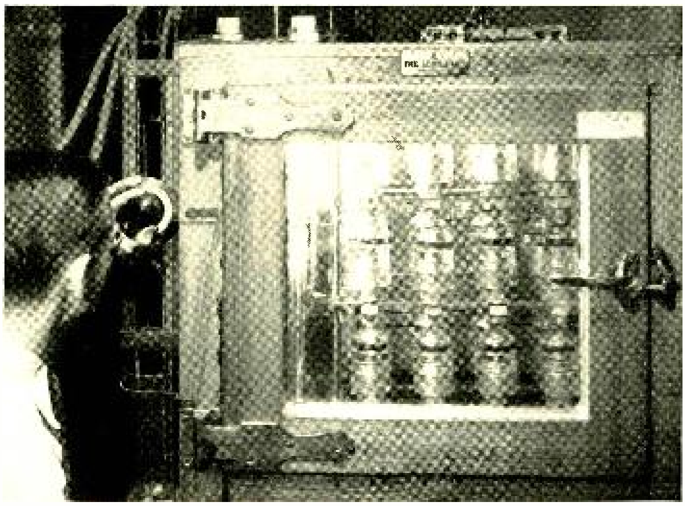
but except for these modifications the condensers are of the standard type. The induction coil is of the moisture proof type and is mounted in a wooden box which is then filled with sealing compound. Before the box is filled with compound the leads are connected to the terminals on the spool-heads and tied to the coil winding so that strains on the wires will not be taken by the terminals.

Each piece of apparatus is equipped with leads of just the right length for connecting to the proper terminal blocks. Four of the leads which run from the base to the cover are necessarily long enough to permit opening the cover, but they are clamped to the side of the induction coil to prevent their getting between the edge of the cover and the base when the cover is closed. The free ends of the leads have closed eye-type cord tips, and lock washers are employed to insure a permanently tight connection. Particular attention has been given to the materials and finishes of every part of the set to prevent corrosion either from moisture or from various gases such as carbon disulphide, acetone, or ammonia.

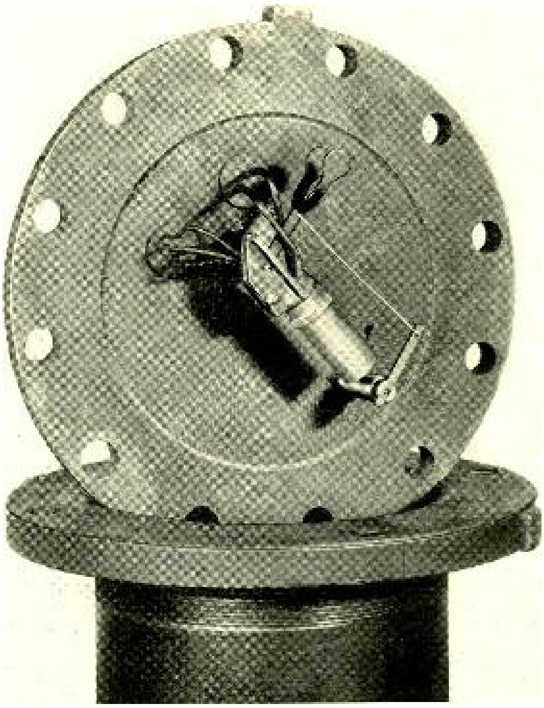
The transmitter, which normally is mounted on an adjustable bracket on the cover of wall-type telephone sets, is located within the locked housing, and only the mouthpiece projects through the housing. With a fixed transmitter there is no movement of the connecting leads as there would be with the bracket mounting, and there is no access to the transmitter except after the set has been unlocked. The only exposed apparatus is the receiver and its cord. The receiver is adequately protected by its hard rubber case and cap, and the cord is of the heavy-duty type clamped firmly both to the case of the receiver and to the cover of the set.

As part of the development a series

of tests were carried on to determine whether explosions could occur with the set as designed. How successfully the set met the tests for a large variety of explosive mixtures is described in the following article.



An important factor in the attenuation of speech currents on open-wire lines is the leakage between the wires of each pair by way of the insulators, pins, and cross-arms. Persistent study of the nature of this leakage has steadily reduced its amount and its variability. In studies conducted in our Chemical Laboratories, many insulators have been so connected that the leakage paths across them are in parallel. The current leaking through and around the insulator to the pin has been measured at various frequencies and humidities, and after the insulators have been given various aging treatments. From these and other tests it seems probable that the leakage permitted by an insulator at carrier frequencies is largely due to a condenser action. One "plate" of the "condenser" is formed by the mounting pin, the other by the wire and a conducting film of high resistance on the surface of the insulator.



Testing in Explosive Atmospheres

By C. H. WHEELER
Telephone Apparatus Development

IN the development of a telephone set for general use in explosive atmospheres as described in an accompanying article,* numerous laboratory tests were made to establish the safety of this set when exposed to a variety of gases and a range of mixtures which approximated or exceeded in explosion hazard any condition likely to prevail in the service for which the set is intended.

Owing to the rather unusual character of the work involved, facilities were not immediately available at Bell Telephone Laboratories for conducting these tests. In view of the common interest in their outcome and the possible desirability of telephone service for gas holder maintenance work, the Consolidated Gas Company of New York cooperated in the carrying out of the tests to the extent of providing the various gases, the different mixtures and numerous analyses while the tests were being made under our supervision at their Gas Testing Laboratory in New York City.

Since the design of the new set provided for no actual breakage of circuits except at the switchhook contacts, the tests were primarily a matter of determining the efficacy of the safety features provided for these contacts. There was considered to be involved also a determination of

*Record, *this issue, p. 297*

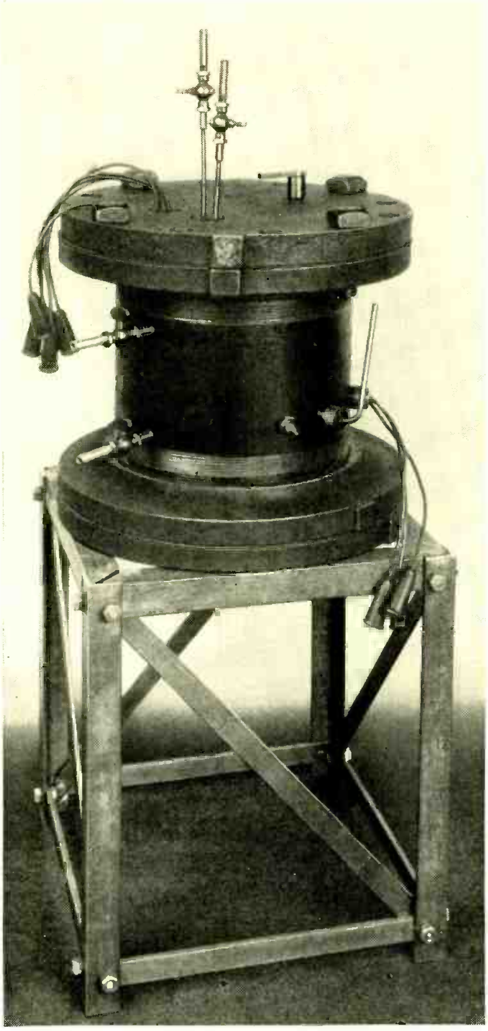


Fig. 1—Through the tubes at the left explosive mixtures were circulated in the test chamber, while the tubes at the top led to the switchhook enclosure

whether or not the minute sparks known to occur between the carbon granules in the conventional microphone button were capable of ignition of surrounding explosive atmospheres.

The tests were made in a special test chamber which consisted of a short length of ten-inch wrought iron pipe which was closed at the top by a heavy cast iron blind flange attached by bolts, and at the bottom by a wax paper diaphragm placed between soft rubber gaskets. This entire assembly was arranged to mount several feet above the floor on an angle iron frame which would allow the paper diaphragm to be readily blown out if the mixture surrounding the switchhook enclosure became ignited.

A switchhook assembly of the type to be used in the telephone set was modified to provide a gas inlet and outlet by brazing two short copper tubes to the switchhook frame. A fixed spark gap with a supplementary lead was provided within the enclosure to permit the use of a high tension spark when desirable. The modified switchhook assembly was mounted on the underside of the top cover of the testing chamber with the two copper tubes projecting through a rubber stopper in the cover. The wires from the switchhook contacts and from the supplementary spark gap were led out through another rubber stopper in the cover, and the switchhook was arranged for operation from the exterior by a link mechanism also extending through the cover.

The main chamber was equipped with gas inlet and outlet tubes placed in the side wall and a small automotive type ignition plug was also placed in this wall. A rod for mounting transmitters extended through a rubber stopper into this chamber and leads for the transmitters were brought out also through a rubber stopper. With the test switchhook or transmitter connected externally to the remainder of the apparatus comprising the telephone set and this in turn connected to a typical central office telephone circuit, it was then possible to approximate operation of the telephone set in explosive atmospheres.

While the set was designed for use on manual lines only, its performance under these tests was determined for both manual and step-by-step lines on account of the somewhat different character of sparks produced at the switchhook contacts when used on these circuits.

The procedure followed in making the individual tests was to pass an explosive atmosphere of predetermined mixture through the switchhook enclosure and through the main explosion chamber surrounding the switchhook assembly and the transmitter. When this mixture closely approached equilibrium, as determined by a comparison of inlet and outlet analyses, the gas flow was stopped and all shut-off cocks were closed to confine the mixtures within the switchhook enclosure and the main chamber. The switchhook contacts were then closed and opened in the typical manner. Unless explosion was recognized to have taken place promptly within the switchhook chamber, operation of the contacts was repeated a large number of times before the decision was made that explosion with a given condition of gas would not take place. It was recognized that the character of the spark and the volume of the switchhook enclosure had considerable influence on the explodability of the various mixtures and the instantaneous pressures produced within the enclosure. Therefore high tension sparks from an ignition coil were then passed across the fixed gap in the switchhook enclosure to explode the mixture and so produce as high a pressure within the enclosure as possible. Under these conditions any failure in the protective features of the contact enclosure would have been likely to have resulted in an explosion of the gas within the main chamber and rupture of the wax paper diaphragm. Such an explosion would correspond to one caused by operation of an insufficiently protected telephone set in an explosive atmosphere.

Tests were carried out using mixtures in air of hydrogen, manufactured gas, acetylene, propane and benzine as representative of conditions likely to be met in general industrial installations, and mixtures in air of ethylene and ether on behalf of service in the presence of anesthesia gases. In this work the known limits of inflammability of explosive gases in air, as given by the International Critical Tables, were taken into account.

The hydrogen, acetylene, propane and ethylene were obtained in steel cylinders under high pressure and as required were released into a small gas

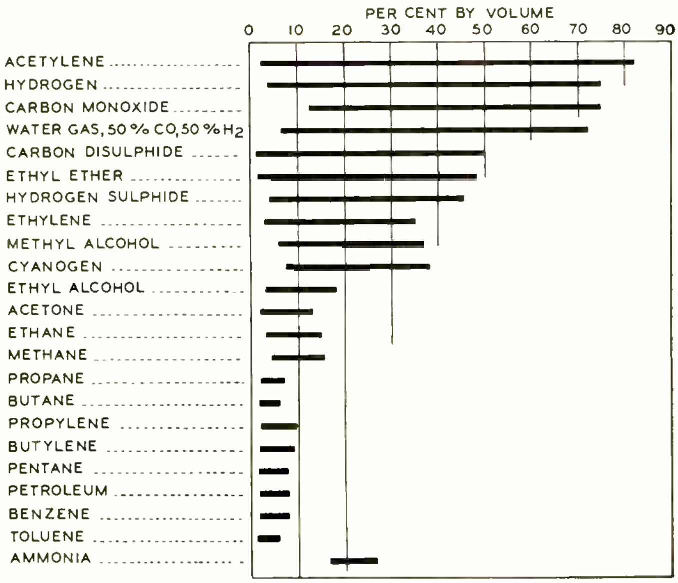


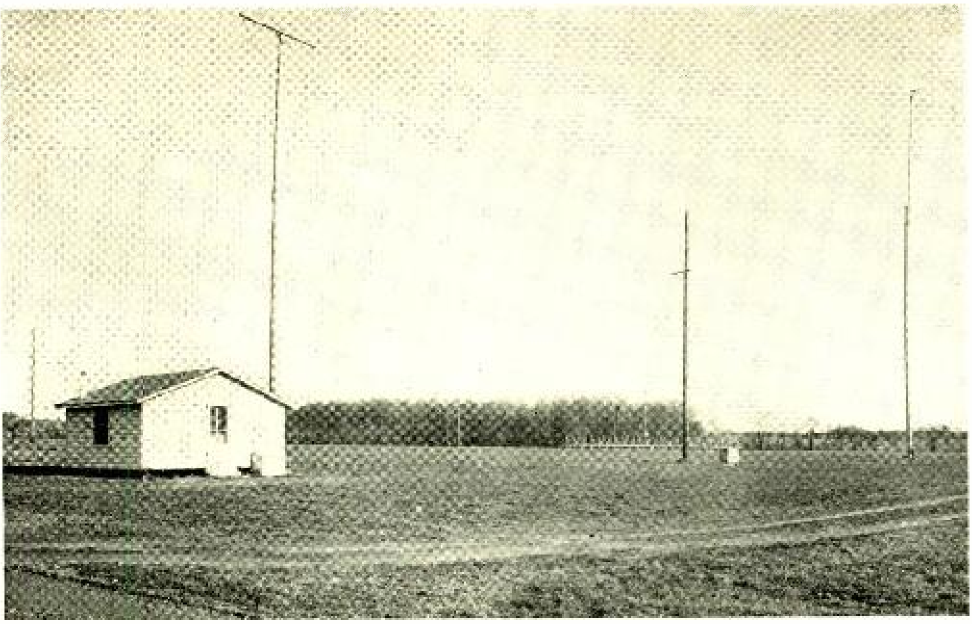
Fig. 2—Range of inflammability of air-gas mixtures as given in the International Critical Tables

holder of the water-seal type where they were stored at low pressure. From this holder together with air from a small compressor, these gases were next passed through suitable flow metering devices into a mixing chamber, which in turn was connected to the switchhook enclosure and inlet tubes of the explosion chamber.

The ether and benzine were obtained as liquids and were vaporized by bubbling air through a special carburetor device maintained at a constant temperature by a water bath. These gas mixtures were further varied at a T-connection by the addition of air from a small compressor as found desirable from the readings of a conductivity meter.

While it was possible to cause numerous explosions within the switchhook enclosure with some of the mixtures and gases tested, in no instance was there any failure of the protective features of the enclosure. That is, such flames as were propagated from sparks within the shell were so effectively cooled by the long leakage paths available for pressure relief that no explosions of what represented the outside explosive atmosphere took place. Likewise, it was not found possible to establish ignition of any of the mixtures by agitation of the microphone buttons when the test transmitters were turned through angles varying from horizontal to vertical. Some of the mixtures used in the tests were, however, capable of explosion with considerable violence as was demonstrated by ignition of the contents of the main test chamber by means of the high tension spark plug provided in the side wall.

In the course of this work the viewpoints as to explosive mixtures likely to be present were obtained from the Gas Company, as well as from representatives of the oil refining industry, and from the medical profession. The U. S. Bureau of Mines has expressed the opinion that the tests were sufficiently complete to establish the safety of the set in its intended field of use.



The Direction of Arrival of Radio Waves

By C. B. FELDMAN
Radio Research

A SIMPLIFIED version of the mode of propagation of short radio waves, on a London to Holmdel circuit for example, might be represented as shown in Figure 1. Here the waves are shown leaving England at three different vertical angles, suffering one or more reflections in the ionosphere, and as a result being received at Holmdel at three different angles with the horizontal. The lengths of these three paths differ and thus waves travelling by them will be delayed by different amounts and, as a result, shifted in phase relative to each other at the receiving station. The amount of phase shift in degrees will vary with the frequency, and thus selective fading results.

Transatlantic propagation is by no means so simple as Figure 1 suggests. It involves several layers in the ionosphere and considerable non-uniformity over the circuit due to the varying latitude and longitude. Completely discrete paths are never found, but

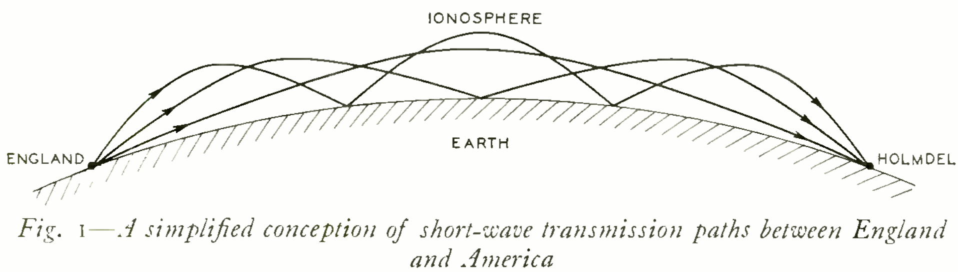


Fig. 1—A simplified conception of short-wave transmission paths between England and America

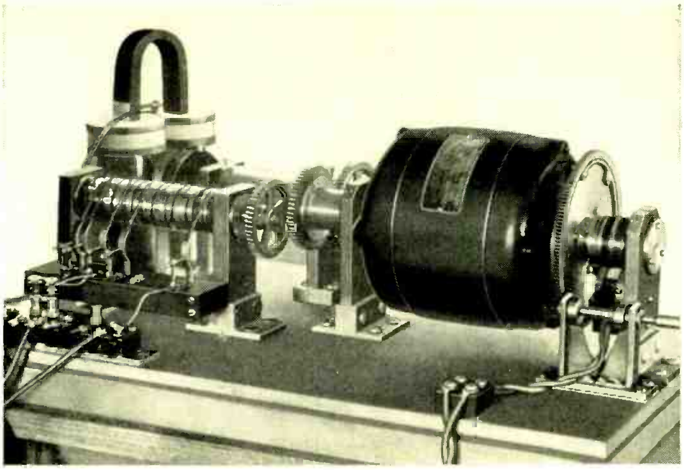


Fig. 2—The synchronous motor that controls the sweep circuit is mounted so that its frame may be rotated for the adjustment of phase

instead a number of more or less separate clusters of paths are observed, each cluster comprising several paths of nearly the same delay and angle. Sometimes an almost continuous distribution of paths seems to exist. Invariably, however, the waves of greater delay possess the higher angle with the horizontal.

Receiving antennas used at the present time have a directional response broad enough to include all the important angles of arrival. As a result, therefore, the received signals suffer a certain amount of fading because of the superposition of signals of the same frequency but differing in phase. With a view to improving short-wave reception, investigations are being carried on at the present time at Holmdel to determine the angle of reception of short waves sent out from England. Efforts to measure these angles by means of a continuous carrier signal are handicapped by interference of the several waves. The mean angle of the cluster of waves and an estimate of the angular spread can be obtained by employing a continuous carrier, but the angles of the individual waves cannot. The studies have been carried out, therefore, by transmitting a series of very short pulses spaced far apart in time relative to the duration of a single pulse. Under these conditions each single pulse is received as a sequence of echoes; the delay between these echoes being caused by the difference in the lengths of the paths they travel. Each of the echoes, on the basis of Figure 1, will be received at a different angle.

The pulses employed are approximately 0.2 millisecond in duration and they are transmitted at the rate of fifty per second. The separation of the pulses is thus 100 times their duration. They are sent out from England by the British Post Office in synchronism with the 50 cycle power

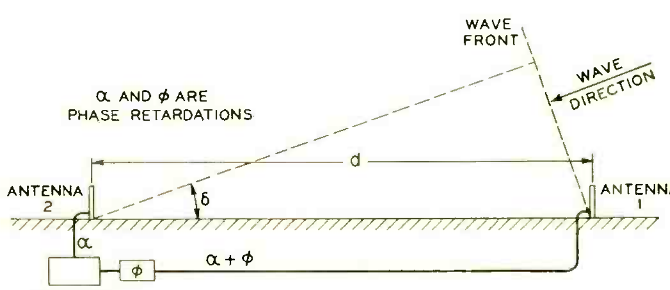


Fig. 3—Two antennas a known distance apart and connected together through a phase changer make it possible to determine the angle of arrival

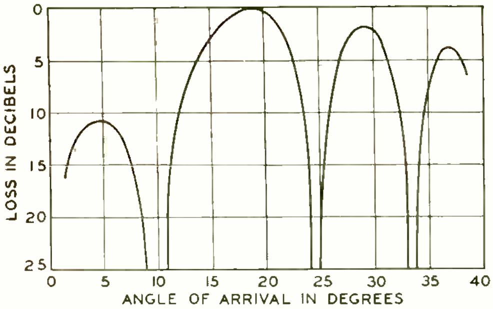


Fig. 4—For any one position of the phase changer there will be a series of vertical arrival angles that result in a null reading

system. At Holmdel they are picked up with wide-band receivers, and the envelope of the rectified output is displayed on a cathode-ray oscillograph provided with a linear time axis making sweeps in synchronism with the pulse frequency of fifty per second. This time axis is obtained with a time constant sweep circuit of the conventional type employing a saturated diode as a resistance and a gas filled tube as a condenser discharger. Synchronization of the sweep with the frequency of the transmitted pulses is accomplished by taking advantage of the frequency stability of the British and American power systems. At Holmdel, where 60-cycle power is available instead of the 50-cycle power supplied at Rugby, a 60-cycle synchronous motor is geared down in a 6 to 5 ratio, and a magnetic switch, operated by the low speed shaft, is used to control the sweep circuit.

In both England and the United States the power systems are used to operate electric clocks and their average frequency is therefore maintained very accurately to the nominal value. There may be slight variations from normal over short periods, however, and to allow correction for these variations as well as for differences in phase, the motor frame is mounted in bearings so that it may be rotated with a crank, as shown in Figure 2. This crank is turned just enough to maintain the pulse patterns in a constant position on the front of the cathode-ray oscillograph.

Two receivers are employed. One is connected to a simple half-wave vertical antenna, and the other to a combination of two similar antennas spaced several wave lengths apart in the direction of the great circle from the transmitting station. The two antennas are connected through an

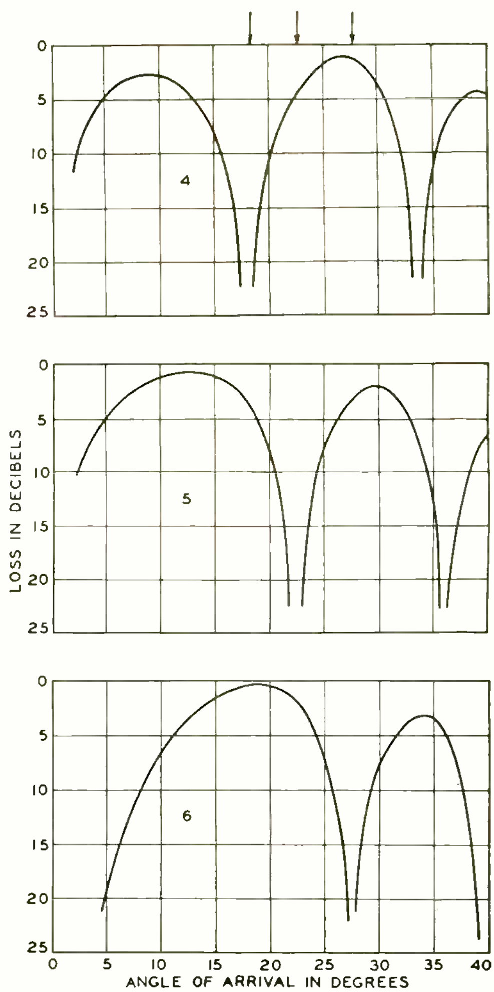


Fig. 5—By moving the phase changer the receiving pattern is shifted so as to bring the null positions to successive angles

adjustable radio-frequency phase changer. A schematic of the arrangement is shown in Figure 3. The outputs of these two associated antennas will be out of phase by an amount which is a function of the distance between them as measured in the direction of the incoming wave. This distance is equal to the horizontal distance, d, times the cosine of the angle that the received wave makes with the horizontal. Thus, the phase displacement of the output of the two antennas is a measure of the angle of reception, and the phase displacement in turn is measured by the amount of phase shift required to bring the two outputs into phase opposition and thus to produce a null reading. Since the two antennas are spaced several wave lengths apart, however, there are several angles of reception that will produce a null reading for the same setting of the phase changer. A typical reception curve for the two antennas for one position of the phase changer is shown in Figure 4.

In determining the angle of reception the output of the two receivers, one connected to the single antenna and the other to the two associated antennas and phase changer, are alternately connected to the cathode-ray oscillograph in such a way that the two traces are displaced, that of the single antenna lying above the other. Each of the 0.2 millisecond pulses, because of multiple reflections in the ionosphere, will arrive as a series of echoes. When picked up by the single antenna they will thus cause a series of deflections of the electron stream of the oscillograph. These will be separated in time—from left to right along the tube—by an amount dependent on the difference between the lengths of the paths they travel. The relative heights of the deflections will depend on the signal strengths of the various paths.

The output of the double antenna, displayed below that of the other, will show the same received signals but the relative heights will depend on the position of the phase changer. As this is moved the relative heights vary because of the relationship between phase shift and angle of reception already discussed. When one of the deflections disappears, indicating that the output of the two component receivers are in phase opposition, the angle of arrival of that particular echo may be determined from the position of the phase changer. Ambiguity due to the several null angles may be avoided by using various antenna spacings.

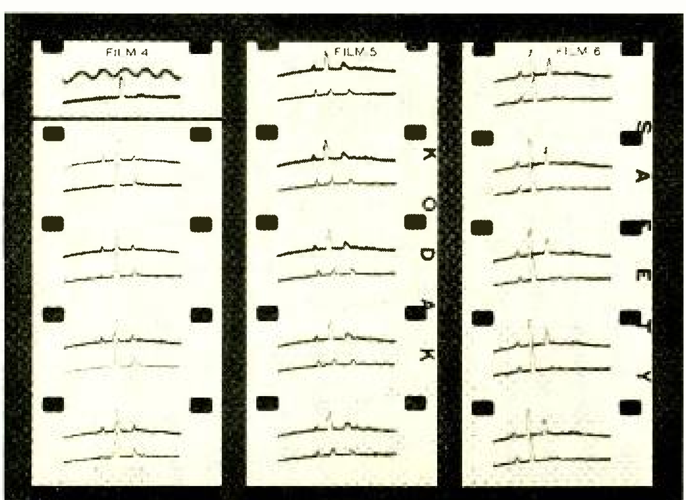


Fig. 6—Three sections of film each frame of which shows the output of the single antenna, above, and of the double, below

The motor control-

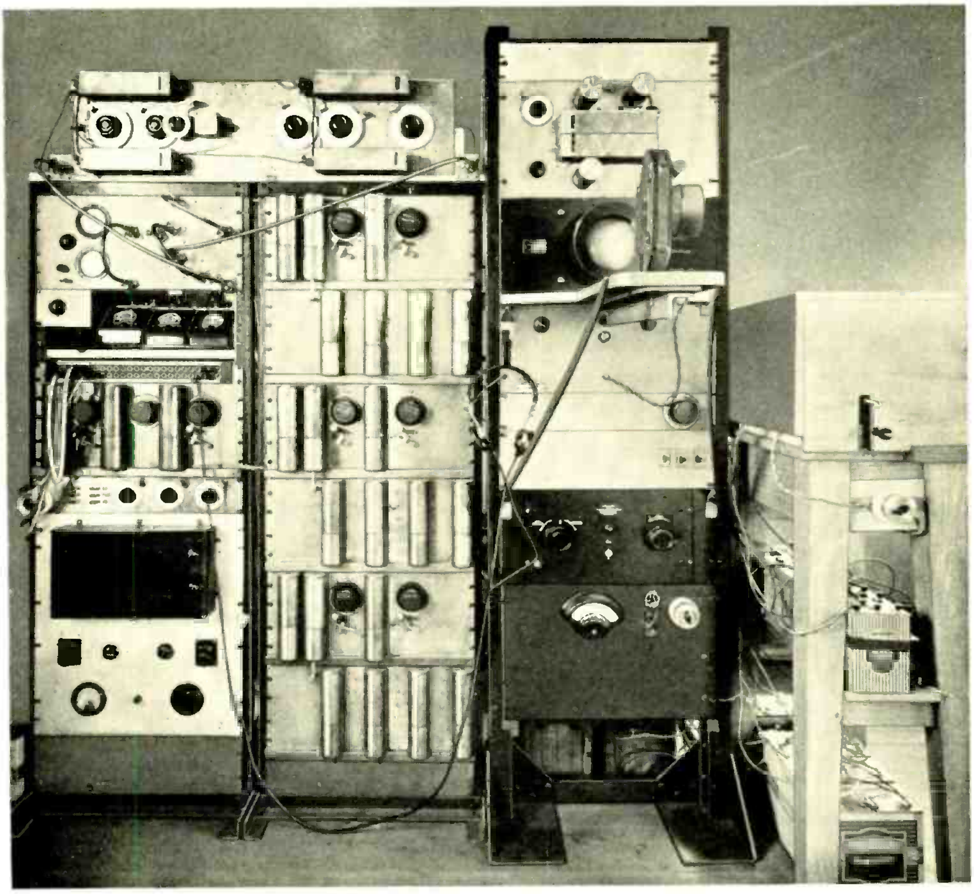


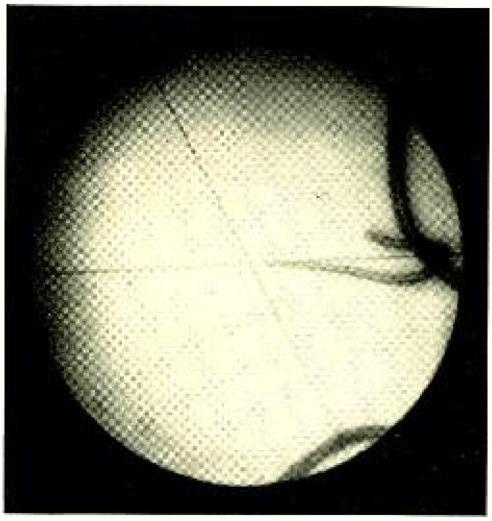
Fig. 7—Set-up of apparatus for determining angle of arrival of radio waves

ling the sweep circuit also drives a commutator that alternately connects the two receivers to the oscillograph. Since there are fifty pulses per second, each receiver traces its curve on the oscillograph 25 times per second, which, because of the persistence of vision, appears as a stationary trace. Any motion is due to a phase shift between the power systems of England and the United States, and is corrected by rotating the frame of the synchronous motor by the crank provided. The traces on the oscillograph are photographed on a sixteen-millimeter motion picture film.

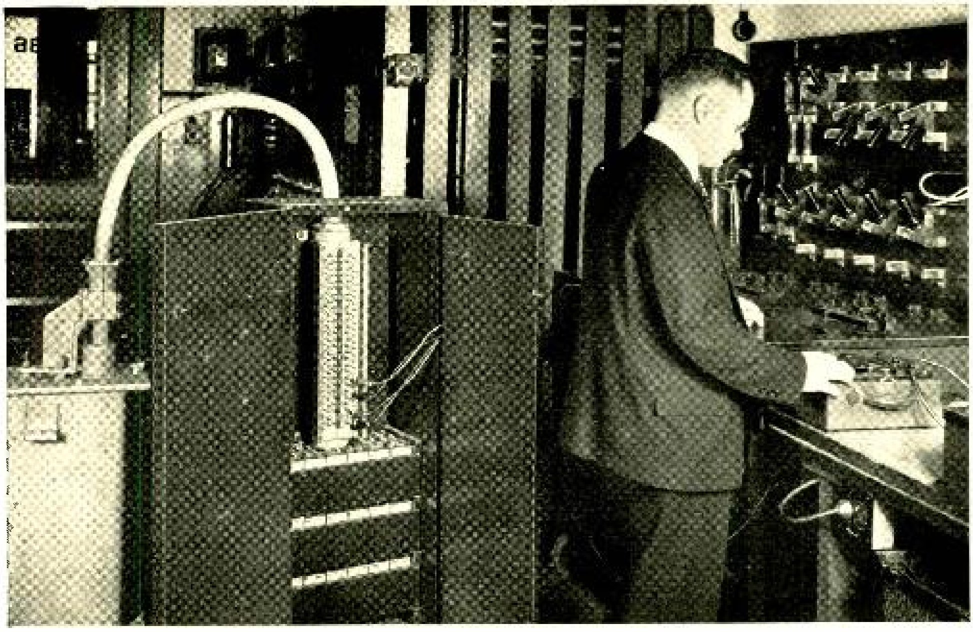
The method of determining the angle of the various paths is indicated by Figure 6, which shows three sections of film each for a different position of the phase changer. In the upper frame of film 4 is the trace of a 1000 cycle wave used for timing purposes. In the other frames of this film can be seen the traces of the envelopes of three groups of received pulses; the upper trace in each frame being that from the single antenna and the lower, from the two associated antennas. In this film the earliest or left hand pulse is practically obliterated on the lower trace, thus indicating that the phase changer has brought the outputs of the two antennas into phase opposition and that the angle of arrival for that particular pulse is determined. Films 5 and 6 indicate similar conditions for two other positions of the phase changer. In film 5 the middle pulse is brought to essentially a zero indication, and in film 6, the right hand pulse.

The effect of moving the phase changer is to shift the receiving pattern of Figure 4 along the axis of angles and thus to change the angle of reception which will give a null indication. This is illustrated in Figure 5. The three positions of the receiving pattern indicated here correspond to films 4, 5, and 6. The angles of reception of the three groups of echoes are indicated at the top of each diagram, and the patterns have been shifted by the phase changer so as to make phase opposition apply to each successively.

This particular method of determining the angle of reception is known as the rejection method, since one of the paths after another is rejected. Other methods are employed to meet different conditions. Angles ranging from a few degrees to about 40 degrees with the horizontal have been observed. The average relation between difference in angle and difference in delay is about 7 degrees per millisecond. All of the waves have been found to arrive substantially within the great circle plane—departure of more than two degrees being uncommon.



In measuring the deflection of a silica spring with a cathetometer (*p.* 316), *the device is raised or lowered until a hair line in the eyepiece falls across a pointer on the spring*



Neutralizing Disturbance Voltages In Communication Circuits

By C. A. BRIGHAM
Telephone Apparatus Development

THE inductive coordination of power and telephone systems requires close cooperation between the various telephone and power companies. Since it is not always practicable to construct power and communication lines on rights of way separated from each other, the two types of circuits must sometimes be run close together for considerable distances. As a result the higher voltages and currents of the power circuits may induce objectionable voltages in the communication circuits. This requires designing and erecting both types of circuits so that interference may be avoided not only under normal conditions, but also under abnormal conditions—particularly those associated with short circuits or grounds on the power lines—which may result in high values of induced voltage on the telephone lines.

One way of avoiding such disturbances is to relocate one or the other of the lines, but even where this procedure is physically practicable it is generally expensive. Studies are constantly being made by the Joint Subcommittee on Development and Research of methods of minimizing the effects of induced potentials. A number of devices for use in both power and communication circuits are under study. One of these devices for reducing the effects of high voltages induced under abnormal conditions is a neutralizing transformer which induces in the telephone circuits opposing voltages approximately equal to those induced by the power circuit. This device is not intended to reduce inductive effects which appear as noise in the circuits, but only fundamental-frequency induction.

When a telephone pole line parallels a power line, each telephone wire will have approximately the same disturbing voltage induced in it for the same length of exposure. All that is required for neutralization is that a second voltage be induced in each wire, equal to the first but opposite in phase. The required neutralizing voltage is obtained by connecting into an auxiliary wire the primary winding of a transformer of approximately one to one ratio. This transformer has as many secondary windings as there are wires on the pole line, and one of them is connected in series in each telephone wire, and poled so that the voltage it produces is opposite in phase to that induced by the power line.

The arrangement is shown schematically in Figure 1 as applied to a single phantom group. The auxiliary wire, which may be either one of the regular telephone wires, if one is available, or a special wire run for the purpose, is grounded at each end of the section of exposure. If the regular telephone wires are used they must be taken out of service or special drainage equipment provided for securing grounds. The transformer, mounted in a welded steel case, is installed as shown in Figure 2 at some convenient pole in the exposed area. Its leads are brought out in a stub cable and carried to a terminal box equipped with protectors to guard the transformers against lightning or other abnormal voltages. Leads from the open-wire lines are also brought to this terminal box, and one of the secondaries of the transformer is connected in series with each communication wire.

In order to obtain a high degree of neutralization, it is necessary that as much as possible of the voltage induced in the auxiliary primary line wire be caused to appear across the primary winding of the transformer. In other words, the impedance between the primary terminals should be large compared with the entire loop impedance of the primary wire circuit. This is accomplished, practically, by use of a condenser across the primary winding, the combination being tuned to the frequency of the power line.

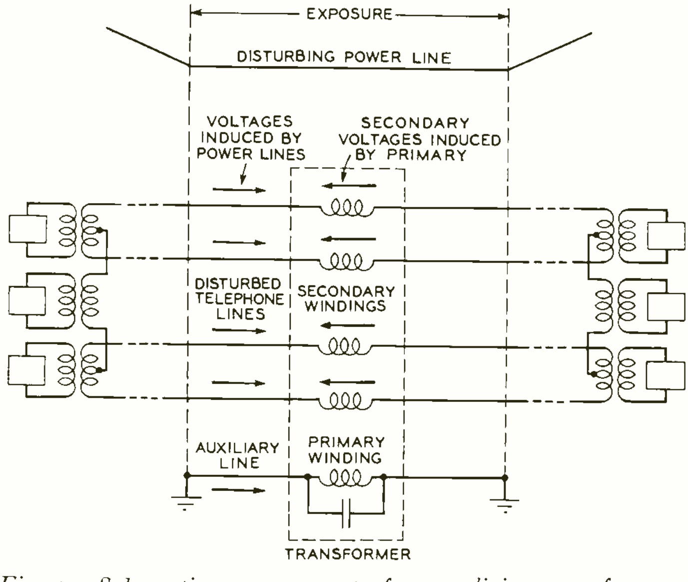


Fig. 1—Schematic arrangement of neutralizing transformer for a four-wire phantom group

The requirements placed on such a piece of apparatus that is to be inserted in communication circuits are necessarily numerous and severe. Examples

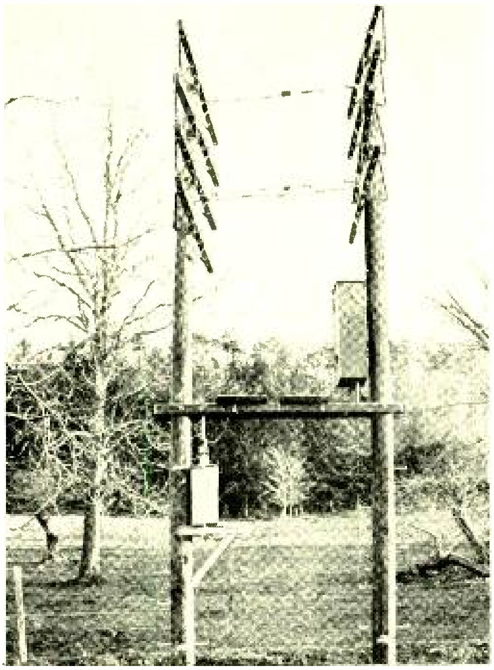


Fig. 2—An actual installation of a neutralizing transformer

of such requirements are that excessive transmission loss, cross-talk, and noise must be avoided. To meet the requirement of low transmission loss, the d-c resistance, mutual capacitance, and leakage inductance of each pair of windings comprising the secondary windings inserted in a single telephone pair must be kept as low as possible. This requires a careful selection of size of wire, number of turns, length of turns, type of insulation, and coupling. To minimize cross-talk, a balance must exist between the resistances of coils, and between direct capacitances. This requires careful manufacture and further balancing by lumped resistance and capacitance units. For a low noise level, the windings in a talking circuit must be electrically balanced with respect to each other and to ground.

The appearance of the transformer, the cable terminal, and the connecting stub cable is shown in the photograph at the head of this article. Beneath the terminal in the cable box are the tuning condensers used with the primary of the transformer. Two primary windings are actually used so that a two-wire circuit may be used as the auxiliary line wire. Twenty-four secondary windings are provided and arranged for use with six phantom groups. The transformer shown is arranged for handling induced potentials up to 250 volts at 60 cycles. In applying the transformers, several of them may be connected in series along the line, with grounds on the primary circuit appropriately placed between the transformers.

Field tests have been made using several of these transformers connected in the communication circuits, with actual short circuits to ground on the paralleling power line. Figure 3, an oscillogram taken during such a test to determine the resultant voltages induced in lines with and without neutralizing transformers, illustrates the efficacy of this device in reducing induced potentials. Furthermore, in the trial installation, no adverse reactions on the communication channels, due to the transformers in the telephone line, were observed.

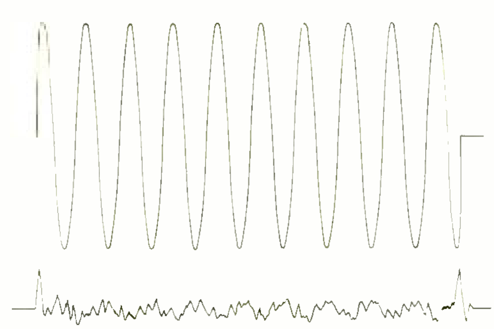
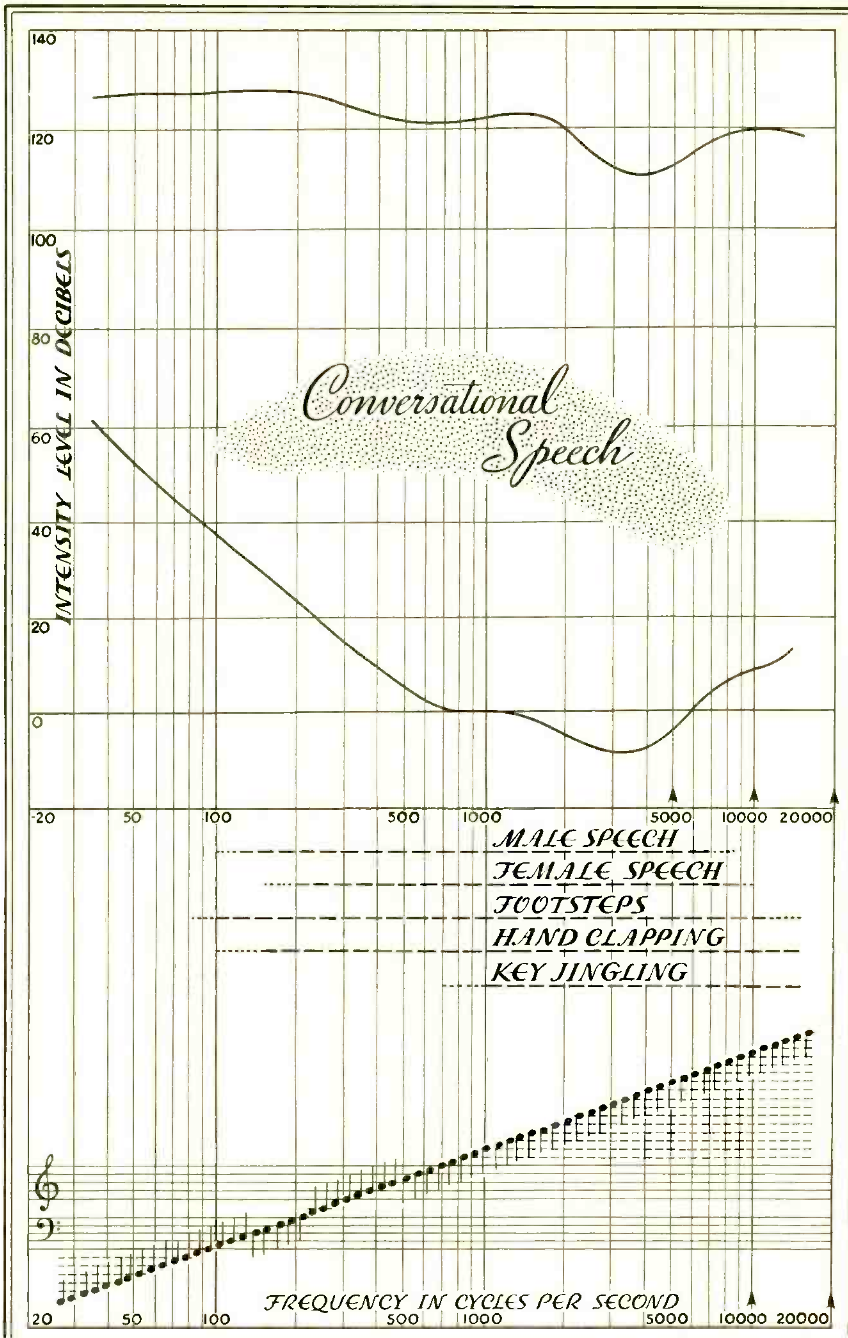
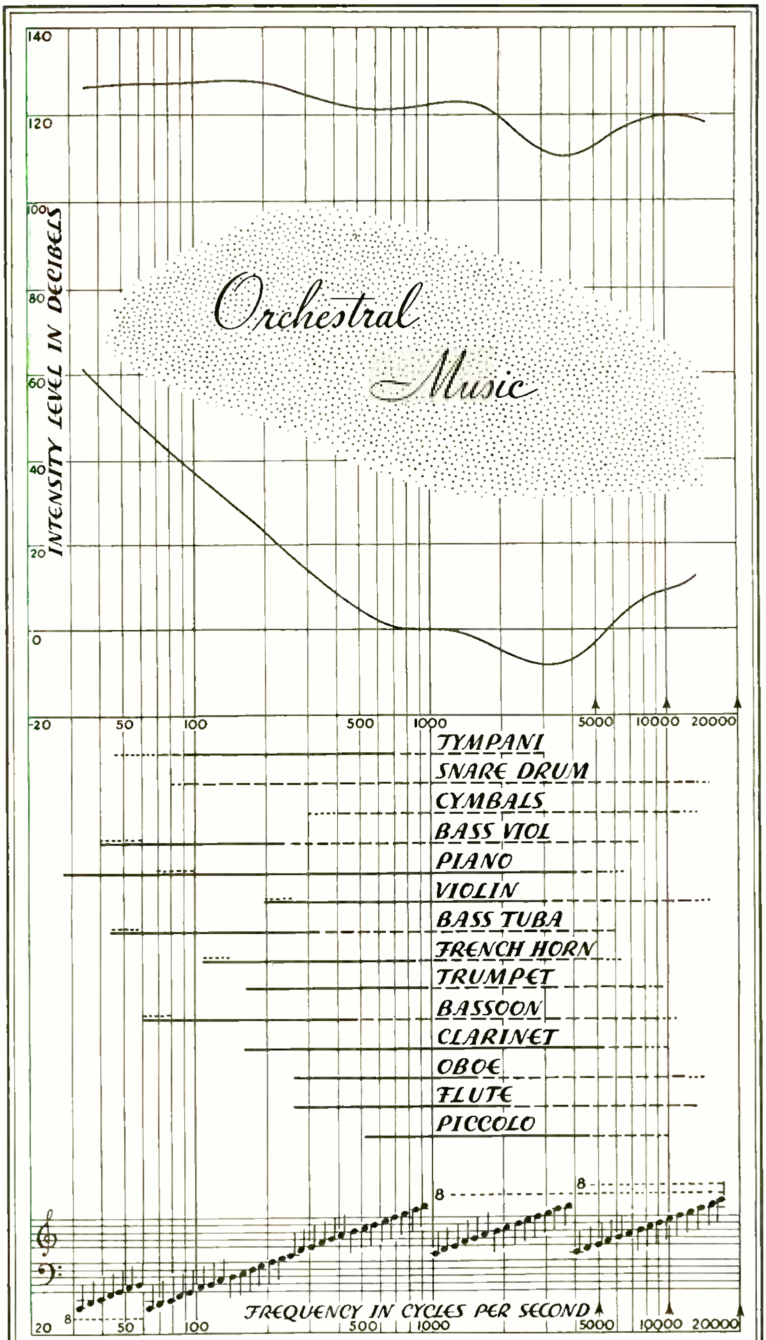


Fig. 3—Voltages induced in telephone lines during short circuit in paralleling power line. Without neutralizing transformer above and with, below



In the upper part of the charts, the area between the thresholds of feeling and audibility represents the totality of audible sounds. The dotted areas are those used in hearing conversational speech at a normal distance, and orchestral music in a concert hall. The intensity scale is in decibels above one ten-thousand-million-millionth of a watt per square centimeter in a plane free wave



In the lower part of the charts, the dashed and dotted lines indicate the pitch ranges of various sounds and instruments audible to 80% and 60% of the auditors, and the solid lines the ranges of the fundamentals of the instruments. Overlaps of dotted and solid lines show that only 60% of the auditors can hear some of the lower notes which some instruments are supposed to produce

Winding Silica Springs

By H. W. WEINHART
Physical Research

ALTHOUGH for the rough measurement of weights reckoned in pounds spring "scales" are often found convenient, the accurate measurement of small weights is customarily done on some form of chemical balance. When, however, the weights are extremely small and great accuracy is required, the spring balance again comes into its own. Here the spring is no longer of metal but of vitreous silica, whose chemical inactivity, high melting point and small cold flow make it particularly suitable for the purpose.

In the past, helical springs of silica, drawn to the fineness of thread, have been made by hand. The operation has been difficult and tedious, and the springs have had irregular shapes and properties far from uniform. Time can now be saved and better springs can be made by a machine which automatically winds the silica fiber into a helix.

The long straight fibers to be formed in spirals are still best drawn by hand. A clear silica rod is heated in an oxy-gas flame until soft. It is then removed from the flame and one end is quickly drawn out to the desired length while the other end is held stationary. The diameter of the resulting fiber is determined by the size of the rod and the extent to which it is drawn. Skill in judging these fac-

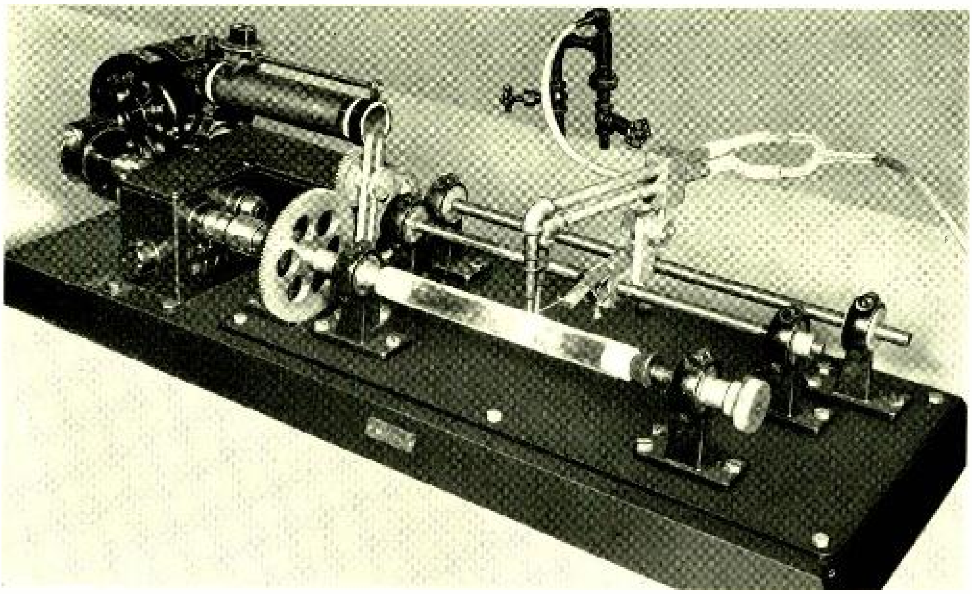


Fig. 1—Once started, the machine for winding springs of fused silica requires no attention until the spring is completed

tors so as to draw uniform fibers of fairly definite size can readily be acquired.

In threading the fiber into the machine, it is passed first through a tension device and then through a guiding slit and is finally fastened at one end to the mandrel on which the spring is to be formed. The mandrel is a smooth silica tube turned by a motor through a thousand-to-one reduction drive. The fiber is softened by flames from a double burner supplied with city gas and air through a glass connection. One flame is adjusted to strike the fiber exactly where it comes in contact with the mandrel, and the other flame is directed on the fiber and mandrel opposite the feeding side. Together they heat the mandrel uniformly over one-third of its circumference, thus preventing kinking of the fiber and giving it all the annealing it requires. The tension device, guiding slit and burner are mounted on a carriage which moves slowly parallel to the axis of the mandrel while it turns. The pitch of the resulting spiral is determined by the relative speeds of mandrel and carriage.

The sensitivity of the springs, measured as their deflection per unit weight, increases rapidly with decrease in the diameter of the fiber, and with increase in the diameter of the spiral and the number of turns. Typical of the sensitivities obtainable is that of a spring three-quarters inch in diameter, of fourteen and a half turns of 0.007-inch fiber, which is extended one millimeter by a weight of four hundred milligrams.

The elongation of a coiled spring depends on the rigidity of its material, and in accurate work the effect of temperature on the rigidity cannot be overlooked. The temperature coefficient of rigidity is of the same magnitude for fused silica as for platinum, and is small compared with that for

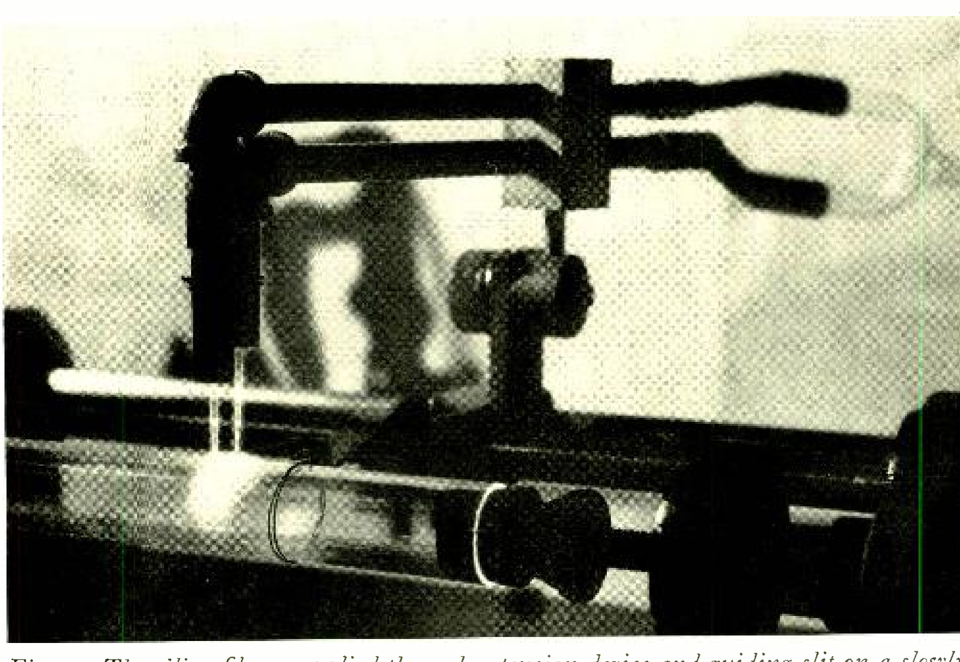


Fig. 2—The silica fiber, supplied through a tension device and guiding slit on a slowly moving carriage, is softened by oxy-gas flames and bent around a revolving mandrel

most other materials. The coefficient is unusual in being negative, so that a loaded silica spring contracts when heated. The contraction per degree Centigrade is about one hundredth of one per cent of the elongation due to the load.

By virtue of their ability to measure extremely small forces with great accuracy, these springs have been given an interesting part to play in the study of the operation of the carbon granule transmitter: that of measuring the contact force between two carbon granules which are in low-pressure contact.* In this work compression springs are used to press the two granules together with forces of one dyne or less while the resistance of the contact is measured. For measuring small changes in weight, tension springs are more convenient. Among the applications such springs have found in these Laboratories are the measurement** of gases evolved by metals, and of moisture absorbed by paper and textiles under varying conditions of environing humidity. The deflection of both tension and compression springs is usually measured by a cathetometer: a telescope which can be raised or lowered along a graduated scale until a horizontal hair-line in the telescope falls across a predetermined point on the spring.

Silica springs are so generally useful in scientific work that these Laboratories have felt it desirable to make available to others the unusually perfect springs produced by the winding machine.

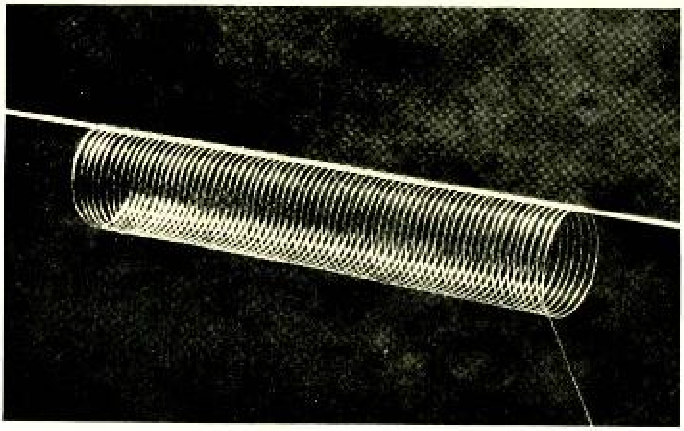


Fig. 3—Typical of the product of the machine is this silica spring of sixty-nine turns, with an inner diameter of three-quarters inch, here shown supported by a wire

*Record, *August*, 1930, *p.* 566.

**Record, *September*, 1933.

Contributors to This Issue

C. A. BRIGHAM spent about eighteen months with the U. S. Navy on radio work, including work at the Radio Schools at Harvard and New London and assignments at Hampton Roads, Haiti, and the Washington Navy yard. At the close of the war he attended George Washington University for a short time and then joined the General Electric Company in Schenectady. There he spent five years on radio development and also attended Union College. He subsequently spent five years with the Kolster Radio Company on loud speaker and radio development, and joined the Technical Staff of Bell Telephone Laboratories in December 1929. Here, with the Apparatus Development department he has been engaged in transformer design—particularly in the development of neutralizing transformers.

C. H. WHEELER joined the Western Electric Company in 1905 to engage in general apparatus drafting. Coincident with his early years here he studied mechanical and electrical engineering and design at Pratt Institute. In 1908 he transferred to the engineering department and was placed in charge of life tests on miscellaneous apparatus. Shortly after he engaged in general engineering work—handling the analysis of models and tool-made samples. He also played a prominent part in the early work on contact protection. During the war he was associated with the development of telephone apparatus for the Signal Corps and of microphone devices for the Navies of the allies. In 1920 Mr. Wheeler took over supervisory duties on general apparatus analysis and is at present in charge of analysis of manual apparatus.

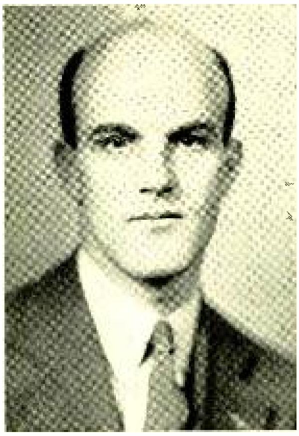
H. S. BLACK came to New York in 1921, after receiving the B. S. degree in electrical engineering from Worcester Polytechnic Institute, and joined the Engineering Department of the Western Electric Company, now these Laboratories. He has since participated in the development of many aspects of carrier telephone systems, including the Type D system, the Type C repeater and line filters, and is the inventor of the type of amplifier, now often called by his name, which he describes in this issue of the RECORD. Mr. Black has in recent years had charge of a

C. A. Brigham

C. H. Wheeler

H. S. Black

C. B. Feldman



J. M. Hayward

H. W. Weinhart

group devoted primarily to carrier repeater development.

C. B. Feldman received from the University of Minnesota the degree of B.S. in 1926, and the degree of M.S. two years later. He came at once to the Laboratories and has been conducting studies of wave propagation, in the course of which he has had a large part in developing coaxial conductors for use as transmission lines between radio receivers and their associated antennas.

Following graduation from the Science and Technology School of Pratt Institute in 1916, J. M. Hayward became associated with the Engineering Department of the Remington Arms and Ammunition Company, and later with the Locomobile Company of America. Later, after an intensive aeronautical engineering course at the University of Toronto, he served during most of the war period with the U. S. Air Service in France, at present being a Major in the Army Air Reserve. In May 1920 he joined the Technical Staff of these Laboratories with the drafting and specification department. In 1922 he transferred to the Apparatus Development Group, where he was at first concerned primarily with the development of station protective apparatus but in recent years has been occupied with work on subscribers sets and other station equipment.

H. W. Weinhart joined the research organization under H. D. Arnold in 1912 and was engaged in the development of the mercury-arc repeater. With the advent of the vacuum tube he was occupied with the development of vacuum-tube repeaters, and later of power amplifiers for the Arlington-Paris radio channel. About this time the transcontinental line was engaging the attention of development engineers and Mr. Weinhart worked on the repeaters for that project. Since then he has been in supervision of a group occupied with the development of many types of vacuum-tube apparatus such as the cathode-ray oscillograph and more recently the various glow tubes for television.