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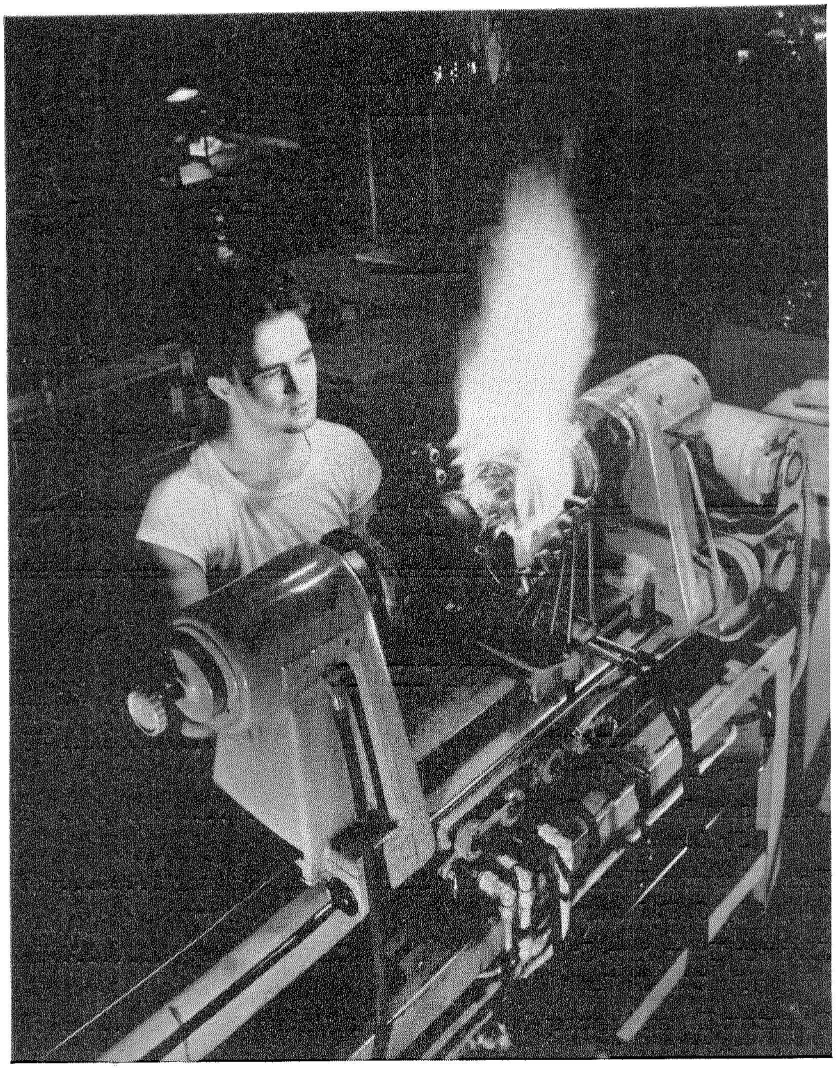

ILLUSTRATED ABOVE IS ONE OF THE OPERATIONS IN ASSEMBLING THE FILAMENT STEM OF A 50-KILOWATT FEDERAL BROADCAST AND INDUSTRIAL VACUUM TUBE. THE OPERATOR IS SEALING THE .125-INCH DIAMETER TUNGSTEN LEADS AFTER INSERTION INTO THE GLASS BLANK. THE PHOTOGRAPH WAS TAKEN AT THE NEW VACUUM TUBE PLANT OF THE FEDERAL TELEPHONE AND RADIO CORPORATION, LOCATED IN CLIFTON, NEW JERSEY.

Pulse Time Modulation

By E. M. DELORAINE AND E. LABIN

Federal Telephone and Radio Laboratories, New York, N. Y.

Editor's Note: Pulse "time" modulation consists essentially in the transmission of signals by pulses of constant amplitude, the instantaneous amplitude of the voice being translated into a variation of time intervals of successive pulses; the rate of this variation corresponds to the instantaneous frequency of the signal. Important advantages include improvement of the signal-to-noise ratio as the band width increases and the possibility of adding repeaters without increasing distortion. Thus this method of modulation appears particularly promising for application to multi-channel radio and coaxial cable transmission systems and UHF broadcasting and television sound channels. High spots relating to the conception and development of pulse time modulation have been included in the article to complete the historical record.

Introduction

PROGRESS in the last decade in the technique of transmission utilizing the higher frequencies poses a problem not involved with the lower frequencies: how to take advantage, from a transmission viewpoint, of the fact that much wider band widths per channel are available than strictly necessary if one considers only the elements of most signals to be transmitted. Such signals include telegraph, telephone, and facsimile. Inasmuch as television signals are of a type calling for very wide bands, they are not considered in the following discussion.

An approach to the problem is to estimate the band width required by the signal as a percentage of the carrier frequencies used and to decide whether, in view of the number of channels required, one can justify "intensive packing" of the channels.

Consider a group of 12 telephone channels. Properly segregated, on a single sideband and an amplitude modulation basis, they occupy a band width of approximately 50 kilocycles.

If we consider the transmission of this group over a pair of wires between 10 and 60 kilocycles, the band width is large compared to the lowest frequency used, i.e., five times.

If we assume the same group transmitted by radio between 10 megacycles and 10.05 megacycles (single sideband carrier suppressed), the band width required is only one-half of one percent of the lowest frequency used.

If we now envisage the same transmission at 1000 megacycles (double sideband with carrier) the percentage becomes only one-hundredth of one percent.

Thus the number of telephone channels that can be handled on a constant percentage band width basis is extremely large when one comes to the higher frequencies. Several thousand telephone channels can be accommodated if required, in so far as band width considerations go.

Present-day telephony-telegraphy, facsimile, etc., requirements, in most regions of the world, would not justify any such large numbers of channels. Hence, practical consideration of how best to utilize the available band width presents a fundamental problem to communication engineers.

Another approach is to consider the band width required due to instabilities of the oscillators and circuits, both at the transmitting and receiving ends, compared to the band width of a telephone signal. It is clear, for example, that with carriers at 10 megacycles and combined instabilities for both ends of 1/10,000, the band width requirement due solely to instabilities is 1000 cycles.

If we assume a telephone band width of 3000 cycles, the widening of the minimum band width due to instabilities is 30%. If, on the other hand, we repeat the calculation for a carrier of 1000 megacycles, the instabilities amount to 100,000 cycles, while the signal band still is 3000 cycles. Consequently, the widening due to instabilities is now equal to 30 times the telephone band width. Hence in the latter case, the band width required by the signal proper is merely a small fraction of the band width needed for transmission.

To determine how to transform the telephone signal in such a way as to employ usefully a greater band width than the original signal is evidently of considerable interest. The value of such a transformation obviously is dependent on advantages that may be involved from the transmission and equipment viewpoint.

One solution is the transformation of the speech signals into frequency-modulated signals. An improved signal-to-noise ratio can be obtained; the improvement, within limits, is proportional to the band width used.

Pulse Time Modulation

The merits of another method of transmission applicable to telephony were considered by the Paris Laboratories of the International Telephone and Telegraph Corporation early in 1937. The method consists essentially of transmitting intelligence by pulses of constant amplitude and duration, the instantaneous amplitude of the voice being translated into a variation of time intervals of successive pulses, the rate of this variation corresponding to the instantaneous frequency of the signal. The band width required is determined by the steepness of the pulses. One can adjust it to be as large as desired. At the time the method was called pulse "time" modulation or pulse "time position" modulation. Its advantages appeared considerable when applied to the higher carrier frequencies.

The signal-to-noise ratio obtainable at the terminal of the link increases as the band width increases. It is consequently possible to utilize all the frequency band available with advantage.

The signals transmitted are of the simplest type. Only short pulses of constant shape with variable timing are utilized.

The merits of the system were well understood from the start. Mr. A. H. Reeves of the Paris Laboratories lists in particular:[1]

The possibility of reducing considerably the influence of parasites of artificial origin.

The possibility of increasing considerably the signal-to-noise ratio of the link on the sole condition that the maximum potential due to noise is lower by a certain quantity than the maximum amplitude of the received pulses.

The possibility of time modulating during part of the pulse interval only, and of eliminating the majority of the interference by blocking the receiver except during the extremely short interval when the pulses are actually transmitted. This improvement, it is explained, applies even if the noise is of an amplitude larger than the pulses.

The value of giving to the impulses additional characteristics which would permit them to be separated from the noise is described. In résumé, the patent reads in part: "it is possible with the means of the invention to obtain a reception practically independent of the noise, even in those places where there are harmful local interferences."

A laboratory report dated July, 1937, reads as follows:

"A new system of modulation called 'pulse modulation' giving a signal-to-noise ratio of the order of 20 to 40 db better than that of the conventional amplitude modulation has been devised and is being subjected to a preliminary experimental study."

Various types of time modulation were considered:[2] the possibility of using one series of pulses in fixed "time position"; another, series time modulated, the interval carrying the intelligence.

It is pointed out that it is possible to suppress the fixed pulses and that this entails advantages, namely, an economy in power and the possibility of providing more channels in a multiplex "distributor" system. These fixed pulses are reproduced locally at the receiver and synchronized by suitable synchronizing pulses at comparatively large time intervals.

The value of the proposed system for multichannel communication was recognized and explicitly stated, also in 1937.[3] Advantages anticipated from the application of pulse time modulation to multi-channel radio and coaxial cable transmission systems are described and emphasis is given to the simplification derived from the use of rugged repeaters capable of operating on trigger action and thereby very materially reducing the usual requirements for stability, distortion, and noise.

Essential work on these circuits in the I. T. & T. Paris Laboratories in 1937 showed that they met expectations. It was decided, therefore, to proceed with field tests.

Mr. Reeves carried out tests in England in 1938. Mr. E. H. Ullrich, who was in charge of this work in Paris (and who is now in England),

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[1] A. H. Reeves, French patent 933,929, June 18, 1937.

[2] A. H. Reeves, French patent of addition 36862, July 5, 1937.

[3] E. M. Deloraine and A. H. Reeves, British patent 31889/37, November 19, 1937.

stated that an experimental link was set up in London in 1938 over a distance of the order of one mile. The transmitter was installed in a motorcar and the receiving station was located in a private house. The measured signal-to-noise ratio improvement at the receiver output was 20 db. Signal-to-noise ratio of 30 db on amplitude modulation was converted into a 50 db signal-to-noise ratio on double pulses. The 20 db separation was maintained down to a ratio of 15 db on amplitude modulation; below this figure the separation decreased.

The value of pulse modulation for broadcasting was considered. Kolster-Brandes, Ltd., the I. T. & T. associate in London primarily concerned with broadcast reception, took up the study of this problem. Mr. C. E. Brigham, then technical head of Kolster-Brandes, had Mr. W. A. Beatty and several assistants specialize on this work; consequently, a number of schemes were proposed and, also, various tests were carried out in the KB Laboratory.

By August, 1939, a number of engineers of I. T. & T. companies had become fully aware of the merits of pulse modulation both in France and in England. Many were active in this field.

Experimental equipments were constructed at the time, both in the Paris and London Laboratories of the I. T. & T., capable of single or multichannel operation on a pulse-time modulation basis.

Pulse Time Modulation—General Theory

After the following general exposition, it seems useful to explain more in detail why pulse modulation improves the signal-to-noise ratio and to give some theoretical results showing quantitively how this improvement depends upon the frequency band used.

Generally speaking, a receiver for any type of modulation can be divided into the following sections:

a. A linear amplifier followed by a linear detector;

b. A series of limiters introducing a fixed or adjustable amplitude gate;

c. A converter or demodulator restoring the audio characteristics of the original signal; and

d. A series of audio filters eliminating all frequencies not used in the desired signal, followed by audio amplifiers which bring the signal to the desired level.

In an *AM* system, (*b*) does not exist and (*c*) is identical with a linear detector which we have supposed to be included in (*a*). In other words, in an *AM* system, the whole receiver can be considered as a linear system as regards the relationship between the output audio signal and the original audio signal at the transmitter, and also as regards the output and input signals.

In an *FM* system, part (*b*) generally precedes the linear detector of (*a*) and part (*c*) is represented by a discriminator of more or less conventional type.

In pulse modulation, (*b*) may precede or follow the linear detector and (*c*) is some type of demodulator circuit not herein described.

The essential difference of *TM* (time modulation) and *FM* as compared to *AM* is that the receiver is no longer a linear system. The relation between the audio output signal of the receiver and the audio input signal at the transmitter obviously must be linear but, in the receiver itself, non-linear devices considerably distort the signal-noise relationship. This difference, in an *FM* or *TM* receiver, necessitates the introduction of the concept of output signal-to-noise ratio as opposed to input signal-to-noise ratio. The input signal-to-noise ratio is the ratio which exists at the input of (*a*) or at the input of (*b*). This ratio is simply the ratio of the amplitude of the incoming wave to the amplitude of the noise (or, if preferred, the ratio of the corresponding powers).

Such a ratio depends essentially on the field strength at the receiver or, for identical propagation conditions, on the transmitted power and on the frequency band of the receiver.

The relation between the frequency band and the amplitude of the noise is well known. It signifies that the equivalent power generated by the noise is proportional to the frequency band of the receiver.

The output signal-to-noise ratio is actually the important factor and represents the ratio of the audio output signal to the audio output noise.

In an *AM* system, the output signal-to-noise ratio is essentially equal to the input signal-to-noise ratio, provided that the input signal-to-noise ratio is calculated on the basis of the audio frequency band used. In an *FM* or *TM* system,

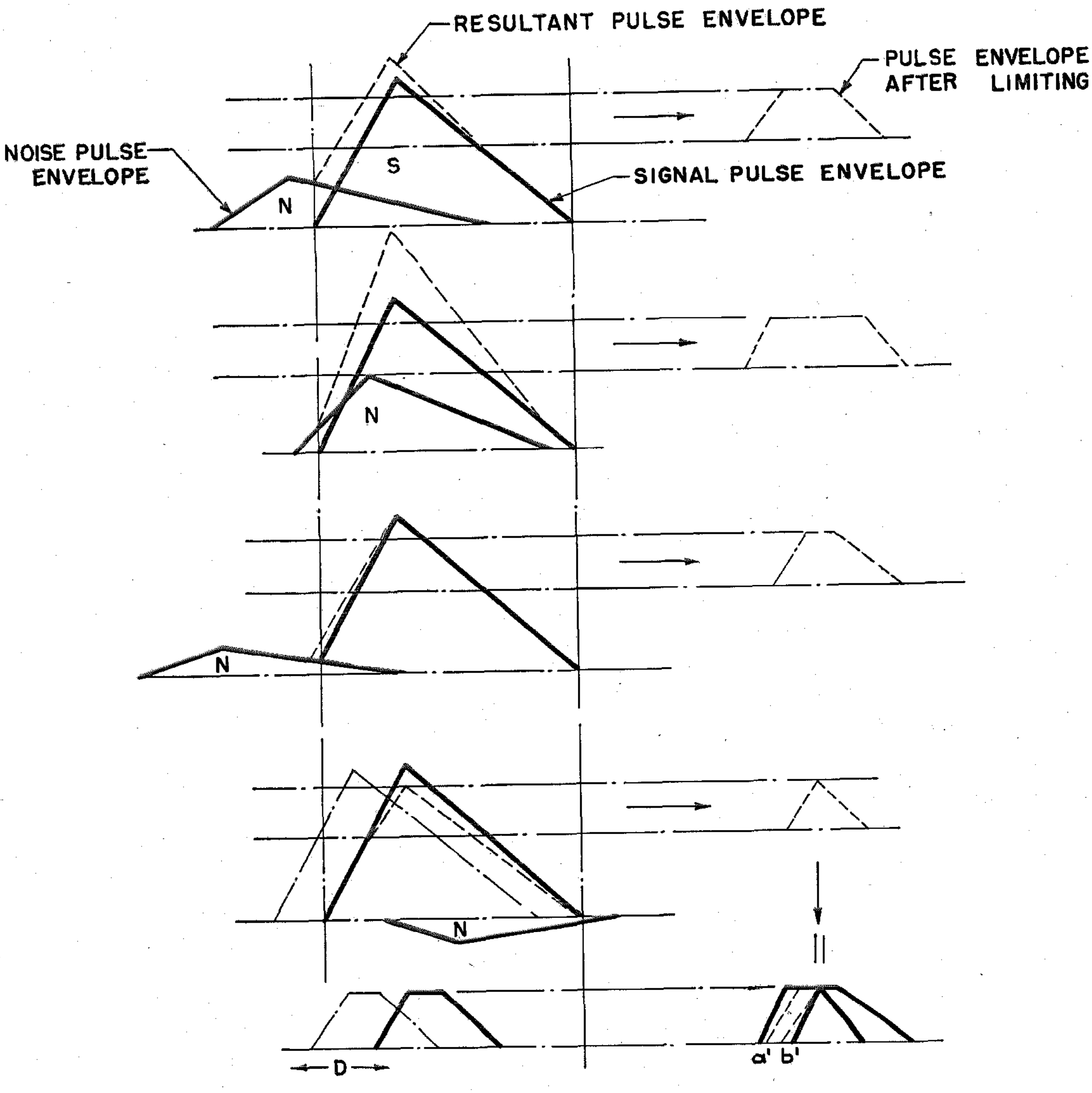
RESULTANT PULSE ENVELOPE
PULSE ENVELOPE AFTER LIMITING
NOISE PULSE ENVELOPE
S
N
SIGNAL PULSE ENVELOPE
N
N
N
a' b'
D

Fig. 1.

there is no such simple relationship between the output signal-to-noise ratio and the input signal-to-noise ratio.

The noise present in the receiver ahead of (*c*) does not, as such, generate any audio noise at the output of (*d*). In an *FM* system the noise, in order to be audible, must affect the frequency of the signal applied to the discriminator. In the same manner in a pulse system, the noise in order to be audible must affect the positioning in time of the pulses used. In other words, the noise is introduced in the system only through the fluctuations of the characteristic factor of the signal: amplitude fluctuation in *AM*; frequency fluctuation in *FM*; time displacement fluctuation in *TM*.

It is therefore clear that the output signal-to-noise ratio may be quite different from the input signal-to-noise ratio, depending on the way this transformation has taken place after the signals have travelled through (*b*), (*c*), and (*d*).

In order to obtain a simple formula, our analysis will be confined to certain simple cases.

If the signal amplitude is larger than approximately twice the noise amplitude, no noise is transmitted through the limiters, and the signal-to-noise ratio at (*c*) measured in voltage ratio may be considered infinite. Actually the presence of noise distorts the pulses in the amplifier (*a*) and the limiters (*b*) and, as previously explained, the signal-to-noise ratio at (*d*) is again finite due to the fluctuations of the position of the pulse despite the complete elimination of the amplitude variations of the noise as such by the limiters. The amount of noise introduced by the demodulator depends entirely on the types of distortion to which the pulse has been subjected by the noise in the amplifier (*a*)–(*b*).

If the entire receiver preceding the limiters is linear, the sole distortion arising is due to the addition of noise to the pulse. This process is represented schematically in Fig. 1. In this figure, the pulse has been idealized and represented simply by a triangle and the noise has been represented by a similar triangle of lower amplitude and the same duration. Representation of noise and pulses by triangles of the same shape is justifiable because the shape is actually determined by the frequency band of the receiver. Distortion introduced in the desired pulses by different noise pulses is indicated in the figure.

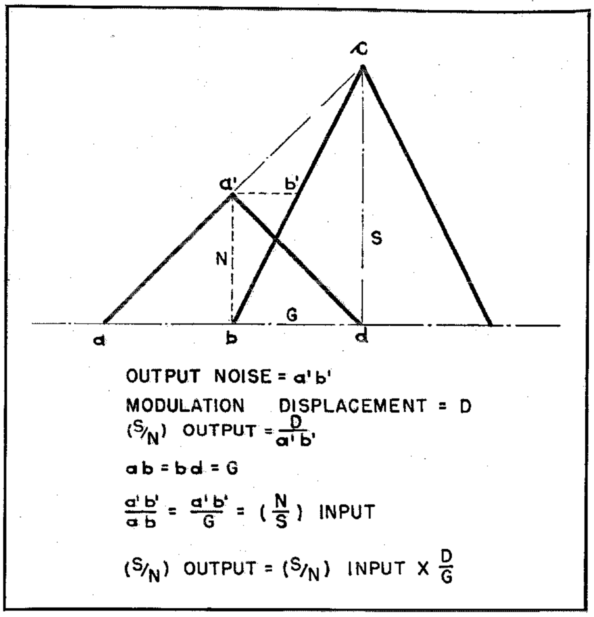

Fig. 2.

As a first approximation, disregarding the change in slope, the distorted pulse may be regarded as an additional pulse whose leading edge is advanced or retarded in time by an amount varying with the position of the noise pulse, but the maximum value of this displacement is proportional to the ratio of noise amplitude to pulse amplitude. This time displacement of the leading edge is converted in the demodulator into audible noise. In other words, any noise small enough in amplitude to be eliminated by the limiters will nevertheless generate an audible noise at the output of the demodulator through the fluctuation of the distorted pulse front.

The amount of noise reintroduced at the output of the demodulator can be calculated easily in the simple case represented in Fig. 1. The noise amplitude after demodulation is proportional to the time displacement of the pulse front while the desired maximum signal amplitude is proportional to the maximum time displacement D allowed in the system. Maximum time fluctuation of the pulse front is obtained for a relative position of the noise pulse and the desired pulse as represented in Fig. 2. Input signal-to-noise ratio is as indicated in Fig. 2, i.e., simply the ratio of the amplitude of the two pulses. The output signal is proportional to the maximum time displacement D; the output noise amplitude is proportional to the displacement of the pulse front.

In Fig. 2, this displacement is represented by the segment a'–b', and it can be calculated as a function of the input signal amplitude, of the input noise amplitude, and the build-up time G of the signal pulse. This build-up time G is equal to the segment a–b in Fig. 2; and a'–b' is obtained from similitude relation in the triangle a–b–c. The actual peak audio output noise is proportional to the amplitude a'–b' and, finally, we obtain the following equations:

$$(S/N)_{\text{output}} = (S/N)_{\text{input}} \times D/G. \tag{1}$$

Maximum time displacement D and the build-up time G can vary within relatively large limits and equation (1) therefore shows that, for the same input signal-to-noise ratio, the output signal-to-noise ratio may be quite different depending on the choice of D and G.

The above elementary calculations are presented as a simple demonstration of equation (1). The reasoning might not be considered entirely convincing since the output signal-to-noise ratio should actually be expressed in r.m.s. value while the calculations involving Fig. 2 are based on peak values. The peak value of the signal is quite clear; however, suitable selection of peak values of the noise is not so obvious. It has been found that the noise amplitude requiring consideration in Fig. 2, in order to approximate experimental values, corresponds to the mean square noise amplitude. The mean square noise amplitude is also the "most probable" one for normal noise voltage distribution.

The maximum possible time displacement D depends on the system used, but it is always a fraction of the time interval between two successive pulses. This time interval itself is determined by the maximum number of pulses required to reproduce correctly the highest signal frequency.

In a single-channel system, if f is the highest audio signal frequency to be reproduced correctly, the number of pulses is equal to $2f$ or $3f$ and, therefore, D is a certain fraction of $1/2f$ or $1/3f$.

In a multi-channel system with n channels, the total number of pulses is $3nf$ and D is a fraction of $1/3nf$.

The time G in equation (1) is equal to the build-up time of the pulse and is directly related to the frequency band of the receiver if it is assumed that the transmitted pulse is steeper than that finally applied to the detector in the receiver. If the frequency band of the receiver is $\pm F$, the build-up time G is approximately related to the frequency band F by:

$$G = 1/3F. \tag{2}$$

For a single-channel system we can, as an example, assume that $D = 20\%$ of the period between successive pulses or

$$D = 1/10f. \tag{3}$$

By expressing D and G in equation (1) with the values of equations (2) and (3), we obtain

$$(S/N)_{\text{out}} = (S/N)_{\text{in}} \times .3F/f. \tag{4}$$

Equation (4) shows that, for a given input signal-to-noise ratio and for a given audio signal spectrum, the useful output signal-to-noise ratio is proportional to the frequency band F used by the system.

In order to compare these results to the signal-to-noise ratio obtainable in an *AM* system, it seems proper to assume the same average power in both cases. It then becomes a relatively simple matter to calculate the input signal-to-noise ratio for the pulse system as a function of the input signal-to-noise ratio for the *AM* system. For the complete computation, certain assumptions concerning the pulse shape and its r.m.s. value are necessary.

Regardless of these assumptions, an equation of type (5) applies. In this equation K is a numerical factor dependent on the pulse shape and also on the "crest factor" of the noise.

$$(S/N)_{\text{input } TM} \doteq K(S/N)_{\text{input } AM}. \tag{5}$$

This equation merely expresses the fact that, when the pulses become narrower and the average power is maintained constant, the peak power is increased in the same proportion as the frequency band and the input noise power so that the *input signal-to-noise ratio remains constant.* The input signal-to-noise ratio for a pulse system with a given average power is, therefore, roughly equal to the signal-to-noise ratio for the same average power with an *AM* system.

When the pulses are not unnecessarily wide, i.e., when they approach the ideal case of a triangle with a decay time equal to the build-up time, the numerical factor K has been found to be close to 1.5. With this value of K, by comparing equation (5) with equation (1) and remembering that, in an AM system, the output signal-to-noise ratio is the same as the input signal-to-noise ratio, we finally obtain

$$(S/N)_{\text{output } TM} = (S/N)_{AM} \times 1.5D/G. \qquad (6)$$

In equation (6), D and G could in turn be expressed as functions of F and f in order to derive

$$(S/N)_{\text{output } TM} = (S/N)_{AM} \times .45F/f. \qquad (7)$$

Equation (7) applies, of course, only for the special choice of time displacement D made in conformation with equation (3). For a different value of D as a function of f, the numerical factor of equation (7) would be different but the form of the equation would not change.*

This relation expresses in a quantitative manner the fact that the signal-to-noise ratio obtained in a pulse modulation system is proportional to the ratio F/f of the total frequency band used to the frequency band of the signal. This relation is similar to that demonstrated several times for FM.

One of the interesting aspects of pulse modulation is expressed by equations (6) and (7): the use of a wide frequency band gives a gain in signal-to-noise ratio.

Furthermore, with pulse modulation, especially at very high carrier frequencies, problems of modulation at the transmitter are greatly simplified; and, in such cases, the use of a large frequency band is in itself justified by normal operating conditions.

Pulse modulation has been proposed mainly for multi-channel operation. For such operation pulse modulation allows time selection as opposed to frequency selection, and it is expected that time selection may have merits when compared with frequency selection.

It might be felt that multi-channel operation with pulses would necessitate a very large frequency band since the frequency used for a single channel is large. Contrary to usual multi-channel operation based on frequency selection, it should be emphasized that the total band width in pulse modulation is essentially independent of the number of channels. The band width is determined by the build-up time of the pulses and not by the number of pulses used. In principle, the number of potential channels can be calculated as a function of the total frequency band and the spectrum of the signal.

Assuming an ideal case where the pulse width can be kept as small as twice the build-up time G, also that the guard time between extreme positions of two successive pulses of different channels can be reduced to three times the build-up time G, then the maximum time displacement D possible for each channel is such that the unmodulated time interval T between two successive pulses is determined by

$$T = 2D + 2G + 3G. \qquad (8)$$

If now it is assumed that the signal-to-noise ratio per channel is the same as in a corresponding AM system of the same average power per channel, then equation (6) gives a relation between D and G, i.e., $D = 2/3\ (G)$. Replacing this value of D in equation (8), we obtain

$$T/G = 19/3. \qquad (9)$$

But T is related to the number of channels N and to the frequency band of the signal f by

$$T = 1/3f(N+1).$$

The factor $N+1$ has been introduced rather than N to take into account the "marker pulse." The build-up time G is related to the total signal band width by equation (2) and therefore equation (9) yields

$$N+1 = 3/19(F/f).$$

For N large with respect to 1, we finally obtain

$$N_{TM} = .15F/f, \qquad (10)$$

where N_{TM} is the number of channels for time modulation.

It is interesting to compare equation (10) with similar equations for AM or FM transmissions.

For AM we may assume that each channel is transmitted by single sideband amplitude modulation of a subcarrier, that a guard band of $1/3f$ is allowed between channels and that transmission is effected by double sideband amplitude modulation of the main carrier. Under these conditions, it is easy to show that equation (11) holds:

$$N_{AM} = .75F/f. \qquad (11)$$

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* From equation (7) it appears possible to use TM with a frequency band F only twice as large as the frequency band f. Other considerations, however, practically impose a lower limit of F several times higher.

For *FM* we may assume that transmission of separate single-sideband amplitude modulated channels is accomplished by frequency modulation of the main carrier with an index so chosen that the signal-to-noise ratio is the same as in *AM*. It can then readily be shown by using well-known formulas of signal-to-noise ratio in *FM* that equation (12) holds:

$$N_{FM} = .35F/f. \qquad (12)$$

In other words, for the same average power, the same radio frequency band and the same audio band, the number of channels theoretically possible with pulse modulation is 1/5 of what it can be with *AM* and 1/2 of what it can be with *FM* transmissions.

As an example, if the modulating signal is taken up to 3 kilocycles, and the total radio frequency band is ±3 megacycles, then

$$\begin{aligned} f &= 3 \text{ kilocycles,} \\ F &= 3 \text{ megacycles,} \\ N_{AM} &= 750, \\ N_{FM} &= 350, \\ N_{TM} &= 150. \end{aligned}$$

At first sight these figures appear very favorable to *AM*. However, a number of channels as large as 750 could hardly be handled in an *AM* system because the non-linear distortions introduced by the repeaters would be in excess of acceptable values.

FM transmission would facilitate the problem of distortion in the repeaters but would not entirely eliminate it. The non-linearities of tube characteristics are the main difficulties in *AM* transmission and a similar difficulty exists in *FM* due to the non-linearity of the phase response of the circuits.

For pulse modulation, there is no source of distortion due either to tubes or to circuit characteristics as long as the frequency band is large enough to reproduce correctly the build-up time. Even from this viewpoint, repeater requirements necessary for pulse modulation are not very severe inasmuch as it is not essential in pulse modulation to produce faithfully the shape of the pulse. In other words, for multi-channel transmissions operating with a large number of relays, pulse modulation, in principle, has a fundamental advantage: distortions introduced in the different repeaters are not cumulative. The only effect of additional repeaters would be to increase the noise if the frequency band of the repeater is not sufficiently large.

Furthermore, pulse modulation has the advantage that it is a transmission system at constant amplitude. This means that limiters can be used in successive repeaters so that the effect of variation in transmission conditions can be minimized.

It should be stressed that the above formulas, especially equation (10), are approximate only and are based on certain assumptions that may or may not be practically obtainable under actual operating conditions. Nevertheless, only the numerical factor of equation (10) could be different. The fundamentally important aspect of this equation is that the number of channels is proportional to the ratio F/f.

The numerical coefficient in equation (10) assumes specifically that the signal-to-noise ratio for each channel is the same as in *AM*. If it is desired to increase the signal-to-noise ratio, it can be done either by increasing the time displacement allowed for each channel and keeping the steepness of the pulse the same (which means that the total frequency F is left unchanged), or by maintaining the displacement the same and increasing the steepness of the pulse (which means that the total frequency band F is increased).

In the first case, the number of channels possible with the same frequency band F would be smaller. In the second case, the number of channels would be the same but the frequency band needed would be larger. This flexibility of the pulse modulation system is obviously of great practical advantage.

Conclusion

While the foregoing outline covers only the broadest aspects of pulse time modulation technique, it will be appreciated from the discussion that this type of modulation opens up the most far-reaching possibilities in the field of transmission using very high frequencies. It should be added that the facts at hand seem to justify the belief that the I. T. & T. Laboratories have pioneered in the field of pulse time modulation.

Brazilian Interior Radiotelephone Service

By LEONARD JACOB, II *

Rio de Janeiro, Brazil

MAY 31, 1944, marked an important step in the rapidly expanding economic life of Brazil. On that day His Excellency, President Getulio Vargas, signed a decree authorizing the Companhia Radio Internacional do Brasil, an associated company of International Telephone and Telegraph Corporation, to install and operate radiotelephone stations for interior telephone service in the Federal District, twenty state capitals and the capitals of the seven remaining territories, a total of twenty-eight stations in all.

To study the map of Brazil is to realize the importance of this development to the social and economic welfare of this great country, which because of barriers of impenetrable jungle, wide rivers, wastelands and vast distances is divided into islands of population, bound together by a common language and common ideals, but with limited social intercourse and trade relations.

With the exception of the central area embracing the Federal District and the States of Rio de Janeiro, Sao Paulo, and Minas Gerais, development has been along the coast line and river courses. The resulting distances between the various cities, the industrial areas, and agricultural districts, in almost all cases, have prevented the extension of land line telephone connection. Communication therefore has been limited to the telegraph lines of the National Telegraphs and the cables of the private cable companies serving the coastal cities.

Except in the central area and several of the southern states, the telephone service leaves much to be desired and this, to a great extent, has been the result of the limitation in the expansion of toll service. This is understandable, for from many of the coast cities the populated areas extend only a few miles inland, leaving the short toll extensions terminating at the edge of the wilderness.

With the opening of telephone communication between all of the important cities of Brazil it is felt that the new circuits will not only serve to bring the people of the widely scattered regions into closer contact with each other, but will provide an incentive toward improvement and unification of the various local telephone facilities, by emphasizing in the public mind the great potentialities of a countrywide system with connections to the telephone systems of the other great countries throughout the world.

The Companhia Radio Internacional do Brasil is particularly fitted to carry on this development as it already operates radiotelephone and radiotelegraph stations for international service in seven interior points, i.e., Fortaleza, Belem, Natal, Recife, Baía, Curitiba and Porto Alegre. These connect through its main stations in Rio de Janeiro with the telephone systems of most of the Americas and Europe; and, after the war, its telephone service will afford world-wide connection.

Cities comprised in the interior radiotelephone network.

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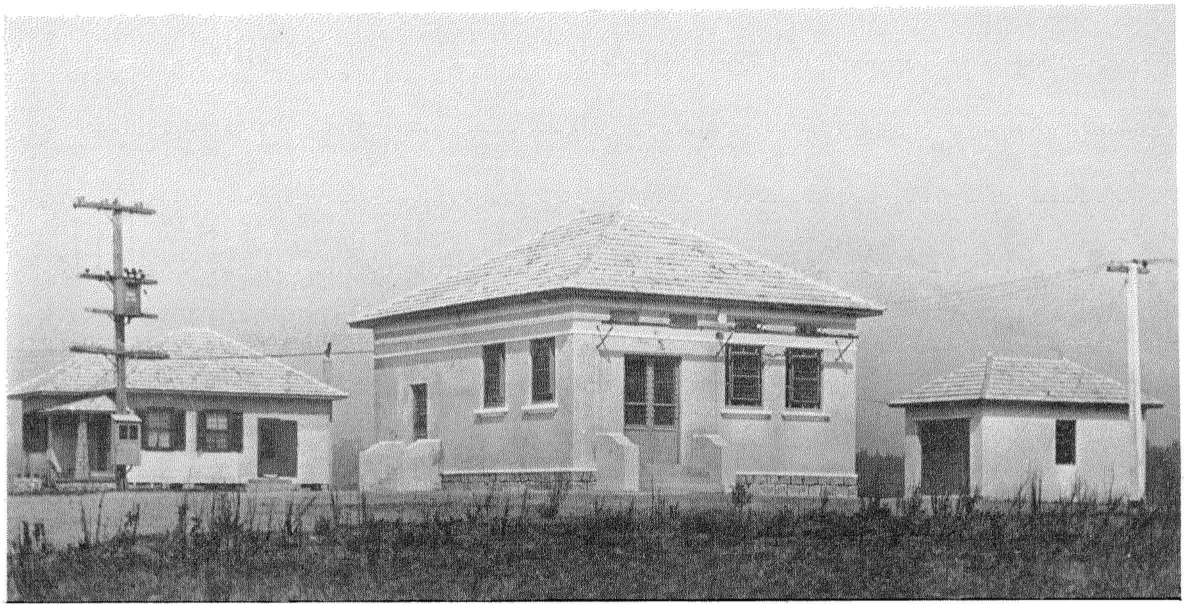
* Second Vice President of the International Telephone & Telegraph Corporation, New York, N. Y.



Porto Alegre station showing typical C.R.I.B. interior station layout in Brazil.

It is contemplated that within a few months the interior service will be in operation between Rio de Janeiro and the several points already connected for international service, and that thereafter the extension of the service will be carried out as rapidly as the supply of equipment and war conditions will permit, although, under the terms of the contract, a period of ten years is provided to complete the proposed network.

It should be mentioned that the successful culmination of the plan for this interior service was in great measure due to the foresight of His Excellency the Minister of Communications, General Mendonca Lima, and Major Landry Sales, Director General of Telegraphs, who were assisted in working out the problems of operation by a special commission, appointed by the President of Brazil, the members of which were Coronel Macedo Soares, Dr. Adroaldo Junqueira Ayres and Joao Carlos Vital, all of whom are among Brazil's outstanding engineers and consultants to the Government.

Once again Brazil has taken a forward step in the development of telephone communications. It is interesting in this connection to recall that Brazil in 1877, encouraged by the enthusiasm of Dom Pedro II, installed one of the world's first functioning telephone systems and hence can claim a leading role in the history of telephone communications.

The Western Union Varioplex Telegraph System

By O. E. PIERSON

Western Union Telegraph Company, New York, N. Y.

Editor's Note: In line with the policy of keeping its readers informed on important developments in the telegraph field, "Electrical Communication" takes pleasure in presenting this description of Varioplex Telegraphy. The equipment described is distributed in the export field by the International Standard Electric Corporation (New York, N. Y.), an I. T. & T. associate. Other recent contributions to "Electrical Communication" by Western Union authors are cited below.[1]

THE Western Union Varioplex is a type of automatic telegraph system in which a large number of individual variable-traffic-capacity lanes of communication are provided by means of a single high-traffic-capacity trunk circuit. These individual lanes or sub-channels are used primarily for furnishing telegraph facilities to patrons whose limited requirements do not justify the cost of a private leased wire. While the cost of this new type of service is relatively low, the service obtained compares favorably with that of a private wire lease. Development of the system was started some ten years ago and was made possible through the application of a unique method of dividing the total traffic capacity of a main line circuit—a method insuring efficient usage of the circuit facilities regardless of the number of components into which the total traffic load is divided or how the load is proportioned.

A Varioplex circuit between two remotely located cities may be arranged to provide facilities for any number up to forty sub-channel connections. This maximum of forty sub-channels is not fixed by any theoretical limitations inherent in the method of operation, but merely through practical considerations. A business firm with offices in the two cities leasing one of these sub-channels is thereby provided with an effectively direct and private circuit between the two offices. Each office is furnished with two teleprinters, one for sending and the other for receiving. Communication may be carried on in either direction or in both directions at the same time.

Fig. 1 shows a view of a familiar type of teleprinter. Messages are transmitted by operating the keyboard of the sending teleprinter in the same manner as that of a standard typewriter keyboard. Incoming messages are automatically printed by the receiving teleprinter. Teleprinters can be supplied either for page or tape copy and for table or console mounting, as desired. They are connected to the central office of Western Union by means of individual conductors. Similar pairs of conductors radiate from the central office to all patron offices having sub-channel leases over that circuit. Any patron may transmit at will, his signals, together with those from other patron lines, converging at the central office, whence, through appropriate apparatus located there, they are transmitted to the distant city over the single common circuit. At the distant point the central office apparatus automatically sorts out each received character and transmits it over the local conductor to the office of the patron for whom it is intended. Charges for this type of service are computed on the basis of the actual amount of traffic sent. In order to furnish the necessary accounting information, each patron's sending line is provided with a character counter to record each character transmitted.

Fig. 2 gives a view of a typical central office group of equipment for a Varioplex installation. An identical set of equipment is also installed at the distant city. The equipment may be divided into three groups or classifications: (1) that individual to each of the patron connections, (2) that common to all connections, and (3) that associated directly with the main line circuit. Fig. 3 shows a close-up view of the major units of one set of the equipment in the first group. Three

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[1] "Facsimile Telegraphy, Some New Commercial Applications," by John H. Hackenberg, Vol. 18, No. 3, 1940. "Train Orders by Facsimile Telegraphy," by J. H. Hackenberg and G. H. Ridings, Vol. 21, No. 2, 1943.

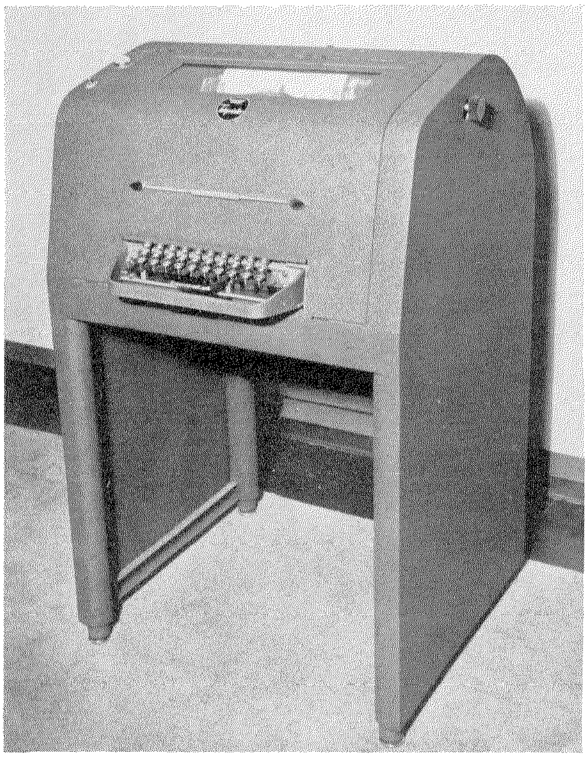

Fig. 1—Typical Western Union teleprinter.

such sets of equipment are mounted on a metal frame or rack and provide facilities for three patron connections. A similar rack is provided for each three patron connections. At the top of the rack are six banks of multi-contact relays, two associated with each patron connection. This equipment, together with vacuum tubes, switches, signal lights, etc., also mounted on this rack, performs functions directly associated with the transfer of signals from the patron sending line to the main line circuit and from the main line circuit to the patron receiving line.

Fig. 4 is a close-up view of a metal rack in which is mounted the equipment designated as group 2. It consists of banks of multi-contact relays, vacuum tube units, rotary stepping switches, signal lamps, manually-operated switches, and various monitorial facilities, all having functions common to all patron connections and providing control of operations in general. Fig. 5 similarly shows the equipment of group 3 which, like that of group 2, is common to the whole circuit. It consists principally of two rotary distributors whose functions are the transmission of signals to the main line circuit and the distribution of the signals received from the distant end of the circuit. It includes also the line duplexing equipment and that used for testing and regulating the main line circuit. This group of equipment is practically the same as that used for ordinary automatic telegraph circuits. Fig. 6 shows the mechanical details of the distributor. Copper brushes, attached to a rotating shaft, trail over pairs of stationary segmented and solid rings, each pair forming an independent commutating circuit. The rings are mounted on a removable plate, the whole assembly being designated as the distributor face plate.

Fig. 7 illustrates in schematic form the essential features of a two-channel or "Double" type of Varioplex circuit. Stations X and Y represent the two remotely located cities between which the circuit operates. The terminal equipment is that used in transmitting from Station X to Y. In an actual installation an identical set of equipment is provided for transmitting in the opposite direction. The main line equipment comprises a segmented sending ring of the sending distributor, two banks of sending relays A and B at Station X and a segmented receiving ring with corresponding banks of receiving relays at Station Y. The brushes of the two distributors rotate in exact synchronous relation successively connecting each sending segment to the corresponding receiving segment for a short interval during each revolution. The segments are divided into two groups of five segments, each group constituting a channel.

The two channels are designated alphabetically as the A and the B channels. Five sending relays and five receiving relays are associated with the five respective segments of each channel and provide the means whereby a character is transmitted over each channel during each revolution of the brushes. The five sending relays apply positive and negative potentials to the respective sending segments and, as the brush traverses the five segments, a combination of positive and negative current impulses is transmitted to the line.

At the receiving end these impulses actuate the five respective receiving relays, causing them to assume operated and released positions in accordance with the signal combination. The five unit impulses provide 32 distinct combinations, each representing a character selection. Of the 32 possible combinations, 31 are used for selective functions in the operation of the teleprinter, and are designated as "normal" characters. The remaining combination or "blank" has no selective function and, when received by a teleprinter, produces no evidence of its reception in the printed copy. It serves as a special signal, however, by which the operation of the central office equipment at the receiving end is controlled from the distant end of the circuit.

If the line connecting the Stations X and Y be one capable of conveying intelligible signals at a rate of 800 characters per minute, the two distributors are adjusted to a speed of 400 R.P.M. Each channel then transmits at the rate of 400 characters per minute. This is the method conventionally used on all high-speed automatic circuits for dividing the total traffic capacity of a circuit into smaller, but more practical components. Each channel functions as an independent traffic lane whose speed is equal to the quotient obtained by dividing the total circuit speed by the number of channels. For circuits with transmitting rates up to 1,600 characters per minute, segmented rings having three or four channel groups are used.

As indicated in Fig. 7, the equipment associated with each sub-channel comprises a reperforator RPF, a transmitter XTR, two sending chain relays SA and SB, and a control relay SCO at the sending station and corresponding relays RA, RB and RCO at the receiving station. The reperforator is a mechanism arranged to respond to signals transmitted from a teleprinter and to record the transmitted characters in the form of perforations in a narrow paper tape. The nature of these perforations will be evident from Fig. 8 which shows the transmitter through which the tape passes as it comes out of the reperforator. A magnetically-operated tape-feed mechanism steps the tape through the transmitter, causing

Fig. 2—Varioplex Central Office equipment.

it to advance one character per revolution of the distributor brushes. During the interval between steps, the tape remains at rest with a character perforation directly over five movable fingers or pins which press against the tape. Each pin engages the tape at a point where a hole may have been perforated and moves upward unless stopped by the tape. Five contacts controlled by the pins are thus positioned in accordance with the perforated combination of holes. The five contacts are multipled as indicated to five respective contact springs of the two chain relays SA and SB through which the circuits may be closed to the five sending relays of either of the two channels. Thus, if relay SA be operated during this interval the five relays of bank A assume operated and released positions corresponding to the character in the transmitter. As the sending brushes pass over the five segments of the A channel, the signal combination representing the character then is transmitted to the line.

A light contact lever, mounted between the reperforator and the transmitter, extends above the tape loop as it passes from the reperforator and into the transmitter. When the tape loop becomes too short to permit further transmitter stepping operations, this arm is lifted by the tape, causing the stepping circuit to become inactive. This automatically governs the stepping action of the transmitter, permitting it to step the tape whenever possible, and stopping it when the tape loop becomes short—an arrangement commonly known as the auto-stop circuit.

Fig. 4—Varioplex Central Office equipment common to all connections.

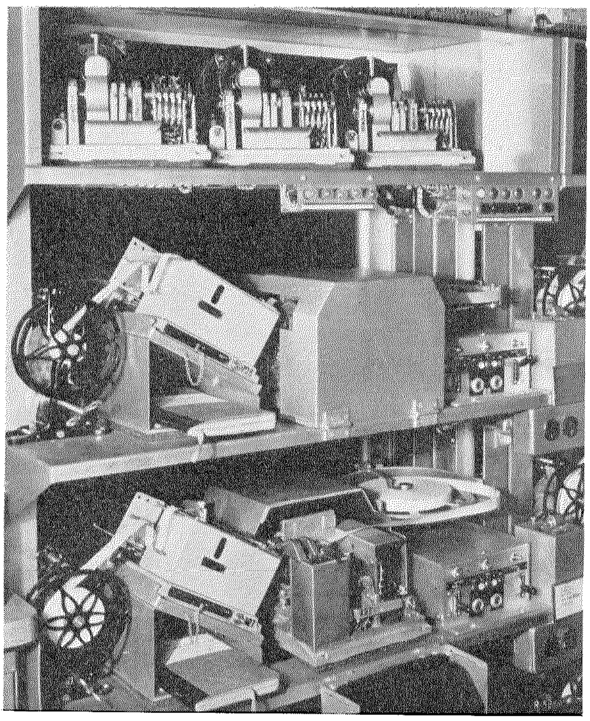

Fig. 3—Varioplex Central Office equipment individual to patron connections.

At Station Y the signal combination is distributed by the five receiving segments of the A channel and causes the five receiving relays of bank A to assume corresponding operated and released positions. The relay RA of the sub-channel, whose character has just been transmitted, operates in unison with the distant SA relay so that, while the character is being selected, relay RA is operated and remains operated during the ensuing revolution of the distributor brushes. The two relays RA and RB of each sub-channel control the circuit of the line extending out to the receiving teleprinter in the patron office. The circuit passes through contacts of the two relays and is closed to a fixed potential when both relays are in their released positions. When either relay is operated, the patron receiving line is disconnected from the fixed potential and connected to a local transmitting device, which is associated with each channel. This transmitting device (TA and TB of Fig. 7) consists of an arrangement of vacuum tubes whose operation is controlled by contacts on the five receiving relays of the respective banks A and B and by a segmented ring of the receiving distributor known as the simplex ring.

With relay RA in its operated position, impulses furnished by the simplex ring segments actuate the input circuit of the vacuum tube unit TA in accordance with the selected character stored in receiving bank A, thereby causing a signal combination to be transmitted over the line to the patron office. This signal actuates the selecting mechanism of the receiving teleprinter, causing the character to be printed. The character could similarly have been sent over the B channel by means of relays SB and RB. No distinction is made with respect to channels in the transmission of characters from sub-channel transmitters. Successive characters are transmitted alternately over the two channels, one character being supplied by each sub-channel in turn. After all have transmitted on character the cycle is repeated. Successive characters from any particular sub-channel may be sent over either channel.

The relays SA and SB constitute the so-called "sending chain" and the relays RA and RB the "receiving chain." They operate in the cyclic

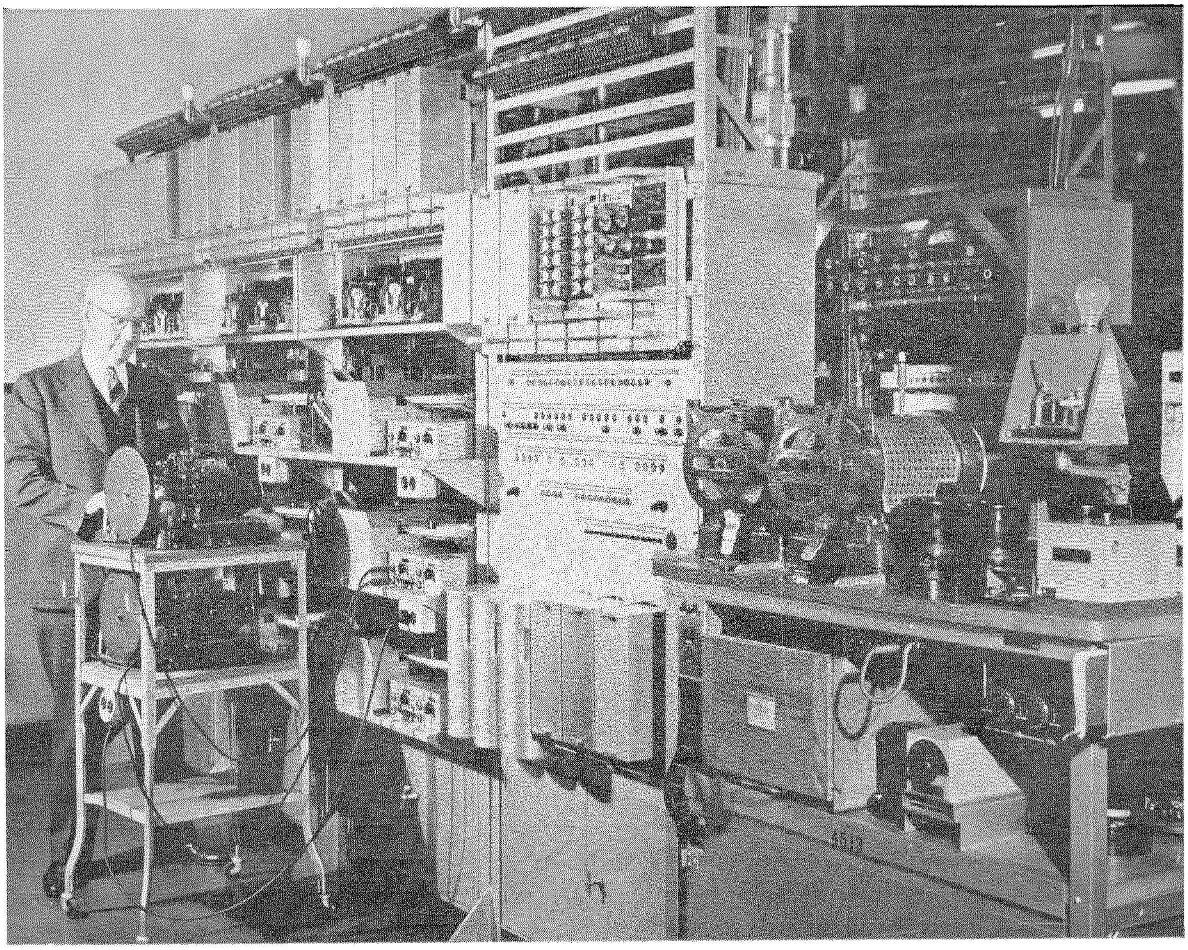

Fig. 5—Varioplex Central Office equipment associated directly with the main line circuit.

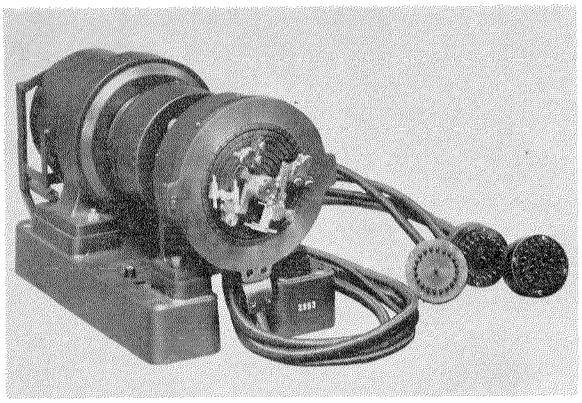

Fig. 6—Mechanical details of Varioplex distributor.

manner characteristic of that type of relay circuit commonly known as a counting chain. As shown in Fig. 7, the two groups of relays are associated with individual sub-channels in the horizontal rows and with individual channels in the vertical rows. For circuits having three channels a third vertical row of relays SC would be used while, for a four-channel circuit, there would similarly be a fourth row of relays SD. The sending and receiving chains are identical in their mode of operation and in the following description references to relays SA, SB and SCO apply likewise to the relays RA, RB and RCO. The relays SCO and RCO are necessarily included in the description, since they control the operation of the chain relays.

A local ring of the distributor furnishes two impulses per revolution for the operation of the chain relays. One operates relays SA and the other relays SB. Similarly for three- and four-channel installations a distinct impulse is used for each group of relays associated with a channel. Each chain relay is provided with a locking circuit and remains in the operated position after being actuated by the local impulse. The circuit is arranged so that, whenever any chain relay is actuated, any other previously operated relay in the same vertical row is released. Thus, there is never more than one SA and one SB relay in an operated position at the same time. The circuit is likewise arranged so that not more than one relay can be operated in the same horizontal row. If all eight sub-channels shown in Fig. 7 were transmitting, chain relays would operate progressively upward, starting with No. 8 and its relay SB in the following order:

	Rev. No. 1	Rev. No. 2	Rev. No. 3	Rev. No. 4	Rev. No. 5
Channel A		SA-7	SA-5	SA-3	SA-1
Channel B	SB-8	SB-6	SB-4	SB-2	SB-8

In the four revolutions of the brushes each sub-channel would then have transmitted one character. The cycle of operations is then repeated and this sequence continues as long as perforated tape is supplied to each transmitter through the operation of the sending teleprinters at the patron offices.

As previously mentioned, the SCO relays control the operation of their associated chain relays. The manner of control is such that the pair of chain relays associated with an SCO relay may be removed from the chain operating circuit, causing them to become inoperative. Such "removal" of a pair of chain relays does not affect the others. They continue to function as before. This action is effected by switching the chain impulse circuits at the contacts of the SCO relays, the chain relays being inoperative if the sending control relay SCO is in the released position, and operative if in the operated position. Thus by controlling the SCO relay so that it remains operated if traffic is available at the transmitter, and released when traffic is not available, the use of the main line circuit is shared only by those sub-channels capable of usefully employing the circuit facilities.

The control of the SCO relay is obtained through a collating arrangement which "reads" the character in the transmitter, causing the sending control relay SCO to operate and release in accordance with the type of character. A sub-channel is said to be "cut out" when its SCO relay is released and "cut in" when its SCO is operated. Cut-in and cut-out operations occur in such manner that the chain continues its normal sequence, the only effect being to shorten or lengthen its operating cycle. Since each cut-in sub-channel sends one character in each of these cycles, it is evident that the transmitting rate of any sub-channel decreases as other sub-channels are cut in and increases as they are cut out. When all but two are cut out the two chain relays remain in their operated positions and each sub-channel then transmits continuously over the same channel and at the maximum channel speed. This is also the case if only one sub-channel is cut in, one channel then becoming idle since it is not practicable to increase the sub-channel speed beyond that of the channel speed.

The continuous flow of characters arriving at the distant Station Y must be distributed to the patron receiving lines in the same order as they are transmitted at Station X. To insure this it is necessary that the receiving chain be made to operate in a cyclical manner identical to that of the sending chain. Since the two chains are alike in all operating respects, it is evident that this will occur if the receiving control relays RCO are operated and released in exact correspondence to that of the sending control relays SCO.

The control of RCO relays is effected through a circuit arrangement which automatically functions whenever an SCO relay is to be operated or released. This circuit, together with its associated apparatus, is called the cut-in system. It functions in response to information conveyed to it by the collating equipment associated with each transmitter. The latter determines when an operation or release of its associated control relay SCO is required and transmits this information to the cut-in mechanism. This causes the cut-in system to function and, upon the completion of its sequence of operations, the SCO and corre-

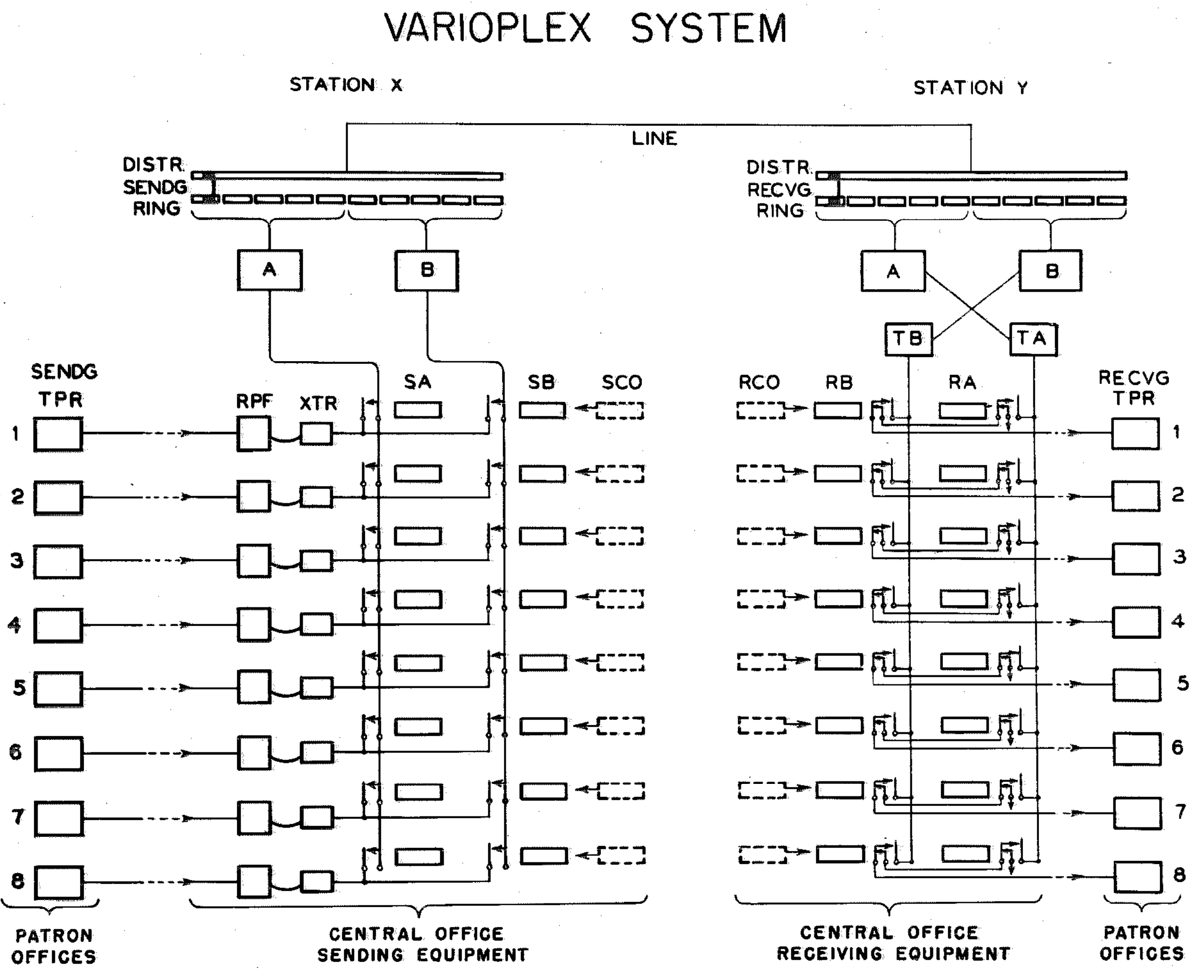

Fig. 7—Schematic of two-channel or "double" type of Varioplex circuit.

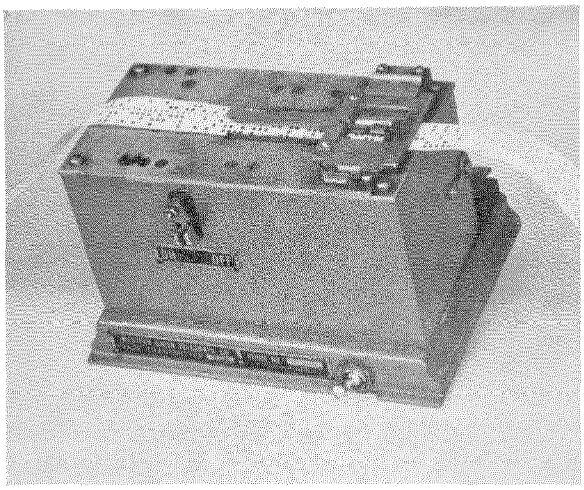

Fig. 8—Tape transmitter.

sponding RCO control relays will have been placed in similar positions, i.e., both operated or both released, in accordance with the request signalled by the collating mechanism. The operation or release of the control relay SCO involves only local functions at Station X. The positioning of the distant control relay RCO involves the transmission of special signals over the line to Station Y. These signals must be distinguishable from those normally received at Station Y, they must indicate the particular RCO relay to be actuated and, finally, they must indicate whether the relay is to be operated or released.

The cut-in mechanism is arranged so that each operation positions four SCO and four RCO relays. These relays, therefore, are divided into groups of four, each group being assigned a distinct position at a set of contact studs of a magnetically-operated rotary switch. The rotary switch is provided with four contacting arms or wipers (in addition to those required for its control) and, as these wipers step from one position to the next, they successively engage the sets of contact studs associated with each group of relays. By means of similar switches at the two circuit terminals, each arranged to contact corresponding groups of SCO and RCO relays at simultaneous intervals of time, it is possible to indicate the particular group of relays to be acted upon by transmitting the special cut-in signal during the interval while the rotary switches are engaging the studs of the desired group of SCO and RCO relays.

The rotary switches are normally at rest at a starting or "home" position. A blank transmitted over the B channel furnishes the start signal for the distant RCO switch, causing it to start stepping at the same instant the SCO switch is started. The blank is transmitted by the cut-in mechanism by diverting the B channel from its normal use during that revolution. When the sending and receiving rotary switches reach the position at which a cut-in operation is to be performed, a second blank is transmitted over the B channel in the same manner as before. Following this a signal combination called the "pattern" character is transmitted over the A channel by the cut-in mechanism. Just prior to its transmission the four sending control relays SCO are positioned in accordance with the indications furnished by the collating circuits of the four sub-channels involved. While all four SCO relays are actuated by the cut-in mechanism and may actually be changed to their opposite positions (operated relays released, and released relays operated), generally only one of the four requires a change, the others remaining in their previous position. Immediately following this positioning operation the A channel sending bank is switched from its normal circuit and four of its relays are connected to contacts of the four SCO relays. This causes the four sending relays to assume positions corresponding to those of the SCO relays, thus transmitting a character in which the pattern of arrangement is displayed.

The B channel receiving bank at Station Y is provided with a collating arrangement which "reads" the incoming characters and determines when a blank is received. A blank received while the rotary switch is resting at the stud position of some group of four RCO relays informs the cut-in mechanism that the next character to be received on the A channel is a pattern character and causes the mechanism to perform a positioning operation analogous to that performed at the sending end. The four receiving control relays RCO are thereby made to assume positions corresponding to the pattern displayed by the received character, thus placing them in exact agreement with the four distant SCO relays.

Following the pattern combination a second character called the "confirmation" is transmitted over the A channel. This character is identical to the pattern character except that the four pattern-displaying impulses are sent with reversed polarities. Its function is to test the operations performed in response to the pattern character. It serves to check both the line transmission as well as the local operations at the receiving end of the circuit. The four RCO relays must be in exact agreement with the positions indicated by the confirmation character at the time this test is made. Should they not be in agreement a signal is immediately transmitted back to the sending station causing all further operation to stop. Audible and visible signals simultaneously inform the circuit attendants of the nature of the trouble after which operation is restarted manually if inspection reveals no further evidence of the trouble. Such circuit stoppage causes all SCO and RCO relays to be released so that, when operation is subsequently started, pattern and confirmation signals are transmitted for all groups, thus insuring a proper positioning of all relays at the start.

The cut-in mechanism also provides means for operating or releasing relays other than SCO and RCO. These other relays are controlled from a certain group of studs on the rotary switches and provide special monitorial or circuit control features. One of these is the "home-stop" function which, when operated, causes transmission to stop from the station whence the signal is sent. Another, known as the "distant-stop," similarly causes transmission to stop from the opposite or distant terminal.

These signals permit manual stoppage of operation in either direction and from either terminal. They introduce no errors in the messages being received; hence they may be operated at any time desired. Stoppage of operation over the main line circuit does not necessitate stoppage of transmission from patron offices. Since most of these stoppages are of short duration, usually a matter of a few seconds, patrons are not in general aware of them at all. Any signals transmitted from patron offices during such stoppages are recorded in perforated tape in the normal manner. The tape, however, does not pass through the transmitter until the main line operation is again started. On occasions where a prolonged stoppage is necessary, a special signal is used to inform patrons that normal operation has been interrupted. This signal does not prevent the patron from transmitting should he so desire, but merely informs him that any subsequent transmission is subject to delay at the central office. All Varioplex circuits, however, are provided with spare main line facilities, spare units of equipment etc., and extended delays or interruptions rarely occur.

The ten years that have passed since the first Varioplex circuit was installed have seen a substantial growth, both in the number of circuits installed, and in the total number of sub-channels. Today there are more than 50 Varioplex circuits of various types and more than 500 sub-channels. They form a network which extends over the entire U. S. A. Many improvements have been made during this period, both in design and in principles of operation. What the future may hold in the way of further improvements or further growth is difficult to predict.

The Varioplex, without question, fulfills a unique need in the telegraph field and we may reasonably assume that the expansion program, now temporarily halted, will again be resumed after the war.

Transit Time and Space-Charge in a Plane Diode

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Editor's Note: This study comprises two parts: I—discussion of transit time and space-charge in a plane diode; II—consideration of the problem of dispersion of transit times for a diode (1) without space-charge and (2) with space-charge.

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I

Introduction

DISCUSSION of the problem of conventional triodes operated at high frequencies would appear to require certain reliable information relative to the role of space-charge effects between cathode and grid during short current discharges. This information can be derived by studying the behavior of diodes. The present article is confined to consideration of the case of the plane diode; exact formulas are developed for the beginning and the end of the discharge when the space-charge does not completely occupy the cathode-anode interval, but moves towards the anode (beginning of discharge) or recedes towards the cathode (end of discharge). So far as the present author is aware this problem has not previously been completely and accurately considered, notwithstanding the fact that its solution should prove valuable in the comprehension of triode phenomena. The problem is, essentially, the one discussed by C. C. Wang (*P. I. R. E.*, April, 1941, pp. 200–213, "Large Signal High-Frequency Electronics of Thermionic Vacuum Tubes"), but his theory is hard to follow and seems open to very serious shortcomings.

1. Plane Problem, Without Saturation

A plane cathode, located at $x=0$, emits electrons without initial velocity. As usually assumed, the field E on the cathode is zero but may become positive. The assumption that saturation is not reached merely excludes the possibility of any negative electric field E on the cathode.[1] The plane anode is located at $x=d$ and has a potential $V(t)$. One may consider x and t as independent variables, but it is often more convenient to follow the motion of an electron leaving the cathode at t_0, and to consider the position x, velocity $\dot{x}$, electric field E as functions of t_0 and t

$$t=t_0+T. \tag{1}$$

T is the transit time for the electron between 0 and $x(t_0, t)$. One must, however, distinguish between the regions where there is a space-charge and those which cannot be reached by any electron. We shall limit ourselves to problems where the space charge extends from 0 to $x_l(t)$, possibly leaving a charge free sheet between $x_l(t)$ and d in front of the anode

$$\left.\begin{array}{lll} \text{I. } 0<x<x_l(t) & \rho(x,t)<0 & \text{electronic charge density} \\ \text{II. } x_l\leqslant x\leqslant d & \rho=0 & \end{array}\right\}. \tag{2}$$

---

[1] A negative electric field would give a positive force on a negatively charged electron.

The fundamental system of Maxwell's equations reads as follows, in M. K. S. Giorgi units:

$$\left.\begin{array}{l} J(t)=\rho\dot{x}+\epsilon_0\dfrac{\partial E}{\partial t}\,; \\ \qquad\qquad J(t) \text{ total current density} \\ \qquad \rho\dot{x} \text{ electronic current density} \\ \operatorname{div} J=\dfrac{\partial J}{\partial x}=0 \\ \quad \epsilon_0\dfrac{\partial E}{\partial t} \text{ displacement current density} \end{array}\right\}. \qquad (3)$$

Hence, J is a function of t only and, at each instant, t, it is constant between cathode and anode.

$$\operatorname{curl} H=J(t), \quad \operatorname{div} H=0 \qquad (4)$$

and its solution is

$$H_z=\tfrac{1}{2}J\cdot y, \quad H_y=-\tfrac{1}{2}J\cdot z, \quad \frac{\partial H_z}{\partial y}-\frac{\partial H_y}{\partial z}=J_x(t). \qquad (5)$$

Also

$$\operatorname{curl} E=-\mu_0\frac{\partial H}{\partial t}\,. \qquad (6)$$

Assuming the electric field contains only an x component, this means

$$\frac{\partial E_x}{\partial z}=-\mu_0\frac{\partial H_y}{\partial t}=\tfrac{1}{2}\mu_0 z\frac{dJ}{dt}\,,$$

$$\frac{\partial E_x}{\partial y}=\quad\mu_0\frac{\partial H_z}{\partial t}=\tfrac{1}{2}\mu_0 y\frac{dJ}{dt}\,.$$

Hence,

$$E_x=\tfrac{1}{4}\mu_0 r^2\frac{dJ}{dt}+F(x\cdot t), \quad r^2=y^2+z^2. \qquad (7)$$

The first term[2] is usually so small that it can practically be neglected and we are left with an electric field $E_x(x\cdot t)$ uniform in the whole yz directions. Then

$$\operatorname{div} E=\frac{\partial E_x}{\partial x}=\frac{\rho}{\epsilon_0}, \quad \rho \text{ space charge.} \qquad (8)$$

Let us now assume that we observe the field $E(x\cdot t)$ while following the motion of an electron emitted at t_0. This means taking $x(t_0\cdot t)$ and computing the time derivative of the field:

$$\left(\frac{dE}{dt}\right)_{t_0\,\text{const.}}=\left(\frac{\partial E}{\partial t}\right)_{x_\text{const.}}+\left(\frac{dx}{dt}\right)_{t_0}\left(\frac{\partial E}{\partial x}\right)_{t_\text{const.}}$$

$$=\left(\frac{\partial E}{\partial t}\right)_x+\dot{x}\frac{\rho}{\epsilon_0}=\frac{1}{\epsilon_0}J(t), \qquad (9)$$

making use of (8) and (3). This is a fundamental relation, which enables one to compute the field distribution (variables $t_0\cdot t$) in the first region $x<x_l(t)$ which electrons can reach

$$E(t_0,\,t)=\frac{1}{\epsilon_0}\int_{t_0}^{t}J(t)dt+E(0,\,t_0). \qquad (10)$$

$E(0,\,t_0)$ is the field of the cathode ($x=0$) at the time $t=t_0$ when the electron is emitted. This field is usually zero, but may become positive when electrons previously emitted happen to fall back on the cathode. These equations (9) and (10) completely solve the problem in the space-charge region I.

I. $0<x<x_l(t)$.

The *total current* $J(t)$ *being given*

$E(t_0\cdot t)$ is given by (10)

$m\ddot{x}(t_0,\,t)=eE(t_0,\,t)$

is the equation of motion, hence

$$\dot{x}=\frac{e}{m}\int_{t_0}^{t}E(t_0\cdot t)dt, \qquad (11)$$

$$x(t_0,\,t)=\int_{t_0}^{t}\dot{x}dt. \qquad (12)$$

Thus the problem is solved by three integrations (10), (11), (12), yielding E, $\dot{x}$ and x as functions of t_0 and t (Llewellyn's procedure).

II. $x_l(t)\leqslant x\leqslant d$.

In the charge free region the solution is different. The field must be a function of time only, and equal to the value $E(x_l,\,t)$ it obtains at the limit $x_l(t)$. Furthermore,

$$J(t)=\epsilon_0\frac{\partial E}{\partial t}\cdot$$

Hence

$$\frac{\partial E(x_l\cdot t)}{\partial t}=\frac{1}{\epsilon_0}J(t). \qquad (13)$$

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[2] This first term corresponds to the "skin effect" and would lead to a non-uniform current distribution with J and E functions of r.

This charge free region may or may not exist, depending on the time variation of the total current J.

The general method is the following: instead of taking the potential of the anode $V(t)$ as a function of time, we shall assume a certain law of variation $J(t)$ for the total current flowing through the tube. We then compute E, $\dot{x}$, x, x_l, and try to solve the relation (12) inversely, namely, from

$$x = x(t_0, t) \tag{14}$$

in an attempt to obtain $t_0 = f(x, t)$, giving the instant t_0 of emission of the electrons reaching x at t. If this can be done, we can substitute t_0 in (10) and obtain $E(x, t)$ from which we may compute the difference of potential between cathode and anode at every instant t.

2. *Beginning of an Electronic Current*

As indicated by the discussion of the preceding section, we must start from a given $J(t)$ law for the total current. Let us first assume

$$J(t) = J_0 < 0, \quad \text{constant total current,} \tag{15}$$

which admits of different solutions.

Note: The J_0 value must be negative in order to be able to correspond to a flow of negative electrons.

A. No Space Charge

From (13) we obtain

$$E = \frac{1}{\epsilon_0} J_0 \cdot t + E_0. \tag{16}$$

Solution is possible as long as E is positive, preventing escaping of electrons from the cathode. If we take $E_0 = 0$ this means *negative time t*, and the voltage of the anode is

$$V = -Ed = -\frac{1}{\epsilon_0} J_0 t d \tag{17}$$

$$E = \frac{1}{\epsilon_0} J_0 \cdot t \qquad t < 0.$$

Here the tube functions as a condenser under constant current but cannot continue indefinitely because of an infinite increase of potential.

B. Space Charge

Starting at $t = 0$, equation (17) would yield a negative field on the cathode, which is contrary to our general assumptions. Electrons leaving the cathode at $t_0 = 0$ build the boundary layer $x_l(0, t)$ of the space-charge region I. On account of the continuity of the field, the electric field acting on these limit electrons is the same as in the charge free region, namely (17), and their motion is

$$\begin{aligned} \ddot{x}_l &= \frac{e}{\epsilon_0 m} J_0 t \\ \dot{x}_l &= \frac{e}{\epsilon_0 m} J_0 \frac{t^2}{2} \\ x_l &= \frac{e}{\epsilon_0 m} J_0 \frac{t^3}{6}. \end{aligned} \tag{18}$$

No integration constants are involved since these electrons are emitted at $x = 0$ with $\dot{x} = 0$ at the time $t = 0$. This boundary layer reaches the anode at the time t_l

$$t_l = \left(\frac{6\epsilon_0 m d}{e J_0} \right)^{\frac{1}{3}} \tag{19}$$

and for $t > t_l$ the space charge completely fills the diode. We must now investigate the field distribution *inside the space charge* during the time interval $0 \leqslant t \leqslant t_l$ in order to obtain the corresponding variation of the plate voltage. Here equations (10), (11), (12) are used.

$$E(t_0, t) = \frac{1}{\epsilon_0} J_0 (t - t_0), \tag{20}$$

where the constant of integration is chosen to give $E = 0$ on the cathode, for electrons leaving the cathode at t_0.

$$\dot{x} = \frac{e}{m\epsilon_0} J_0 \frac{(t - t_0)^2}{2}, \tag{21}$$

which also gives $\dot{x} = 0$ on the cathode at t_0.

$$x = \frac{e}{m\epsilon_0} J_0 \frac{(t - t_0)^3}{6}, \tag{22}$$

yielding $x = 0$ at t_0. Solving equation (22):

$$t_0 = t - \left(\frac{6m\epsilon_0}{e J_0} x \right)^{\frac{1}{3}}, \quad T = \left(\frac{6m\epsilon_0}{e J_0} x \right)^{\frac{1}{3}} \tag{23}$$

$$t = t_0 + T$$

and we may write the field (20) as a function of x, t.

In region I

$$E(x,\,t)=\frac{J_0}{\mathrm{E}_0}\left(\frac{6m\epsilon_0}{eJ_0}x\right)^{\frac{1}{3}}=\left(\frac{6m}{e}\right)^{\frac{1}{3}}\left(\frac{J_0}{\epsilon_0}\right)^{\frac{2}{3}}x^{\frac{1}{3}},\quad 0<x<x_l. \tag{24}$$

The potential difference throughout the space-charge is:

$$V(x_l,\,t)=-\int_0^{x_l}Edx=-\left(\frac{6m}{e}\right)^{\frac{1}{3}}\left(\frac{J_0}{\epsilon_0}\right)^{\frac{2}{3}}\frac{3}{4}x_l^{\frac{4}{3}}$$
$$=-\left(\frac{6m}{e}\right)^{\frac{1}{3}}\left(\frac{J_0}{\epsilon_0}\right)^{\frac{2}{3}}\frac{3}{4}\left(\frac{eJ_0}{6\epsilon_0 m}\right)^{\frac{4}{3}}t^4,$$

using (18)

$$V(x_l,\,t)=-\frac{e}{8m}\left(\frac{J_0}{\epsilon_0}\right)^2t^4. \tag{25}$$

The minus sign gives a positive potential, as the electronic charge e is negative. In order to obtain the potential of the anode, we must add the potential difference through the charge free region; hence

$$V(d,\,t)=-\frac{e}{8m}\left(\frac{J_0}{\epsilon_0}\right)^2t^4-\frac{1}{\epsilon_0}J_0t(d-x_l)$$
$$=-\frac{e}{8m}\left(\frac{J_0}{\epsilon_0}\right)^2t^4-\frac{J_0}{\epsilon_0}t\left(d-\frac{eJ_0}{6\epsilon_0 m}t^3\right)$$
$$V(d\cdot t)=+\frac{1}{24}\frac{e}{m}\left(\frac{J_0}{\epsilon_0}\right)^2t^4-\frac{J_0}{\epsilon_0}td. \tag{26}$$

This formula will be used for $0<t<t_l$, equation (19). At the final instant t_l, the time derivative of V is zero and the plate voltage reaches a maximum.

For all later time, the situation is stable, with constant current and constant anode voltage, which is exactly the same as in the usual Langmuir theory. If we take (26) with

$$t_l=\left(\frac{6\epsilon_0 md}{eJ_0}\right)^{\frac{1}{3}}$$

from (19), we obtain the well-known result (Langmuir)

$$V(d,\,t_l)=V(d)=+\frac{3}{4}\left(\frac{J_0}{\epsilon_0}\right)^{\frac{2}{3}}\left(\frac{6m}{-e}\right)d^{\frac{4}{3}}>0. \tag{27}$$

The results are explained on Fig. 1. Electrons start leaving the cathode at $t=0$ and reach the anode at t_l; hence t_l is the transit time for the first electrons. In this special example this first transit time happens to be equal to the transit time T in the stable state. This is immediately seen by comparing t_l, equation (19), with the transit time given by (23) for the case $x=d$ (see Fig. 1).

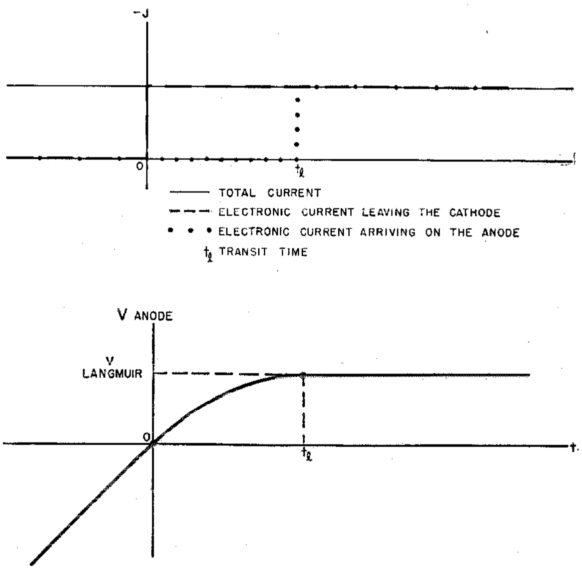


Fig. 1.

3. *Another Example of the Beginning of an Electronic Current*

The preceding example yields a very special case of voltage curve, which will be realized only under exceptional circumstances. A more general solution is obtained by taking

$$J(t)=\epsilon_0(A+Bt),\quad A<0,\quad B<0 \tag{28}$$

which, by a suitable change of time origin, dispenses with the constant coefficient A. We prefer to retain the equation (28) as it stands, and to use $t=0$ as the instant when the anode voltage becomes positive, which means the instant when the first electrons leave the cathode.

For *negative times*, there is no space-charge and the solution is formulated similarly to (16) and (17):

$$\left.\begin{aligned}&\frac{dE}{dt}=\frac{1}{\epsilon_0}J=A+Bt\\&\begin{cases}E=At+B\frac{t^2}{2}\\V=-Ed=-d\left(At+B\frac{t^2}{2}\right)\end{cases}\end{aligned}\right\}. \tag{29}$$

No integration constant is included in these formulas since E and V are assumed to be naught at $t=0$.

For *positive time* t, a space-charge extends to a limit $x_l(t)$. Equations (29) still give the field in the charge free region; hence on the *first layer of electrons*, equations (18) are replaced by

$$\left.\begin{aligned} \ddot{\xi}_l&=\frac{m}{e}\ddot{x}_l=E=At+B\frac{t^2}{2}\\ \dot{\xi}_l&=\frac{m}{e}\dot{x}_l=A\frac{t^2}{2}+B\frac{t^3}{6}\\ \xi_l&=\frac{m}{e}x_l=A\frac{t^3}{6}+B\frac{t^4}{24} \end{aligned}\right\}. \tag{30}$$

No integration constants are needed here. It will simplify the formulas to use $\xi=\frac{m}{e}x$ consistently for all distance measurements ($x>0$ means $\xi<0$). The anode distance will be designated

$$\delta=\frac{m}{e}d<0 \tag{31}$$

in the same units. The time t_l at which the first electrons reach the anode is now given by

$$6\xi_l=6\delta=At_l^3+B\frac{t_l^4}{4}, \tag{32}$$

a relation which can be discussed numerically.

For electrons inside the space-charge, we refer to equations (10), (11), (12) or their application in (21), (25). Let us call t_0 the time of emission of the electrons, and write

$$\frac{J}{\epsilon_0}=A+Bt=A+Bt_0+B(t-t_0);$$

then by three integrations:

$$\left.\begin{aligned} E&=(A+Bt_0)(t-t_0)+\frac{B}{2}(t-t_0)^2\\ \dot{\xi}&=\frac{A+Bt_0}{2}(t-t_0)^2+\frac{B}{6}(t-t_0)^3\\ \xi&=\frac{A+Bt_0}{6}(t-t_0)^3+\frac{B}{24}(t-t_0)^4 \end{aligned}\right\}, \tag{33}$$

$$(t-t_0=T \text{ transit time})$$

where the integration constants have been adjusted to yield $E=\dot{\xi}=\xi=0$ on the filament ($t=t_0$). We want to compute the potential difference through the space-charge layer; this can be performed in the following way:

$$V=-\int_{x=0}^{x}E_t dx=-\frac{e}{m}\int_0^{\xi}E_t d\xi$$
$$=-\frac{e}{m}\int_0^{T}E_t\left(\frac{\partial\xi}{\partial T}\right)_t dT, \tag{34}$$

where E_t is the field at given time t (for any variable t_0 or x), and $\left(\frac{\partial\xi}{\partial T}\right)_t$ means the partial derivative of ξ at constant time t. Let us then rewrite ξ and E as a function of t, T instead of t_0, T:

$$\left.\begin{aligned} E&=(A+Bt_0)T+\frac{B}{2}T^2=(A+Bt)T-\frac{BT^2}{2}\\ \xi&=\frac{A+Bt_0}{6}T^3+\frac{B}{24}T^4=\frac{A+Bt}{6}T^3-\frac{1}{8}BT^4\\ \left(\frac{\partial\xi}{\partial T}\right)_t&=\frac{A+Bt}{2}T^2-\frac{1}{2}BT^3 \end{aligned}\right\}. \tag{35}$$

Hence

$$-\frac{m}{e}V(t,T)$$
$$=\int_0^T\left(A+Bt-\frac{BT}{2}\right)(A+Bt-BT)\frac{T^3}{2}dT$$
$$=\frac{(A+Bt)^2}{8}T^4-\frac{3B}{20}(A+Bt)T^5+\frac{B^2}{24}T^6. \tag{36}$$

$V(t, T)$ is the potential, at time t, for the point reached by electrons which leave the cathode at $t_0=t-T$. V is zero for $T=0$ as it should be.

In order to obtain the potential of the anode during the transition period, we must first use (36) throughout the space-charge, i.e., putting $t=T$, as the first layer of the space-charge is the one which leaves the cathode at $t_0=0$.

$$-\frac{m}{e}V_{\text{sp.-charge}}$$
$$=\frac{(A+Bt)^2}{8}t^4-\frac{3B}{20}(A+Bt)t^5+\frac{B^2}{24}t^6$$
$$=\frac{A^2}{8}t^4+\frac{1}{10}ABt^5+\frac{1}{60}B^2t^6. \tag{37}$$

Adding the voltage difference through the charge free region (eq. 29 for the field) we obtain the anode voltage

$$-\frac{m}{e}V_{\text{anode}}=\left(\frac{A^2t^4}{8}+\frac{1}{10}ABt^5+\frac{1}{60}B^2t^6\right)$$
$$+\left(At+B\frac{t^2}{2}\right)(\delta-\xi_l),$$

where ξ_l results from (30).

$$-\frac{m}{e}V_{\text{anode}}=-\frac{1}{24}A^2t^4-\frac{1}{40}ABt^5+\frac{1}{240}B^2t^6+\left(At+B\frac{t^2}{2}\right)\delta, \quad (38)$$

giving the anode potential for $0<t\leqslant t_l$. After t_l the space-charge completely fills up the cathode-anode interval and the utilizable formulas are (35) and (36), which summarize the relations inside the space-charge:

$$\left.\begin{aligned} \frac{m}{e}d=\delta&=\frac{A+Bt}{6}T^3-\frac{B}{8}T^4 \\ &=\frac{J(t)}{6\epsilon_0}T^3-\frac{1}{8\epsilon_0}\frac{dJ}{dt}T^4 \\ -\frac{m}{e}V&=\frac{J^2(t)}{8\epsilon_0^2}T^4-\frac{3J}{20\epsilon_0^2}\frac{dJ}{dt}T^5+\frac{T^6}{24\epsilon_0^2}\left(\frac{dJ}{dt}\right)^2 \end{aligned}\right\}. \quad (39)$$

These formulas have been rewritten as functions of $J(t)$, $\frac{dJ}{dt}$ being taken at the time t when the voltage V is measured. T is the transit time $t-t_0$ for the electrons reaching the anode at that same time t. The first equation (39) yields T, and this value transferred into the second equation (39) gives the anode voltage V. The difficulty occurs in solving the first equation (39).

The same equations can be reformulated. We have assumed a linear time dependence for the current; hence

$$J(t)-\frac{3}{4}T\frac{dJ}{dt}=J(t-\tfrac{3}{4}T) \quad (40\text{-A})$$

and

$$J^2-\frac{6}{5}J\frac{dJ}{dt}T+\frac{1}{3}\frac{dJ}{dt}T^2=\left(J-a_1\frac{dJ}{dt}T\right)\left(J-a_2\frac{dJ}{dt}T\right),$$

$$\left\{\begin{aligned} \frac{m}{e}d&=\delta=\frac{T^3}{6\epsilon_0}J(t-\tfrac{3}{4}T) \\ -\frac{m}{e}V&=\frac{T^4}{8\epsilon_0^2}J(t-a_1T)J(t-a_2T) \\ \left.\begin{matrix}a_1\\a_2\end{matrix}\right)&=\frac{3\pm\sqrt{\frac{2}{3}}}{5}=\begin{matrix}0.764\\0.436\end{matrix} \end{aligned}\right\}. \quad (40\text{-B})$$

The root $a_1=0.764$ is very near $\frac{3}{4}$, which is the coefficient in the first formula (40-B); hence

$$-\frac{m}{e}V\approx\frac{3}{4\epsilon_0}\delta TJ(t-0.44T),$$

$$V\approx-\frac{3d}{4\epsilon_0}TJ(t-0.44T), \quad (41\text{-A})$$

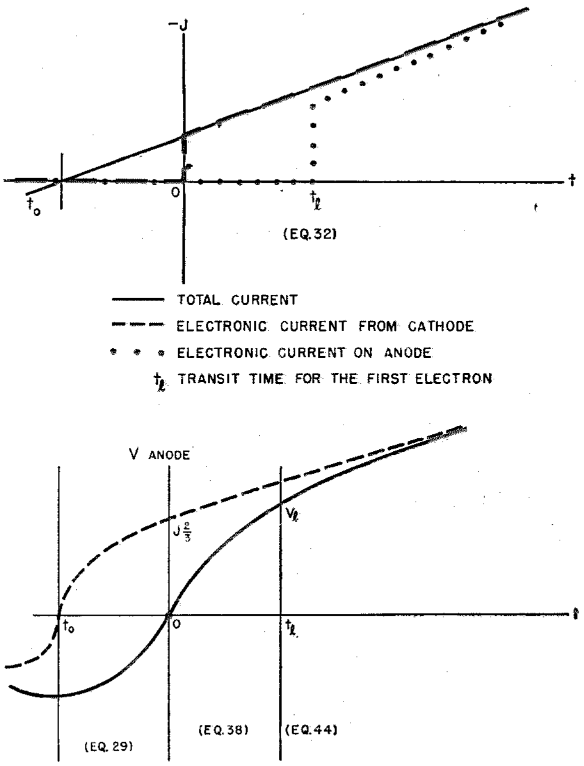


Fig. 2.

which should yield a good approximation to the actual value. Now

$$T=\left[\frac{6\epsilon_0 md}{eJ(t-\frac{3}{4}T)}\right]^{\frac{1}{3}}; \quad (41\text{-B})$$

hence

$$V\approx-\frac{3d^{\frac{4}{3}}}{4\epsilon_0^{\frac{2}{3}}}\left(\frac{6m}{e}\right)^{\frac{1}{3}}\frac{J(t-0.44T)}{[J(t-0.75T)]^{\frac{1}{3}}}$$

$$\approx\frac{3}{4}d^{\frac{4}{3}}\left(\frac{6m}{-e}\right)^{\frac{1}{3}}\left[\frac{1}{\epsilon_0}J(t-0.29T)\right]^{\frac{2}{3}}, \quad (41\text{-C})$$

where we have again used expansions like (40) and regrouped the terms conveniently. In the case of constant current J, this yields the classical result (27).

The preceding formula strictly applies to the case of a current varying as a linear function of time, equation (28), but equation (41-C) may be used also in the more general case of a current varying slowly in a time T equal to the transit time. The anode voltage $V(t)$ should approximately follow the exponent (2/3) of the current variation at time $t-0.29T$, with T given by (41-B). The results are explained in Fig. 2.

On the cathode the field is zero for all positive times; hence the current is purely electronic for $t>0$. On the anode there is still a field E, for any positive time, and its time variation leaves a small displacement current; hence, for increasing currents, the electronic current is always less than the total current. For decreasing voltage and current, the electronic current would be larger than the total current since the displacement current would be negative.

It is interesting to compute the electronic current on the anode, and the shortest way to do it is to subtract the displacement current from the total current, and take

$$J_{\text{electronic}}=J-\epsilon_0\left(\frac{\partial E}{\partial t}\right)_d. \tag{42}$$

Computing $\frac{\partial E}{\partial t}$ at a given point $x=d$, formula (35) gives E as a function of t, T; t, T should be connected by the condition $\xi=\text{const.}$

$$d\xi=0=\frac{BT^3}{6}dt+\left(\frac{A+Bt}{2}-\frac{BT}{2}\right)T^2dT, \tag{43-A}$$

$$\left(\frac{dT}{dt}\right)_{x=\text{const.}}=-\frac{BT}{3(A+Bt-BT)}.$$

Hence, taking E from (35)

$$\begin{aligned}\left(\frac{\partial E}{\partial t}\right)_{x_{\text{const.}}}&=\left(\frac{\partial E}{\partial t}\right)+\frac{\partial E}{\partial T}\left(\frac{dT}{dt}\right)_x\\ &=BT-(A+Bt-BT)\\ &\qquad\times\frac{BT}{3(A+Bt-BT)}=\frac{2}{3}BT,\end{aligned} \tag{43-B}$$

giving the electronic part of the anodic current

$$\begin{aligned}J_{\text{electronic}}&=\epsilon_0(A+Bt)-\epsilon_0\tfrac{2}{3}BT\\ &=\epsilon_0(A+B[t-\tfrac{2}{3}T])=J(t-\tfrac{2}{3}T).\end{aligned} \tag{44}$$

This leads to the following conclusion: The anodic voltage V, equation (41-C), corresponds to the total current at $t-0.29T$, and the electronic part of the current is equal to the total current at $t-0.67T$; hence the delay between voltage and electronic current is $0.38T$ when T is the transit time. The result should apply under almost any condition since it is independent of the B coefficient which gives the rate of change of the current.

4. End of an Electronic Discharge

The theory developed in the preceding section gives practical formulas for the beginning of an electronic discharge, as well as for the current-voltage relation during the discharge if the transit times T are not too large. We must now investigate what happens at the end of an electronic discharge, where negative anode potentials will push the electronic space-charge back towards the cathode.

Let us assume a total current

$$J=\epsilon_0 B't, \qquad B'>0, \tag{45}$$

which represents a decreasing flow of electrons towards the anode. For negative times, we assume the space-charge to fill the cathode-anode interval, and this will go on until a certain instant t_1 when the last electrons reach the anode. Hence, for $t<t_1$, we may use formulas (33) to (36) of the preceding section. Let us rewrite them here, with the variables t, T, which means that every quantity is given at time t for the position ξ reached by electrons leaving the cathode at $t_0=t-T$:

$$\left.\begin{aligned}\xi(t,T)&=\frac{B'T^3}{6}(t-\tfrac{3}{4}T)\\ \dot{\xi}(t,T)&=\frac{B'T^2}{2}(t-\tfrac{2}{3}T)\\ E(t,T)&=B'T\,(t-\tfrac{1}{2}T)\end{aligned}\right]\quad \begin{aligned}&t_0=t-T\\ &t\leqslant t_1\end{aligned} \tag{46}$$

$$-\frac{m}{e}V(t,T)=\frac{B'^2T^4}{4}\left(\frac{t^2}{2}-\frac{3}{5}tT+\frac{1}{6}T^2\right), \quad t<0.$$

ξ, E, V were already computed in (35), (36) and $\dot{\xi}$ results from a similar transformation on (33). It should be noted that $\dot{\xi}$ is the time derivative of ξ taken at constant t_0 and not at constant t.

All these quantities do not become zero at the same instant, i.e., various delays occur in the current or field values. Let us first compute the time t at which the last electrons reach the anode, that is, when the velocity on the anode is zero

$$\dot{\xi}=0, \quad t_1=\tfrac{2}{3}T_1,$$

$$\begin{aligned}\xi=\delta=\frac{m}{e}d=\frac{B'T_1^4}{6}\left(\frac{2}{3}-\frac{3}{4}\right)&=-\frac{B'T_1^4}{72}\\ &=-B'\frac{9}{128}t_1^4\approx-0.070B't_1^4\end{aligned} \tag{47}$$

or

$$t_1=\left(\frac{md}{-eB'0.07}\right)^{\frac{1}{4}}.$$

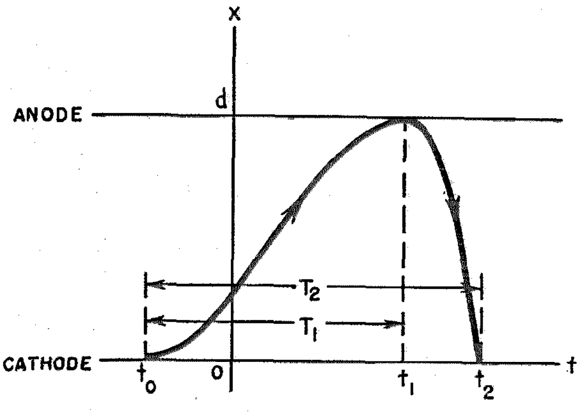


Fig. 3.

δ is negative on account of negative electric charge e. The transit time T_1, for the last electrons, differs materially from the transit time t_l equation (32), for the first electrons, a circumstance with important implications.

Considering the cathode, we note that electrons leave the cathode during all negative times, and that the emission stops at $t=0$. ($t=0$, $T=0$, $\xi=0$, $\dot{\xi}=0$ in equation 46.)

For positive times electrons fall back on the cathode and, after t_1, a gap is created between the electronic space-charge and the anode. Electrons returning to the cathode are characterized by

$$\left.\begin{array}{ll} & \xi=0; \\ \text{hence} & t_2=\tfrac{3}{4}T_2>0 \\ \multicolumn{2}{l}{\text{and } T_2 \text{ transit time from cathode and}} \\ \multicolumn{2}{l}{\text{back to the cathode.}} \end{array}\right\} \qquad (48)$$

These electrons are emitted at $-\dfrac{T_2}{4}$ and fall back on the cathode at $+\dfrac{3T_2}{4}$ with a velocity

$$\xi=\frac{B'T_2^3}{2}\left(\frac{3}{4}-\frac{2}{3}\right)=\frac{B'T_2^3}{24}=\frac{8}{81}B't_2^3>0. \qquad (49)$$

$\dot{\xi}>0$ means a negative velocity because of $-e$.

The last electrons to return to the cathode are those which are emitted at $-\frac{1}{3}T_1$, and reach the anode at $t_1=\frac{2}{3}T_1$ according to (47); hence $t_0=-\frac{1}{4}T_2=-\frac{1}{3}T_1$ is the instant of emission. The instant these last electrons return to the cathode is given by

$$t_2=\frac{3}{4}T_2=T_1=\frac{3}{2}t_1, \qquad (50)$$

where t_1 results from (47) (see Fig. 3). For all negative times electrons leave the cathode, taking $T=0$ in equation (46), we can obtain the field E or the potential V on the cathode. Both quantities are naught.

For all positive times $0<t<t_2$ conditions on the cathode are obtained by taking $t=\frac{3}{4}T$ as in (48), which refers to an electron which falls back on the cathode. From (46), we obtain

$$E=B'T^2\left(\frac{3}{4}-\frac{1}{2}\right)=\frac{1}{4}B'T^2=\frac{4}{9}B't^2, \qquad (51)$$

which is a positive field attracting the electrons back to the cathode and, on the cathode, corresponds to a displacement current.

$$\epsilon_0\frac{\partial E}{\partial t}=\frac{8}{9}\epsilon_0 B't \qquad (52)$$

and the total current is $\epsilon_0 B't$; hence the electronic part of the current is 1/9 of the total current. The electronic reverse current is

$$J_{\text{el.}}=\frac{1}{9}\epsilon_0 B't=\frac{1}{9}J. \qquad (53)$$

Knowing the electronic current and the velocity we may compute the heat developed by bombardment:

$$Q=\frac{1}{2}\frac{m}{e}\rho V^2=\frac{1}{2}\frac{m}{e}J_{\text{el.}}|\dot{x}|=\frac{1}{2}J_{\text{el.}}\dot{\xi}=\epsilon_0\frac{1}{18}\times\frac{8}{81}B'^2t^4.$$

For the whole interval 0, t_2 the integration of Q yields

$$Q_{\text{total}}=\int_0^{t_2}Q\,dt=\epsilon_0\frac{1}{9}\,\frac{4}{81}B'^2\frac{t_2^5}{5}. \qquad (54)$$

It is necessary to follow the motion of the last layer of electrons, which lose contact with the anode at t_1, equation (47), and impinge on the cathode at $t_2=\dfrac{3}{2}t_1$ (50). Their motion is given by (46):

$$\xi_l=\frac{B'T^3}{6}\left(t-\frac{3}{4}T\right)$$

with

$$T=t+\frac{1}{2}t_1, \qquad (55)$$

according to (50) and Fig. 3; hence

$$\xi_l=\frac{B'}{24}\left(t+\frac{1}{2}t_1\right)^3\left(t-\frac{3}{2}t_1\right). \qquad (56)$$

On this last layer of the space-charge the field is computed from (46) and (55).

$$E=B'T\left(t-\frac{1}{2}T\right)=B'\left(t+\frac{1}{2}t_1\right)\left(\frac{1}{2}t-\frac{1}{4}t_1\right)$$
$$=\frac{B'}{2}\left(t^2-\frac{{t_1}^2}{4}\right). \tag{57}$$

The same value of the field is found throughout the gap which exists between the space-charge and the anode, and the corresponding displacement current accounts for the imposed J value (45).

We must now turn to the computation of the voltage distribution at a given time $t_1 \leqslant t \leqslant t_2$. The original voltage formula V of (46) is correct for $t<0$ when the cathode corresponds to $T=0$ and thus $V=0$. For positive times we already noted that the cathode corresponds to $t=\frac{3}{4}T$ as in (48), since electrons then return to the cathode at this time. Accordingly we must modify our former computation of equations (34), (36) and write

$$V=-\int_{x=0}^{x} E_t dx=-\frac{e}{m}\int_{T=\frac{4}{3}t}^{T} E_t\left(\frac{\partial\xi}{\partial T}\right)_t dT$$
$$=\frac{e}{m}\int_{T}^{\frac{4}{3}t} E_t\left(\frac{\partial\xi}{\partial T}\right)_t dZ. \tag{58}$$

Hence

$$-\frac{m}{e}V(t,T)=-\int_{T}^{\frac{4}{3}t}\frac{B'^2}{2}\left(t-\frac{T}{2}\right)(t-T)T^3dT$$
$$=-\frac{B'^2}{2}\int_{T}^{\frac{4}{3}t}\left(t^2T^3-\frac{3}{2}tT^4+\frac{T^5}{2}\right)dT, \tag{59}$$

$$-\frac{m}{e}V=\frac{B'^2}{4}\left|t^2\frac{T^4}{2}-\frac{3}{5}tT^5+\frac{T^6}{6}\right|_{T}^{\frac{4}{3}t}$$
$$=-\frac{B'^2}{4}\left[t^6\left(\frac{1}{2}\left\{\frac{4}{3}\right\}^4-\frac{3}{5}\left\{\frac{4}{3}\right\}^5+\frac{1}{6}\left\{\frac{4}{3}\right\}^6\right)\right.$$
$$\left.-\frac{t^2T^4}{2}+\frac{3}{5}tT^5-\frac{T^6}{6}\right].$$

This formula can be used to compute the anode voltage when $0<t<t_1$, since during that interval the space-charge still fills the cathode-anode interval. For $t_1<t<t_2$ the formula is applicable for computing the potential difference through the space-charge which extends up to $T=t+\frac{1}{2}t_1$, according to (55), with the addition of $-E(d-x_l)$ with E taken from (57) because of the voltage across the gap. The result is rather complicated and hard to discuss and we will, therefore, confine ourselves to the computation of a few special points, $t=0$, t_1 and t_2.

For $t=0$ both formulas (46) and (59) yield $-\frac{m}{e}V_a=\frac{B'^2}{24}T^6$ and can be used with $\delta=\frac{m}{e}d$ $=-\frac{B'}{8}T^4$ and $T=\left(\frac{8md}{-eB'}\right)^{\frac{1}{4}}$. Hence

$$V_{a_0}=\frac{B'd}{3}\left(\frac{8md}{-eB'}\right)^{\frac{1}{2}}=\frac{2\sqrt{2}}{3}B'd\left(\frac{md}{-eB'}\right)^{\frac{1}{2}}, \quad t=0. \tag{60}$$

For $t=t_1$, we must use (59) with $T_1=\frac{3}{2}t_1$; numerical computation yields

$$-\frac{m}{e}V_{a_1}\approx-0.028B'^2t^6{}_1, \quad t_1=\left(\frac{md}{-0.07eB'}\right)^{\frac{1}{4}},$$
$$V_{a_1}\approx-\frac{2.8}{7}B'd\left(\frac{md}{0.07eB'}\right)^{\frac{1}{2}}$$
$$\approx-0.1B'd\left(\frac{md}{-eB'}\right)^{\frac{1}{2}}, \tag{61}$$

a very small negative value.

For $t \geqslant t_2$ the space-charge disappears and we simply have the electrostatic field (57); hence

$$V_a=-\frac{B'd}{2}\left(t^2-\frac{{t_1}^2}{4}\right), \tag{62}$$

which for $t=t_2=\frac{3}{2}t_1$ yields

$$V_{a_2}=-B'd{t_1}^2=-\frac{1}{\sqrt{0.7}}B'd\left(\frac{md}{-eB'}\right)^{\frac{1}{2}}$$
$$\approx-0.83B'd\left(\frac{md}{-eB'}\right)^{\frac{1}{2}}. \tag{63}$$

These points are useful in drawing a smooth curve joining the $J^{\frac{2}{3}}$ curve, equation (44), valid for $t<0$, with the t^2 curve (62) for $t>t_2$ (see lower curve of Fig. 4). Current values are plotted on the upper half of Fig. 4, showing the electronic currents on anode and cathode, and the total current as a straight line. Displacement current represents the difference between total and electronic current.

5. Reproduction of a Given Voltage Curve

The results obtained in the preceding sections make it possible to predict, at least approximately, the electronic current resulting from a given voltage applied at the anode. Let us postulate, for instance, a sinusoidal voltage law

$$V=U\sin\omega t. \tag{64}$$

When the voltage is negative, there is practically no electronic current (but for a short time-interval at the end of the discharge). Consider the conditions at the beginning of the discharge, for small positive t, using the results of section 3. We must choose both coefficients A and B, and we may do so by taking

$$t=0, \quad \frac{dV}{dt}=U\omega, \tag{65-A}$$

$$t=t_l, \quad V_l=U\omega t_l, \tag{65-B}$$

which yield an initial part of the curve (Fig. 2) very close to a straight line. This procedure is reasonable provided t_l is much smaller than $\frac{2\pi}{\omega}$.

Now, from (38)

$$\left(\frac{dV}{dt}\right)_{t=0}=-Ad, \quad A=-\frac{U\omega}{d} \tag{66}$$

and from (32), (39), taking $x=d$, $\xi_l=\delta$

$$\begin{aligned} 6\frac{m}{e}d&=At_l^3+\frac{B}{4}t_l^4=At_l^3\left(1+\frac{Bt_l}{4\mathrm{A}}\right) \\ -\frac{m}{e}V_l&=\frac{1}{8}\left(A^2t_l^4+\frac{4}{5}ABt_l^5+\frac{2}{15}B^2t_l^6\right) \\ &=\frac{A^2t_l^4}{8}\left[1+\frac{4}{5}\frac{Bt_l}{A}+\frac{2}{15}\left(\frac{Bt_l}{A}\right)^2\right] \end{aligned} \tag{67}$$

or

$$V_l=-\frac{6dt_l}{8}A\frac{1+\frac{4}{5}\xi+\frac{2}{15}\xi^2}{1+\frac{1}{4}\xi}, \quad \xi=\frac{Bt_l}{A}. \tag{68}$$

Making use of (66) we may write condition (65-B) as follows:

$$\begin{aligned} &\frac{3}{4}\left[1+\frac{4}{5}\xi+\frac{2}{15}\xi^2\right]=1+\frac{1}{4}\xi \\ &\frac{1}{10}\xi^2+\left(\frac{3}{5}-\frac{1}{4}\right)\xi-\frac{1}{4}=0 \\ &\xi^2+3.5\xi-2.5=0 \\ &\xi=-1.75\pm\frac{1}{2}\sqrt{3.5^2+10}=-1.75\pm\frac{1}{2}\sqrt{22.25} \\ &\qquad\qquad\qquad\qquad=-1.75\pm2.35. \end{aligned}$$

ξ must be positive; hence

$$\xi=\frac{Bt_l}{A}=0.6. \tag{69}$$

Turning back to the first equation (67), it now becomes

$$6\frac{m}{e}d=At_l^3(1+0.15);$$

hence:

$$t_l=\left(\frac{5.2md}{eA}\right)^{\frac{1}{3}}=\left(\frac{5.2md^2}{-eU\omega}\right)^{\frac{1}{3}}, \tag{70}$$

which gives the transit time for the first electrons to reach the anode.

In the middle part of the pulse, we can use the relation (41) and (44). As the current J is almost constant, near its maximum,

$$T=\left(\frac{6\epsilon_0md}{eJ}\right)^{\frac{1}{3}},$$

$$V=\frac{3}{4}d^{\frac{4}{3}}\left(\frac{6m}{-e}\right)^{\frac{1}{3}}\left(\frac{J}{\epsilon_0}\right)^{\frac{2}{3}}=U,$$

and

$$T^2U=\frac{3}{4}\left(\frac{6m}{-e}\right)d^2,$$

$$T=3d\sqrt{\frac{m}{-2eU}}. \tag{71}$$

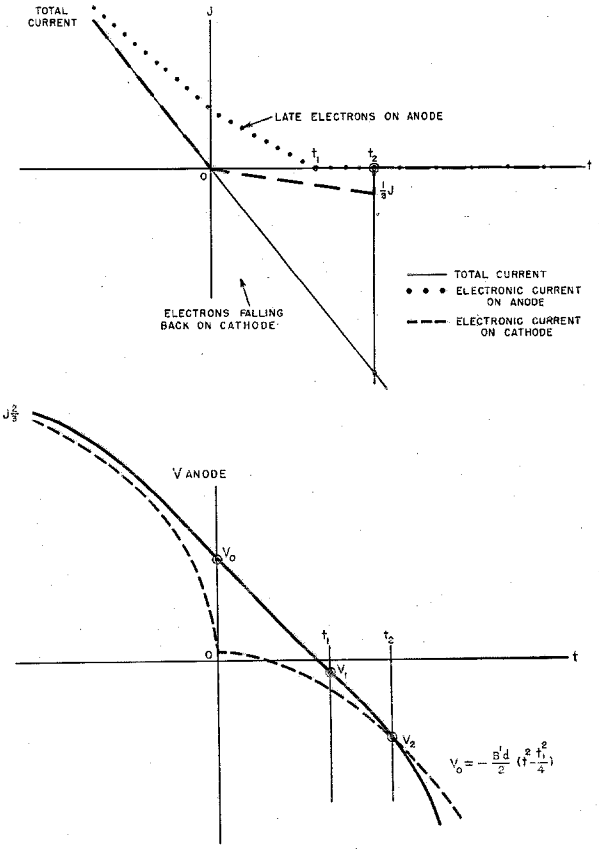


Fig. 4.

The important factor, however, is not this transit time for the fastest electrons, but the delay between maximum voltage and maximum electronic current, which, according to (44), amounts to

$$T'=0.38T=1.14d\sqrt{\frac{m}{-2eU}}. \tag{72}$$

Conditions at the end of the discharge also may be obtained by adjusting the coefficient B' of section 4 in such a way as to fit the voltage curve. One ought to take the average slope of the curve through the points V_0, V_1, V_2 of Fig. 4 and equate it with $-U\omega$. Here, however, calculations are hardly necessary as this potential curve cuts the axis very near the point t_1, which means that the anode potential is zero very shortly before the electronic current on the anode falls to zero. Hence, for practical purposes, voltage and anodic current on the anode reach zero simultaneously.

An electronic discharge with space-charge is characterized by the initial transit time t_l, equation (70), and the delay between maximum voltage and electronic current, equation (72). Fig. 5 illustrates the general behavior.

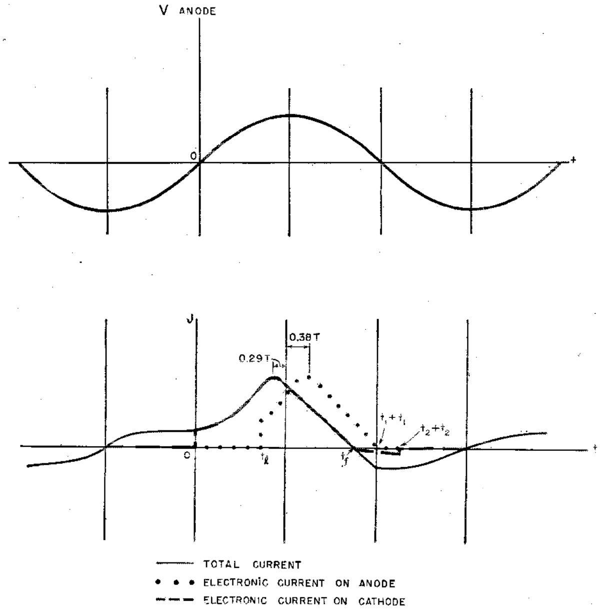


Fig. 5.

TRANSIT TIMES IN DIODES AND THEIR DISPERSION

II

Introduction

If the transit time of electrons in a vacuum tube were a constant under all conditions, it could be compensated by a convenient phase shift on the voltages applied on the electrodes. Most of the difficulties involving transit times are due to the fact that they are not constant, but differ materially for electrons leaving the cathode at different instants. This dispersion of transit times is the problem considered in the following exposition: first for a vacuum tube without space-charge and, second, for a tube with space-charge effect. The results are summarized by graphs and curves which reveal great differences in the behavior of both types of tubes.

1. Diode Without Space-Charge

If space-charge be neglected, the equation of motion of an electron is very easy to formulate. Let

$$V=V_m \sin \omega t, \tag{1}$$

$$E=-\frac{V}{d}$$

be the voltage and field E in a plane diode where the cathode-anode distance is d. Then the motion of an electron leaving the cathode ($x=0$) at t_0 is given by

$$\ddot{x}=k \sin \omega t, \quad k=-\frac{eV_m}{md}>0 \quad \text{since: } e<0$$

$$\dot{x}=-\frac{k}{\omega}(\cos\theta-\cos\theta_0), \quad \theta=\omega t, \quad \theta_0=\omega t_0$$

$$x=\frac{k}{\omega^2}[(\theta-\theta_0)\cos\theta_0-\sin\theta+\sin\theta_0]. \tag{2}$$

Assumption (1) corresponds to *class C* amplification, and the first electron to be emitted is the one leaving the cathode at $t_0=0$. We shall compute the transit times, or, preferably stated, the *transit phase angles*.

$$\theta'=\theta_d-\theta_0, \tag{3}$$

θ_d being the angle θ obtained from (2) for $x=d$, we shall select the following special cases:

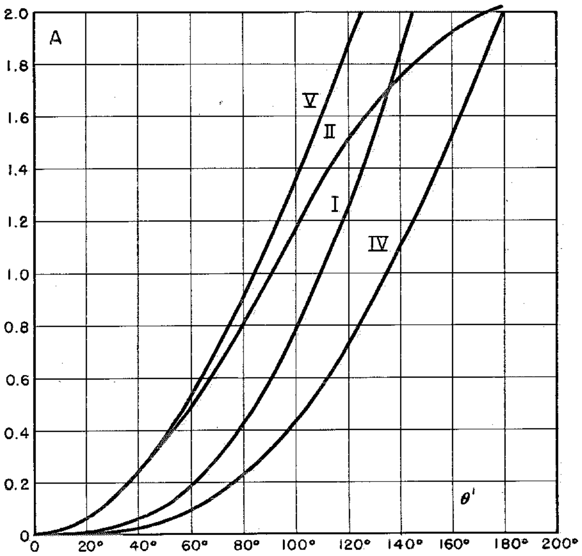


Fig. 1.

$$\left.\begin{array}{lll} \text{I.} & \text{First electron} & \theta_0=0 \\ \text{II.} & \text{Medium electron} & \theta_0=\frac{\pi}{2} \\ \text{III.} & \text{Fastest electron} & \text{giving } \theta' \text{ minimum} \\ \text{IV.} & \text{Last electron} & \end{array}\right\}. \quad (4)$$

The following parameter occurs in all cases:

$$A=\frac{\omega^2 d}{k}=-\frac{m\omega^2 d^2}{eV_m}=2\left(\frac{\omega d}{u}\right)^2$$

$$\text{with } \tfrac{1}{2}mu^2=-eV_m. \quad (5)$$

u is the velocity of an electron passing through a static potential difference V_m. A is a dimensionless parameter. Equation (2) becomes

$$A=\theta' \cos\theta_0-\sin(\theta_0+\theta')+\sin\theta_0. \quad (6)$$

I. *First Electrons: Transit Phase Angle* θ'_{I}

Equation (6) yields

$$A=\theta'_{\text{I}}-\sin\theta'_{\text{I}}, \quad \theta_{0_{\text{I}}}=0. \quad (7)$$

II. *Medium Electrons:* θ'_{II}

$$A=1-\cos\theta'_{\text{II}}, \quad \theta_{0_{\text{II}}}=\frac{\pi}{2}. \quad (8)$$

III. *Fastest Electrons:* θ'_{III}

These fastest electrons are defined by the condition

$$\frac{d\theta'}{d\theta_0}=0,$$

$$\cos(\theta'+\theta_0)+\theta'\sin\theta_0-\cos\theta_0=0. \quad (9)$$

IV. *Last Electron:* θ'_{IV}

The last electron reaches the anode with zero velocity; hence equation (2)

$$\cos\theta=\cos\theta_0,$$

which means that this electron is emitted at $\theta_0=\pi-\frac{\theta'_{\text{IV}}}{2}$ and reaches the anode at $\theta=\pi+\frac{\theta'_{\text{IV}}}{2}$. Using these values in equation (6),

$$A=-\theta'_{\text{IV}}\cos\frac{\theta'_{\text{IV}}}{2}+2\sin\frac{\theta'_{\text{IV}}}{2}. \quad (10)$$

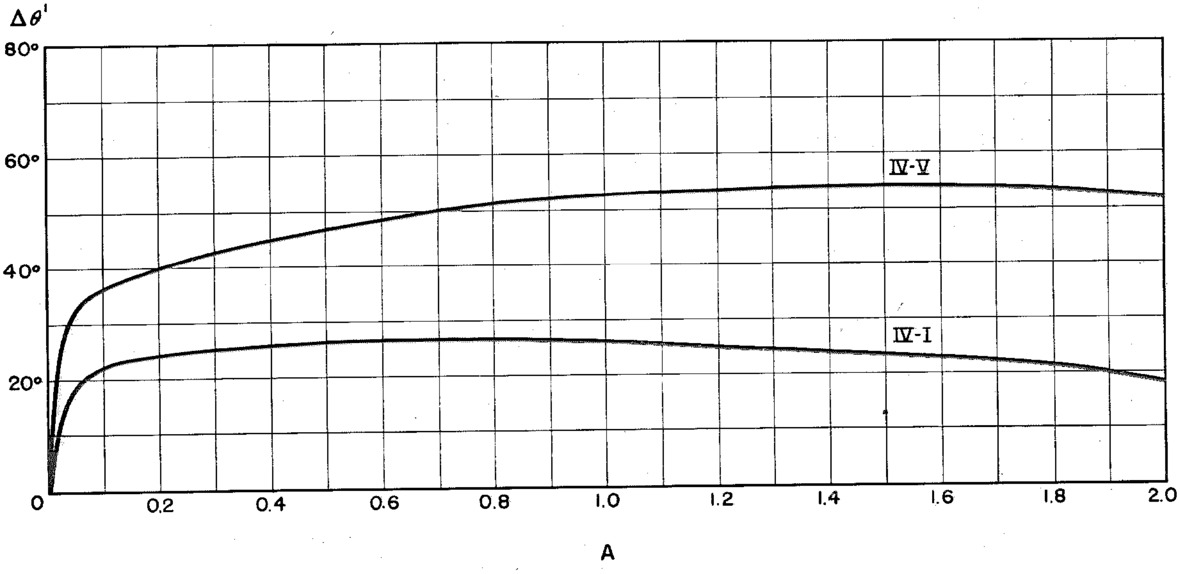


Fig. 2.

These different relations are best treated in the following way: first consider θ' as an independent variable, and draw the curves representing A as a function of θ', according to any one of equations (7), (8), (9) or (10).

These curves, with the exception of case III for which case V has been substituted as explained below, are reproduced in Fig. 1. It is easy to obtain the differences $\Delta\theta'_{\rm II}=\theta'_{\rm II}-\theta'_{\rm I}$, for instance, corresponding to any given A value, and to plot the curves representing these differences as functions of A (Fig. 2). Now, A is proportional to ω^2; hence it is only necessary to compute $\sqrt{A}$ in order to obtain the curves for $\Delta\theta'$ as functions of frequency. The method is satisfactory in cases I, II, IV, but in case III (fastest electron) the solution of the two simultaneous equations (6) and (9) is rather cumbersome. Hence, instead of discussing the ideal case III, the following one, V, has been selected: electrons leave the cathode at $\frac{\pi}{2}-\frac{\theta'}{2}$ and reach the anode at $\frac{\pi}{2}+\frac{\theta'}{2}$.

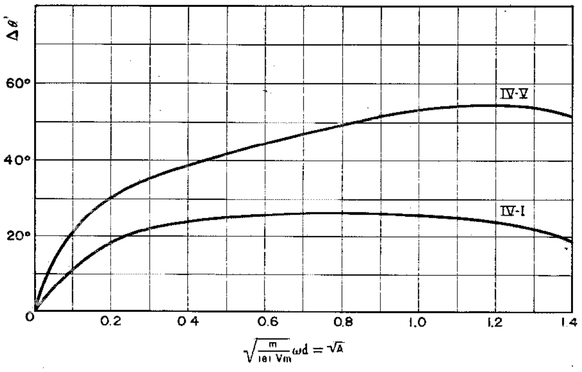
$$\text{V.} \qquad \theta_0=\frac{\pi-\theta'}{2}, \quad \theta=\frac{\pi+\theta'}{2},$$

yielding

$$A=\theta'_{\rm V}\sin\frac{\theta'_{\rm V}}{2}. \tag{11}$$

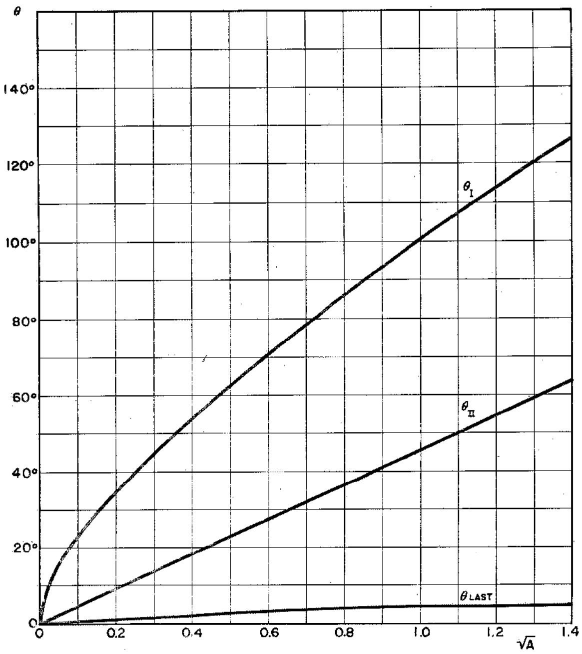
The curves of Fig. 1 represent A as a function of θ' for the different cases, and Fig. 2 shows the difference $\theta'_{\rm IV}-\theta'_{\rm V}$ or $\theta'_{\rm IV}-\theta'_{\rm I}$ as functions of A, which means ω^2. The very striking point in *both curves* of Fig. 2 is their sharp increase at the beginning, followed by a very flat maximum

$$0.2<A<1.8, \quad \theta'_{\rm IV}-\theta'_{\rm V}\approx 50°, \qquad \theta'_{\rm IV}-\theta'_{\rm I}\approx 25°. \tag{12}$$



DIODE WITHOUT SPACE-CHARGE

Fig. 3.



DIODE WITH SPACE-CHARGE

Fig. 4.

This striking feature leads to the conclusion that *tubes* with *small space-charge effects* may exhibit almost *constant efficiency for a large frequency interval corresponding* to (12).

$$0.2<\frac{m}{|e|\,V_m}(\omega d)^2<2,$$

$$0.6<\sqrt{\frac{m}{|e|\,V_m}}\,\omega d<1.4. \tag{13}$$

Such a comportment is very different from the one to be expected from tubes with large space-charge effect. Fig. 3 is a graph of $\Delta\theta'$ as a function of

$$\sqrt{A}=\sqrt{\frac{m}{|e|\,V_m}}\,\omega d.$$

2. *Diode With Space-Charge*

A theoretical discussion of space-charge effect in a diode is given in part I with resulting formulas:

First electrons (section 5, equation 70)

$$\theta_{\mathrm{I}} = \omega t_l = \left[5.2\frac{m\omega^2 d^2}{|e|U}\right]^{\frac{1}{3}} = (5.2A)^{\frac{1}{3}}, \tag{14}$$

where A is the same parameter as in equation (5) above.

Medium electron (section 5, equation 71)

$$\theta_{\mathrm{II}} = \omega T = \frac{3}{\sqrt{2}}\omega d\sqrt{\frac{m}{|e|U}} = 3\sqrt{\frac{A}{2}}. \tag{15}$$

As pointed out in part I, the most important quantity in practice is not so much θ_{II} but the phase shift between maximum voltage and maximum current. This amounts to

$$\theta_{\mathrm{VI}} = 0.38\theta_{\mathrm{II}} \approx 0.8\sqrt{A}, \tag{16}$$

according to the relation obtained in equation (72) of part I. As for the *last electrons*, we noticed that they reach the anode a very short time after the anode voltage becomes zero; hence the corresponding phase shift is negligible.

To obtain curves comparable with those of Fig. 3, the angles in degrees are measured and Fig. 4 plotted,

$$\left.\begin{aligned} \theta_{\mathrm{I}} &= 1.73\frac{180}{\pi}A^{\frac{1}{3}} \approx 100(\sqrt{A})^{\frac{2}{3}}, \\ \theta_{\mathrm{VI}} &= 0.8\frac{180}{\pi}\sqrt{A} \approx 45\sqrt{A}. \end{aligned}\right\}. \tag{17}$$

Comparison of Figs. 3 and 4 shows that the space-charge effect results in very serious increase in phase shifts, and does not exhibit any tendency towards the flat maximum of Fig. 3. It is evident, therefore, that the *efficiency* of tubes with large space-charge effect should *decrease continuously with increasing frequency.*

Errata, Vol. 22, No. 1, 1944

PLASTICS—A BRIEF REVIEW OF THEIR PHYSICAL AND ELECTRICAL PROPERTIES

The following changes should be made in the published article:

Page 72, Table II	
Coefficient of thermal expansion °C.	$3.0\text{–}3.5\times10^{-5}$
Page 73, Table III	
Volume resistivity ohms-cm.	Greater than 10^{14}
Page 77, Table XIII	
Coefficient of thermal expansion	12 to 16×10^{-5}
Page 79, Table XVII	
For modulus of elasticity psi, substitute— Tensile stress at 20% elongation psi	1100, 1100 and 1400
Page 80, Table XVIII	
Modulus of elasticity	$35\text{–}41\times10^{4}$

Complex Transmission Line Network Analysis

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Introduction

THIS paper outlines a method of reducing a complex transmission line network to a conventional transmission line circuit, permitting application of the ordinary equations with which the reader is assumed to be familiar. The method employs a number of theorems concerning the currents in co-axial and balanced transmission lines and on their shields. From these theorems the currents flowing in the lines are determined and the equivalent circuits obtained.

Grounds at U. H. F.

It must be emphasized that there is no such thing as a practical common ground at U. H. F. A ground in the lower frequency range is a line, a surface, or a volume, all points of which always remain at exactly the same potential and phase. This is not feasable when the dimensions of the line, surface, or volume approach a large fraction of a wavelength. A bus bar in a broadcast receiver, for example, can be considered a ground line, but at 100 megacycles it would be a transmission line and would no longer have the same potential at all points.

At U. H. F., instead of grounds, consideration of the equilibrium conditions that must be maintained on the transmission lines used in the circuits is required. Another important factor, as will be evident from the discussion, is the continuity of shield that must be maintained at all times in order to avoid coupling to extraneous currents.

Co-axial Transmission Line Equilibrium Conditions

The co-axial transmission line consists of a conducting wire concentrically disposed in a hollow conducting tube filled with a dielectric, which may be air. In Fig. 1 two sectional views are shown of a co-axial transmission line with three currents, I_1, I_2, and I_0, indicated in the side section. When a transmission line of this type has a shield which is well constructed, and is used above 50 megacycles, it can be assumed without loss of generality that the shield is perfect. This does not imply that it is a perfect conductor, but rather that there is no coupling between the I_0 on the outside of the shield and the interior currents I_1 and I_2. This also means that the current I_2 on the inside of the shield must be exactly equal and opposite to the current I_1 on the inner conductor. The problem in the co-axial line, as regards maintaining proper equilibrium conditions, is to prevent any coupling between the true currents I_1 and I_2 and the interfering or unbalancing current I_0 that might be induced on the outside of the shield. It is also important from power considerations to maintain constant surge impedances along the line.

The first current theorem may now be stated:

A. The current on the inside of the shield of a well shielded co-axial transmission line is equal and opposite to the current on the inner conductor.

Balanced Transmission Line Equilibrium Conditions

The balanced transmission line consists of two parallel conductors (in a dielectric) which may or may not be surrounded by a symmetrically disposed shield. For shielding purposes, all balanced transmission lines should be enclosed in a shield. Fig. 2 illustrates an end and side sectional view of such a line. In the side section are shown four currents, labeled I_1, I_2, I_3, and I_0. I_3 is the total resultant current flowing on the inside of the shield and I_0 is the total resultant current flowing on the outside of the shield. In a perfectly balanced line I_1 would be equal and opposite to I_2, and I_3 would be zero. If I_1 is not equal and opposite to I_2, then I_3 will be equal and opposite to the vector sum of I_1 and I_2. This is indicated in Fig. 3 where I_1 and I_2 are not exactly 180 degrees out of phase. Their sum is no longer zero but equal to the unbalanced current I_V flowing along the transmission lines. This I_V behaves as though it were a current flowing in a given direction along both of the transmission lines in parallel, considering them to be acting jointly as the inner conductor of a co-axial line with the return current flowing on the inside of the shield. This return current is designated as I_3. I_0 is again the extraneous current induced on the outside of the shield. The first problem encountered in maintaining the normal equilibrium conditions in a balanced transmission line is to keep I_1 equal and opposite to I_2 so that I_3 will be zero; and the second problem is to prevent I_0 from coupling into the transmission line at any point. Again from power considerations it is important to maintain the surge impedance along the line constant.

From these considerations the second theorem is obtained:

B. The current flowing on the inside of the shield of a well shielded balanced transmission line is equal and opposite to the vector sum of the currents on the balanced lines.

Continuity of Currents

In a transmission line network there can be no accumulation of current at any point in the circuit provided that the point is considered as one having no physical dimensions. This leads to the following theorem:

C. At any point in a transmission line network, the sum of all the currents flowing in and out of that point is zero.

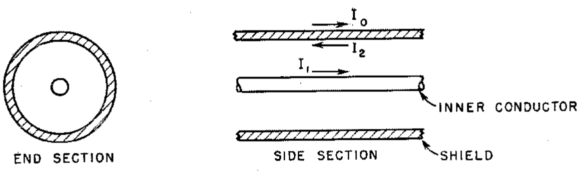


Fig. 1—Co-axial transmission line.

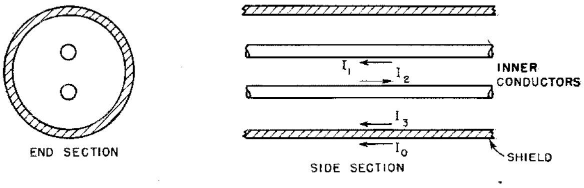


Fig. 2.—Balanced transmission line.

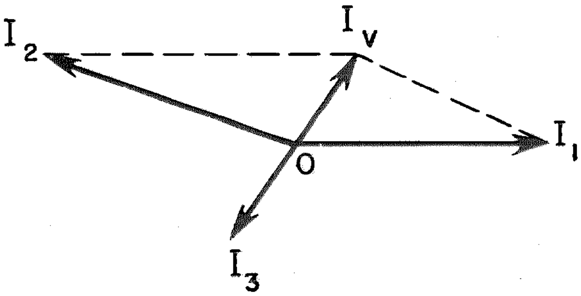


Fig. 3—Unbalanced current in a balanced transmission line.

This is an extremely valuable theorem in analyzing transmission line networks since it is thereby possible to determine whether or not an impedance is introduced in the circuit at any point. Depending on whether the current is a series current or a parallel branch current, the introduction of a series impedance or a parallel impedance is disclosed.

From the impedance concept in transmission line circuits another theorem is obtained:

D. If there are two equal and opposite currents flowing into a passive transmission line network it can be replaced by an impedance, the magnitude and phase of which may be a function of frequency.

Break in Shield of a Balanced Line

Consider the case of a break in the continuity of shield of a balanced line such as shown at S in Fig. 4. I_{1B} and I_{2B} are the currents in the lines and I_{3B} is equal to the unbalanced current. If a plane is passed through the break S then from the current theorems:

$$-I_{1B} = I_{1B'}$$

$$-I_{2B} = I_{2B'}$$

$$-I_{3B} = I_{10}$$

$$-I_{3B'} = I_{10'}.$$

Since the unbalanced current I_{3B} depends on the sum of I_{1B} and I_{2B}, and $I_{3B'}$ depends on the sum of $I_{1B'}$ and $I_{2B'}$:

$$I_{3B} = I_{3B'}.$$

From the current considerations it can be seen that the currents on the lines continue straight through but that the unbalanced shield current is directly connected to the outside of the shield.

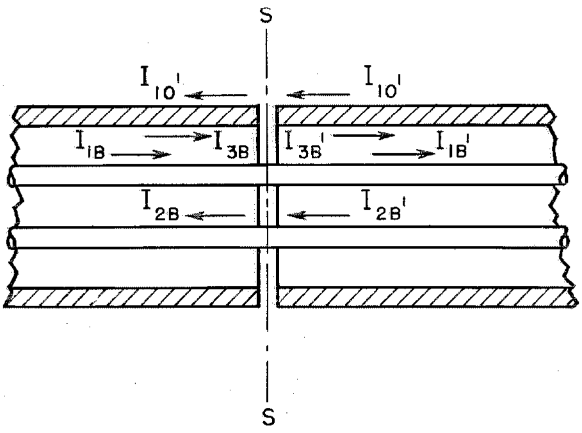


Fig. 4—Break in balanced line shield.

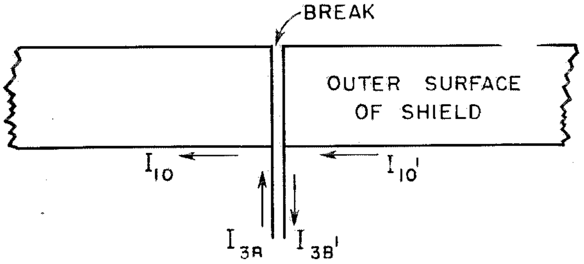


Fig. 5—Equivalent circuit of shield of Fig. 4.

In Fig. 5 is shown the equivalent circuit of the broken shield. It is an antenna made up of the outside of the shield being fed at the break by the unbalanced current. If the unbalanced current can be reduced to zero, then a break in the shield will not cause any coupling between the inside currents and the external currents. This is true since I_{3B}, and hence I_0 is zero.

Break in the Shield of a Co-axial Line

In Fig. 6 is shown a section of a co-axial line with a break in the shield at O. In this case I_{1C} and I_{2C} are the co-axial currents and I_{10} the current on the outside of the shield. From the current theorems:

$$I_{1C} = -I_{1C'}$$

$$I_{1C} = -I_{2C}$$

$$I_{1C'} = -I_{2C'}$$

$$I_{2C} = -I_{10}$$

$$I_{2C'} = -I_{10'}$$

$$I_{10} = -I_{10'}.$$

Between the points B and C the equal and opposite currents I_{10} and $I_{10'}$ can be considered as an effective two-terminal impedance. The equal and opposite currents $I_{2C'}$ and $I_{1C'}$ can also lead to an impedance between A and C.

This results in the equivalent circuit shown in Fig. 7 where $I_{2C'}$ and $I_{1C'}$ are considered to be feeding a matched line of surge impedance Z_0. Thus the break in the shield introduces a series antenna made up of the outside of the shield being fed at the break by the co-axial current itself. A break in the shield of a co-axial line always introduces unity coupling between the outside currents and the co-axial line currents.

Analysis of Shielded Loop

In Fig. 8 is shown a section of a shielded loop of mean diameter D which consists of a wire inside of a shield with the shield broken at the top of the loop at the point AA'. The loop is thus composed of two co-axial lines running between the points B and A and between the points B and A'. At the point B we have two currents I_{1B} and I_{2B} which are the currents in the balanced line entering the loop. I_{1B} continues at the point B to become I_{1C} and I_{2B} continues to become the current I_{3C}. I_{1C} will have an equal and opposite current flowing along the inside of its shield, shown as I_{2C}. I_{3C} will have an equal and opposite current flowing along its shield, shown as I_{4C}. If there is any difference between the currents I_{1C} and I_{3C} it will result in an unbalanced current I_{3B} flowing along the inside of the balanced shield. For I_{3B} to be zero it must be shown that I_{1C} is equal to I_{3C}. If the break in the loop is located at the center and if it is shown that the co-axial currents are equal at AA', it can be assumed that the currents I_{1C} and I_{3C} at B will be equal so that no unbalanced current I_{3B} will flow.

First, at A, I_{5C} flows into the break with an equal and opposite current I_{6C} flowing on the inside of the shield. However, at the point A there is also a current I_{10} flowing outside the shield. Then, in accordance with Theorem C, I_{10} must equal I_{6C}. If the break is very small I_{5C} will be equal to the current shown as I_{7C}. (Any stray capacity coupling is neglected.) The inner shield current in equilibrium with I_{7C} is noted as I_{8C}, and it is observed that A' I_{8C} must equal the external current I_{20}. Thus, the following equalities obtain:

$$I_{5C}=-I_{6C}$$

$$I_{7C}=-I_{8C}$$

$$I_{6C}=-I_{10}$$

$$I_{8C}=-I_{20}$$

Therefore, $I_{10}=-I_{20}$.

Thus, as long as I_{5C} has no place to flow other than to I_{7C}, it will force a balance of I_{10} and I_{20}. This means that if any similar parallel currents flow up the shield, such as currents that might be induced by mast effect, they will encounter a very high impedance at the break AA' and consequently no current will flow beyond the break. On the other hand, the current induced in the loop will be a circulating current wherein I_{10} will be equal and opposite to I_{20}. This induced loop current will therefore be unity coupled to the wire within the shield. In this manner the loop discriminates between the power picked up by the loop and the power pickup by the mast and loop acting as a vertical antenna.

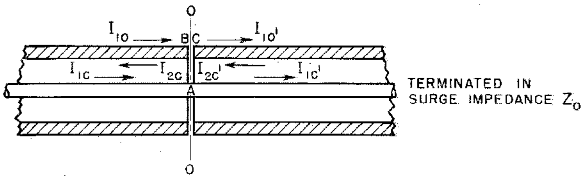


Fig. 6—Break in co-axial transmission line shield.

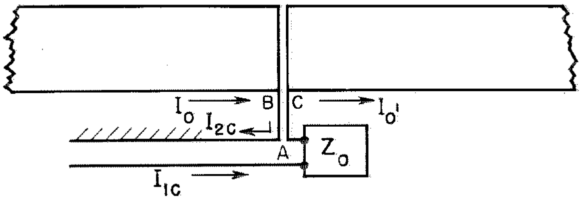


Fig. 7—Equivalent circuit of Fig. 6.

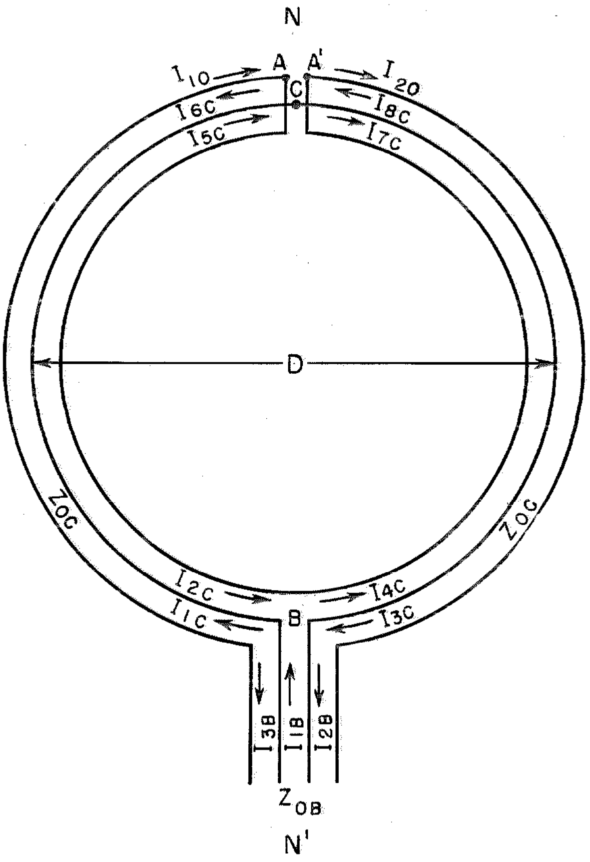


Fig. 8—Section balanced loop showing currents.

The Equivalent Circuit of the Shielded Loop

In order to obtain the equivalent circuit of the shielded loop shown in Fig. 8, a neutral plane $N-N'$ should be passed through the center line of the loop. This simplification can always be used with a perfectly symmetrical circuit such as the shielded loop. Fig. 9 illustrates the equivalent circuit. The balanced line carrying the current I_{1B} joins the co-axial line carrying the current I_{1C} at the point B. The co-axial line then extends for a length equal to half the circumference of the balanced loop which is $\pi\frac{D}{2}$.

At the end of the co-axial line which is at point A, the impedance Z_A is joined to the co-axial line. It is directly coupled since, as shown in Fig. 8, I_{10} continues directly to become I_{6C}. Thus, between the points A and C, half the impedance of the antenna exists. A similar analogy can be drawn for the other half of the loop.

The impedance of the loop antenna itself is the impedance across AA' of the loop measured with the inner conductor removed. This impedance is thus placed at the end of a "twin co-axial" type of balanced transmission line which has a characteristic impedance of twice

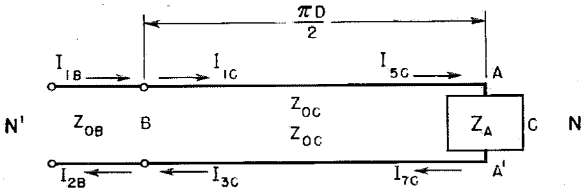


Fig. 9—Equivalent circuit of Fig. 8.

Z_{0C} where Z_{0C} is the surge impedance of each co-axial line. The balanced connecting line is joined to this twin line at the point B.

Complex Networks

In Fig. 10 is shown a complex network joining two transmission lines of surge impedance Z_0. The far end of the transmission line is terminated in its surge impedance Z_0. It is desired to find the input impedance at the point J at a distance L_1 from the break in the inner shield. The break in the inner shield couples the input transmission line to a co-axial transmission line whose inner conductor is the shield of the input line and whose outer conductor is a large shielding cylinder. This "outer" transmission line has a surge impedance Z_{01}. At a distance L_4 from the break in the shield, the transmission line of surge impedance Z_0 is joined to the outer line. The effect of the discontinuity caused by the change in size is neglected. It is now necessary to set up the continuity of currents at points A, B, C and D. At the point A a current of I_{1A} is entering while a current of I_{1B} is leaving. At the point B two currents exist, I_{2A} and I_{1C}. At the point C there are also two currents, I_{2B} and I_{1D}. At the point D the currents are I_{2C} and I_{20}. Across the points FG a resistive load of value Z_0 is presented to the "outer" line since it is connected to a terminated transmission line of surge impedance Z_0.

The following equalities exist:

$$I_{1A} = -I_{1B}$$

$$I_{2A} = -I_{1C}$$

$$I_{2B} = -I_{1D}$$

$$I_{2C} = -I_{2D}$$

$$I_{1A} = -I_{2A}$$

$$I_{1B} = -I_{2B}$$

$$I_{1C} = -I_{2C}$$

$$I_{1D} = -I_{2D}.$$

It is now necessary to set up an equivalent circuit with current relationships as indicated above. From Fig. 10 it follows that AEC is a short-circuited line of length L_3 and BHD is a short-circuited transmission line of length L_2. Fig. 11 shows the equivalent circuit. Point J to point A represents a transmission line of surge impedance Z_0. Across AC there is a reactance made up of a shorted transmission line of length

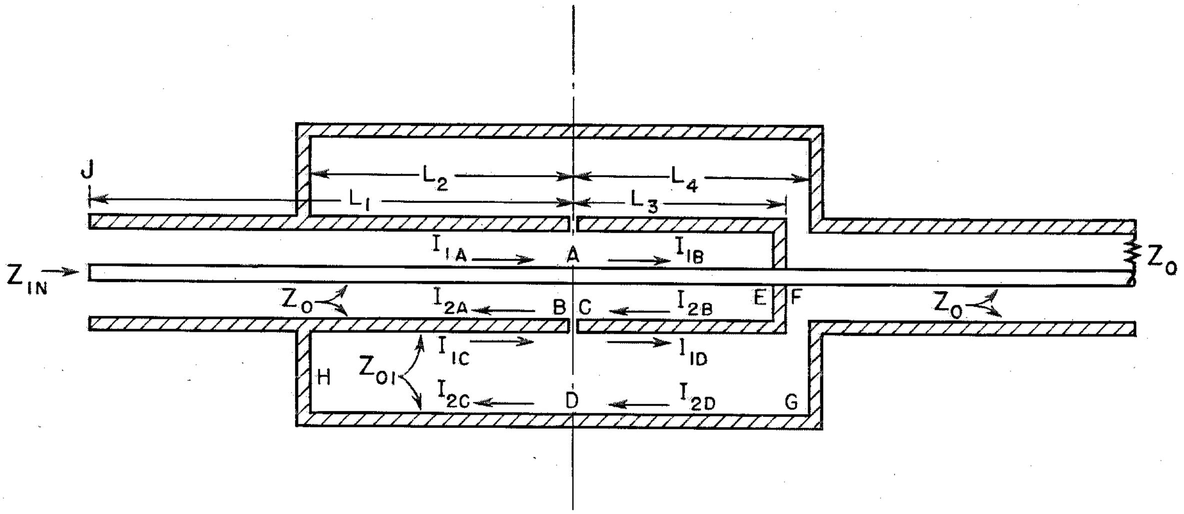


Fig. 10—Complex network.

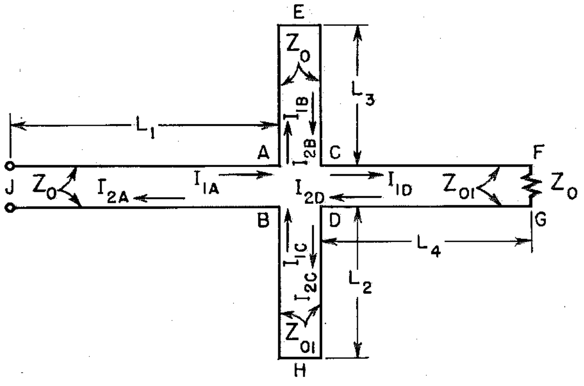


Fig. 11—Equivalent circuit of Fig. 10.

L_3 and surge impedance Z_0; across *BD*, a shorted transmission line of length L_2 and surge impedance Z_{01}; and across *CD*, a transmission line of surge impedance Z_{01} and length L_4 that is terminated in a pure resistive impedance of Z_0 at the point *FG*. This is true because the input impedance of a properly terminated transmission line can be considered to consist of a pure resistance of the value Z_0 which is its surge impedance.

Fig. 12 shows a simplified form of Fig. 11 where the input impedance is calculated for a transmission line of length L_1 with a surge impedance of Z_0. This transmission line in the equivalent circuit is terminated at the points *AB* in three series impedances: the input impedance of the shorted transmission line *AEC*, the input impedance of the shorted transmission line *BHD*, and the input impedance of the transmission line *CFGD* terminated in a resistive impedance Z_0. From this figure the input impedance at *J* may be calculated.

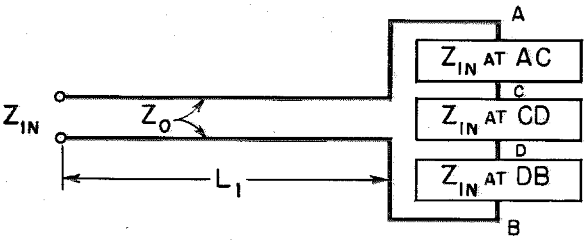


Fig. 12—Simplified equivalent circuit of Fig. 10.

Summary

This type of analysis of a complex network allows the insertion of all continuity currents in the network with the use of the equilibrium constants of balanced and co-axial transmission lines stated in the theorems. The equivalent network should then be set up in simplified form wherein the same current relationships must hold. If such is not the case, the circuits are *not* equivalent. Once the equivalent transmission line network is obtained, lumped constants using the transmission line formulae can easily be substituted.

Cathodic Protection and Applications of Selenium Rectifiers

By W. F. BONNER

Federal Telephone and Radio Corporation, Newark, New Jersey

THE principles of galvanic corrosion have long been known. They are, briefly, that any metal, such as a steel pipe or a lead cable sheath or a storage tank, when placed in contact with an electrolytic substance like soil or water, sets up a flow of current similar to that which occurs inside a dry battery. A number of electric circuits are thus created which may follow varied and unpredictable courses through the electrolyte: from the wall of a buried oil or gas pipe line to a fitting of dissimilar metal; from a power or telephone cable to an adjacent conducting structure; between points in contact with different kinds of soil, etc. A few examples are shown in Fig. 1. There are also situations in which currents are caused to flow from an underground structure as the result of stray currents from nearby electric railway systems. In either case, minute quantities of the metal continuously leave the pipe or sheath at points where the current emerges from the metal (the anodes). This causes pitting and wearing away of the metal at these areas with subsequent failure of pipe or cable.

Cathodic Protection

The obvious way to combat corrosion of the metal at anodic points is to cause a reversal of the current, making the entire area which it is desired to protect cathodic instead of anodic. One way to do this is to establish in contact with the metal to be protected a galvanic anode of a metal which is higher in the electromotive series. Zinc, being higher on the galvanic scale than iron, makes the iron cathodic and has been utilized for this purpose since the middle of the last century, although it is now largely confined to the protection of the hulls of marine vessels. Moreover, it has been found that the most efficient and economic method of countering the corroding current is to cause a direct current to flow from an outside source, through the metal and the electrolyte, in the opposite direction so that the net effect is to make the contacting soil or water anodic and the structure to be protected cathodic, thus entirely eliminating the loss of metal in the area.

This practice, known as cathodic or counter-electrolysis protection, has been in common usage on petroleum pipe lines since 1910 or thereabouts, and it has also been successfully applied to a considerable variety of other structures. Obviously, a continuous and permanent source of low voltage direct current is needed for the operation of a cathodic protection installation. Throughout the development of the art, various types of current sources have been utilized: motor generator sets or copper oxide rectifiers associated with available alternating current; direct current generators operated by internal-combustion engines, sometimes in conjunction with storage batteries, and similar expedients. In remote locations, in the absence of a power line, windmills have been used to operate small direct current generators.

Advantages of Selenium Rectifiers

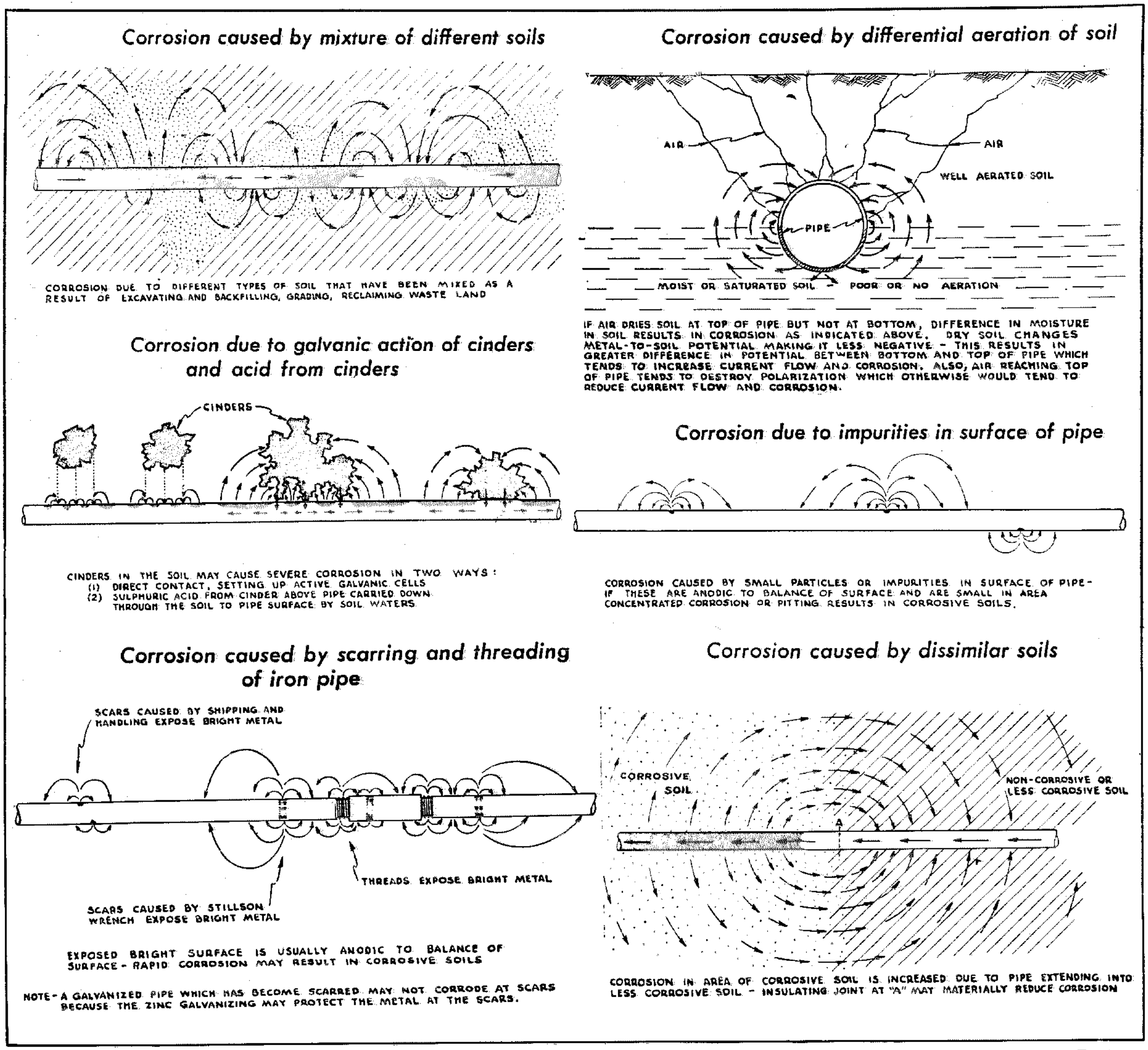
There are, however, certain problems which continually arise, such as the maintenance of generators in places difficult of access, fluctuation of current from variation of temperature, and variation of current needed due to change in moisture content of the soil with consequent loss of efficiency of some rectifier units. All of these problems have not always been solved by the devices previously in use.

These difficulties have largely been overcome by the use of Selenium Rectifiers as a current source. They may be enclosed in units which are light, compact, portable and suitable for pole mounting and similar applications. Furthermore, their operation is substantially uniform even though subjected to the wide temperature fluctuations encountered in outdoor use, as shown by the temperature curve in Fig. 2. Moreover, the efficiency of Selenium Rectifiers remains substantially constant through comparatively large load variations (see Fig. 3), thereby keeping at a minimum power losses due to seasonal or other changes in current requirements. Advantageous also is absence of moving parts, obviating the necessity of frequent maintenance check-ups; and, now that power lines have been extended by the Rural Electrification Administration to substantially every cross-road throughout the nation, Selenium Rectifiers can be utilized to produce direct current for cathodic protection on an increasing variety of structures. A unit embodying Selenium Rectifiers suitable for outdoor use is shown in Fig. 4.

Protection of Buried Structures

The applications of cathodic protection may be considered under two general headings: protection of buried structures from corrosion by soil, and protection of structures from corrosion by water and other liquids.

In the former case, it is necessary to force the current into the earth, from the earth into the metal to be protected, and return it to the source. Fig. 5 shows the conventional method. Contact with the earth is made by burying scrap metal, such as rails or pipe, or carbon rods, a calculated



Corrosion caused by mixture of different soils

CORROSION DUE TO DIFFERENT TYPES OF SOIL THAT HAVE BEEN MIXED AS A RESULT OF EXCAVATING AND BACKFILLING, GRADING, RECLAIMING WASTE LAND

Corrosion due to galvanic action of cinders and acid from cinders

CINDERS IN THE SOIL MAY CAUSE SEVERE CORROSION IN TWO WAYS:
(1) DIRECT CONTACT, SETTING UP ACTIVE GALVANIC CELLS
(2) SULPHURIC ACID FROM CINDER ABOVE PIPE CARRIED DOWN THROUGH THE SOIL TO PIPE SURFACE BY SOIL WATERS

Corrosion caused by scarring and threading of iron pipe

EXPOSED BRIGHT SURFACE IS USUALLY ANODIC TO BALANCE OF SURFACE - RAPID CORROSION MAY RESULT IN CORROSIVE SOILS

NOTE - A GALVANIZED PIPE WHICH HAS BECOME SCARRED MAY NOT CORRODE AT SCARS BECAUSE THE ZINC GALVANIZING MAY PROTECT THE METAL AT THE SCARS.

Corrosion caused by differential aeration of soil

IF AIR DRIES SOIL AT TOP OF PIPE BUT NOT AT BOTTOM, DIFFERENCE IN MOISTURE IN SOIL RESULTS IN CORROSION AS INDICATED ABOVE. DRY SOIL CHANGES METAL-TO-SOIL POTENTIAL MAKING IT LESS NEGATIVE - THIS RESULTS IN GREATER DIFFERENCE IN POTENTIAL BETWEEN BOTTOM AND TOP OF PIPE WHICH TENDS TO INCREASE CURRENT FLOW AND CORROSION. ALSO, AIR REACHING TOP OF PIPE TENDS TO DESTROY POLARIZATION WHICH OTHERWISE WOULD TEND TO REDUCE CURRENT FLOW AND CORROSION.

Corrosion due to impurities in surface of pipe

CORROSION CAUSED BY SMALL PARTICLES OR IMPURITIES IN SURFACE OF PIPE - IF THESE ARE ANODIC TO BALANCE OF SURFACE AND ARE SMALL IN AREA CONCENTRATED CORROSION OR PITTING RESULTS IN CORROSIVE SOILS.

Corrosion caused by dissimilar soils

CORROSION IN AREA OF CORROSIVE SOIL IS INCREASED DUE TO PIPE EXTENDING INTO LESS CORROSIVE SOIL - INSULATING JOINT AT "A" MAY MATERIALLY REDUCE CORROSION

Courtesy of *The Petroleum Engineer*

Fig. 1—Electrolytic corrosion.

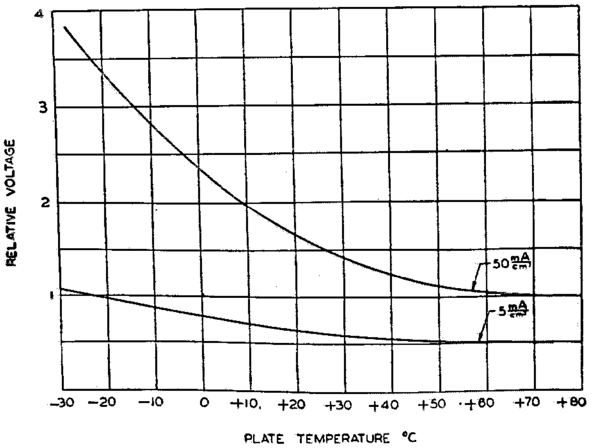


Fig. 2—Voltage change with temperature for full load and one-tenth full load. (Inasmuch as the resistance of the rectifier is usually only about 10% of the circuit resistance, the change in voltage drop in the rectifier is usually negligible, being largely compensated for by decreased copper resistance at low temperatures.)

distance from the structure. Direct current is applied with the positive terminal connected to the ground bed. The purpose is to cause the direct current to flow through the soil to all exposed portions of the pipe, thereby making the soil anodic wherever it contacts the metal.

Pipe Lines

The most extensive use of cathodic protection at present is to prevent corrosion of petroleum pipe lines. In 1942 there were at least 3,000 miles of protected lines employing over 750 cathodic units. Current sources in some instances included generators driven by internal-combustion engines or windmills in inaccessible localities, but, with the almost universal extension of power lines to remote places, the most convenient source of d-c is now Selenium Rectifiers operating from the local a-c power supply, because of their ease of transportation and the fact that they may be left on location for long periods of time without maintenance. The amount of current required varies considerably but in general depends mainly on: (1) state of insulation on the pipe and area of exposed metal, (2) soil conditions, and (3) kind of metal in the structure to be protected. These and other factors can be determined only by trained personnel, and a survey should be made for each installation. It is to be noted that structures that are installed with some protective coating still need cathodic protection, due to the fact that minute breaks in the coating are likely to result in a concentration of corrosive anodic currents at the breaks and rapid failures at these points. Efficient coating, however, does greatly reduce the amount of current needed for protection.

Tank Farms and Refineries

Cathodic protection is also successfully utilized at tank farms, where the corrosion of storage tank bottoms is an economic problem of importance. The map of Fig. 6 illustrates a typical installation. Here a considerable surface of metal requires protection due to the dimensions of the tanks and the interconnecting pipe lines. Concentration of surfaces over a comparatively small territory, however, makes it possible to distribute the power units and anodic ground beds evenly and economically; further, an appreciable saving can be effected by judicious selection of the number and distribution of the units. While the large metallic surface to be protected by each unit requires a comparatively heavy flow of current, commercial power at most locations is available and needs only to be rectified. For this purpose Selenium Rectifiers possess the advantage, over other protective devices, that they require practically no maintenance so that their efficient

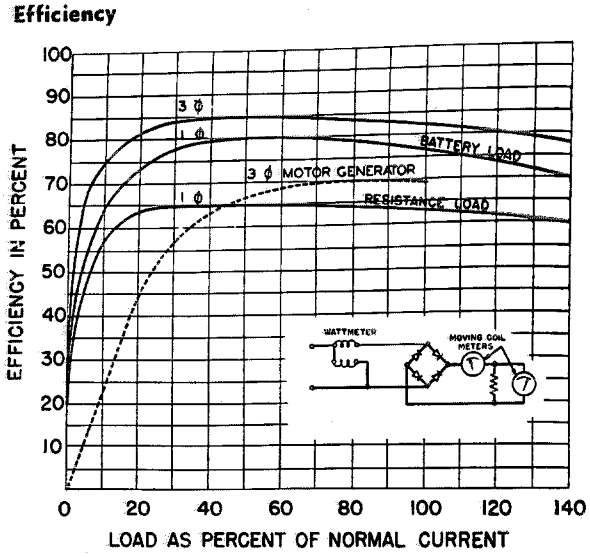


Fig. 3—Efficiency of Selenium Rectifier operating at full load voltage compared to average typical efficiency of a motor generator set with exciters.

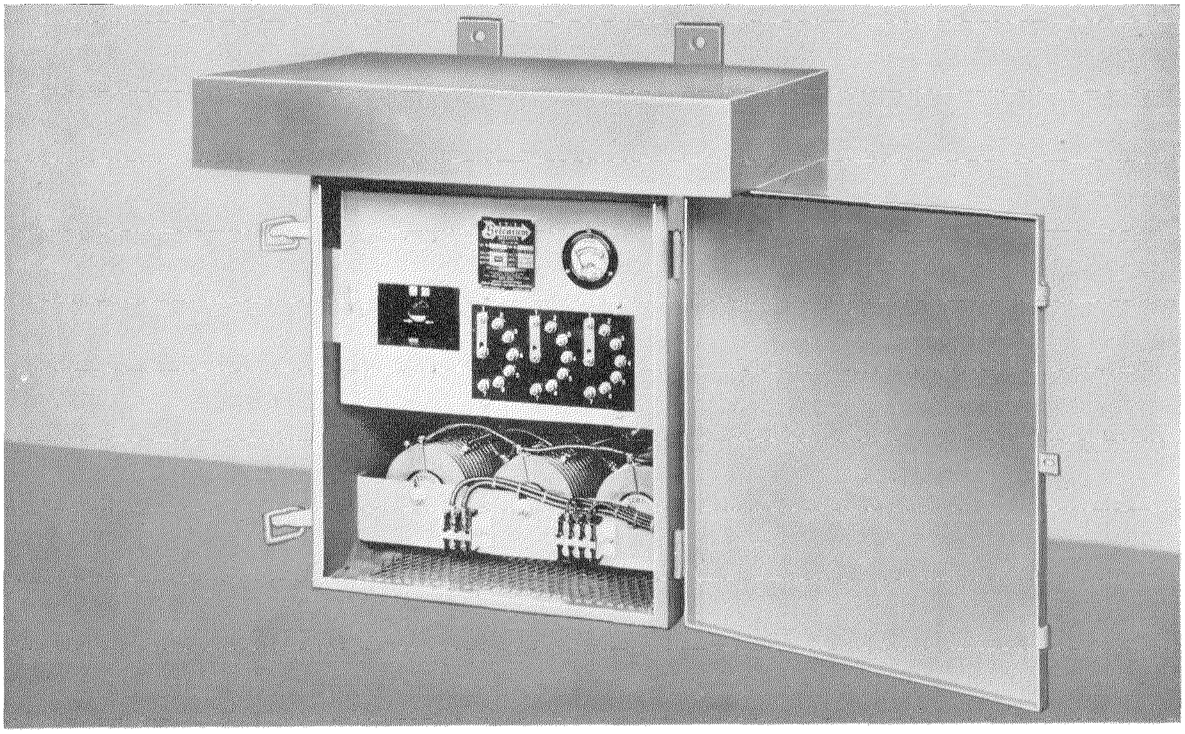


Fig. 4—Federal cathodic protection rectifier.

operation is not dependent on the availability of a permanent maintenance force at the tank farms. Any power used at tank farms for cathodic protection is usually supplementary; hence it can be classed as marginal and therefore used at the lowest step of the prevailing rate schedule. Thus the expense of periodically reconditioning each tank bottom can be eliminated at a reasonable fixed charge.

A similar situation prevails where cathodic protection is applied to the protection of underground structures of refineries. D. Holsteyn, in a description of the installation in the Shell Oil Company refinery at Deer Park, Texas,[1] states that steel equivalent to 600 miles of 4-inch pipe line is buried in an area approximately one mile by half a mile. Locations for anodic ground beds, etc., were determined as the result of an extensive survey of ground conductivity and other factors, and Mr. Holsteyn estimates that the complete period for amortization of the cost of installation of the units by savings due to corrosion prevention is 10.6 months (see Fig. 7). The success and economy of cathodic protection on the underground piping in the refinery proper has caused the program to be extended to other areas. Owing to their high efficiency over a wide range of current requirements, Selenium Rectifiers render very satisfactory service in refinery installations.

City Networks

In city networks, even in crowded quarters, cathodic protection can be utilized effectively to protect gas and water distribution lines. In New Orleans, for instance, it has been in use for many years on high pressure gas transmission and distribution lines in the city and outlying area, and also on a steel low-pressure gas distribution network in the city proper. These lines are laid in wet sand muck in an area which is poorly drained and which was formerly a cypress swamp subject to tidal overflow, so that protection against corrosion was necessary. Many details such as the design and position of insulating joints, location of anodic ground beds, location of feed lines, etc., had to be carefully

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[1] *Petroleum Refiner,* June 1943.

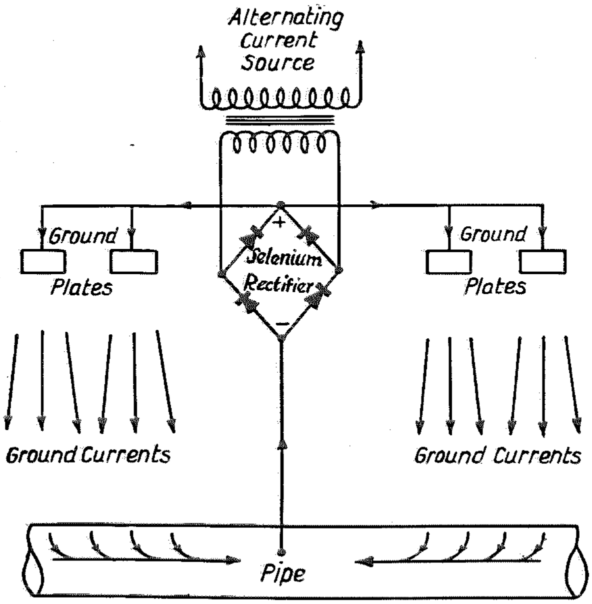

Fig. 5—Schematic diagram of cathodic protection applied to buried pipe.

worked out; also, under crowded city conditions, the presence of stray currents and similar elements had to be considered. Near-by costly telephone, telegraph and power cables, which might become disrupted by small earth currents, necessitated a careful survey; otherwise, not only would the cathodic protection installation be ineffective but it might cause damage to other structures. Selenium Rectifier units provide a convenient direct current source under city conditions because their compactness enables them to be mounted near the points of application, thereby reducing direct current line losses.

Aqueducts

On large water lines or aqueducts, problems similar to those of petroleum pipe lines are encountered with the exception that the larger diameter of the lines presents more surface requiring protection. On the Mokelumme Aqueduct in California cathodic protection has been installed and H. A. Knudsen, mechanical and electrical engineer for the East Bay Municipal Utility District, Oakland, California, produced figures leading to the conclusion that for a total cost of $85 per mile, a saving of about $1,300 per mile per year results.[2] As to power, the public service power (60-cycle, single-phase, a-c) was used, and Mr. Knudsen says in part, regarding Selenium Rectifier units: "The operating characteristics of this unit are excellent for cathodic protection. No service of any kind has been required, and the efficiency is on a par with motor-generator sets."

Telephone Cable Sheaths

Buried telephone cables are sometimes protected by cathodic protection, mainly in locations where stray currents exist. The source of these currents is utilized for this protection by means of a drainage wire attached to the sheath and to the negative line of the source. A unit employing a half-wave Selenium Rectifier, functioning as an electrolysis switch, may be positioned between the cable and the line to protect the sheath from becoming anodic during occasional current reversals. In practice this protection is applied only to the extent necessary to reasonably mitigate the effects of such stray currents. Corrosion on the cable sheaths is thereby avoided and, at the same time, corrosion effects on other underground structures not employing cathodic protection may be reduced. Selenium Rectifier units also may be used as boosters to increase the current drain from ordinary drainage wires.

Protection of Submerged Structures

The application of cathodic protection to prevent corrosion of structures submerged in liquids sets up different problems from its application in soil, but the problems are, at the same time, capable of more precise solution since the liquids involved are apt to be more homogeneous than soil. Laboratory tests can, therefore, be run to ascertain certain factors pertinent to an installation in order to achieve maximum efficiency regarding flow of current and the number and distribution of electrodes.

For a particular installation it is necessary to ascertain: (1) the minimum current necessary to protect one unit area of the surface on which

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[2] *Journal of the American Water Works Association*, Jan. 1938.

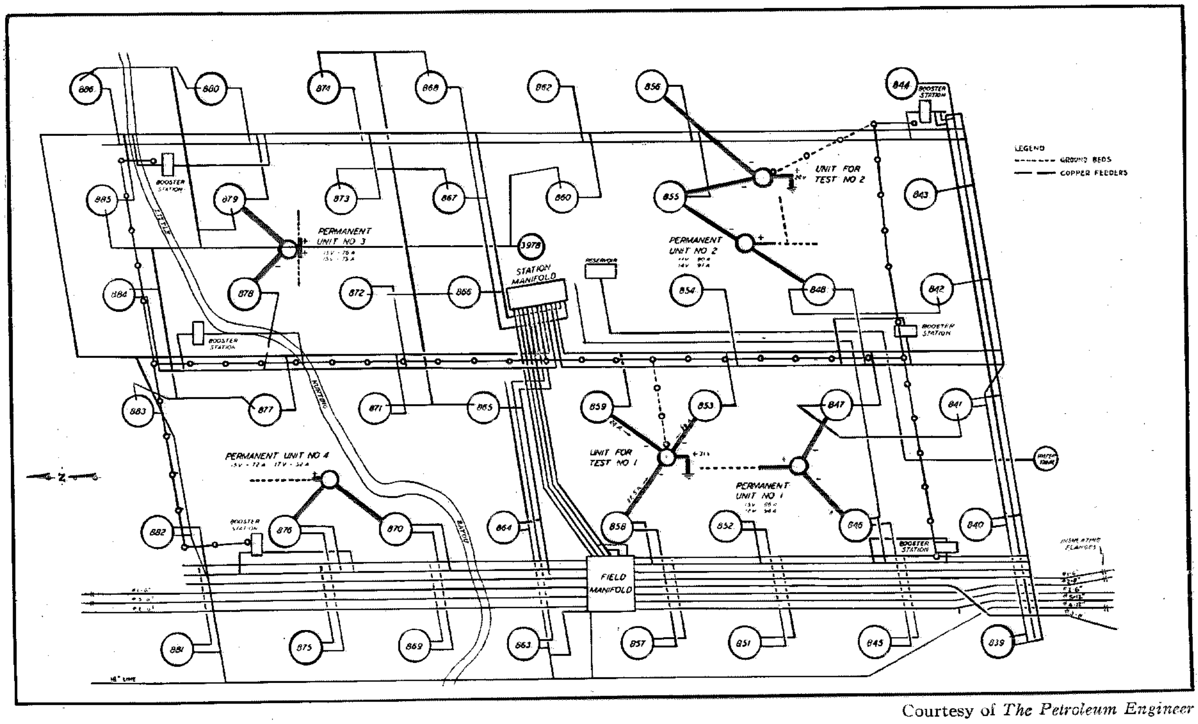
corrosion is to be prevented, and (2) the voltage needed to force this current through the liquid (computable from the resistance of the liquid). Both these figures may be obtained in the laboratory, utilizing samples of the liquid and the metal involved. Various other devices, such as calomel cells and exploring electrodes of different types, may also be used on the installation itself to determine the current needed to provide adequate protection.

General agreement on testing methods has not yet been reached. Nevertheless the state of the art is sufficiently well advanced for the design of numerous and varied types of installations with satisfactory results.

When the above data are known, the problem of distribution of the anodic electrodes arises. For efficient protection, it is necessary to cause a current of the minimum protective amperage to flow into the portion of the protected metal furthest away from the anode, and at the same time avoid having to send a wastefully excessive current to points nearer the anode. It is obvious that the highest efficiency would result with the anode equidistant from all points of the cathodic surface, but, of course, this condition rarely obtains in practical applications. The anode position should be such that the difference between its distance to the nearest and furthest cathodic surfaces is as small as possible.

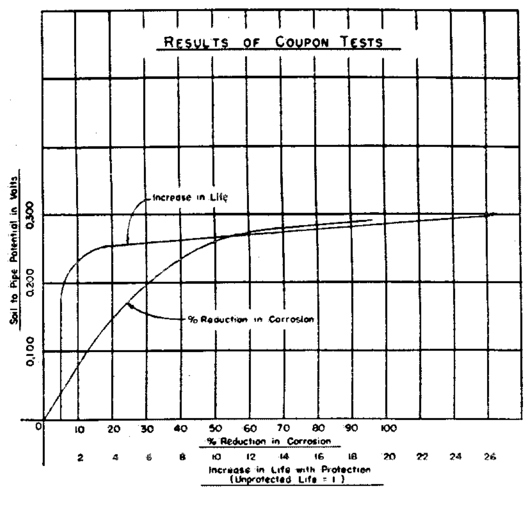
Open-Tank Condensers

This principle is illustrated by the application of cathodic protection on open-tank condensers in oil refineries where expensive corrosion occurs on the submerged coils. The anodes used consist of sets of steel plates (sometimes carbon rods) submerged vertically in the condenser tanks, extending down close to the bottom. The plates are suspended from horizontal beams or pipes which rest on insulating supports. Positive busses run to the supporting beams, the negative busses being connected to the tank and the headers of the coils. All connections are soldered or welded. Current requirements are usually about five to ten amperes per square foot of exposed tank and coil surface. Here again Selenium Rectifier units are particularly suitable for use as a d-c power source because they take up little space in the refinery and are readily adjustable to the re-



Courtesy of *The Petroleum Engineer*

Fig. 6—Map of cathodically protected tank farm.



TEST DATA

Coupon Group Number	Weight Loss in Grams (Unprotected)	Weight Loss in Grams (Protected)	Soil to Pipe Potential in Volts	% Reduction in Corrosion	Increase in Life with Protection (Unprotected Life = 1.0)
1	1.025	0.039	0.300	96.2	26.2
2	0.722	0.057	0 271	92.1	12.7
3	0 435	0.295	0 228	32.2	1 5
4	0.905	0 740	0 120	18.2	1.2

Courtesy of *The Petroleum Refiner*

Fig. 7—Effect of cathodic protection on buried structures in refinery, as shown by coupon tests.

quired current without appreciable loss of efficiency.

A refining company in Michigan has had an installation of this type in service since late 1938 in its 6,000 square foot distillate condenser box. Prior to that time the coils had to be replaced at intervals of approximately eight to nine months, but at the time reported (July, 1941) the coils in use when cathodic protection was applied were still in good condition.

An oil corporation in California likewise has had several installations operating successfully for about two years on its 50,000-barrel plant. It is reported that corrosion seems to be checked; also, that better heat transmission results through elimination of hard-scale formation on the tubes.

Shell-and-Tube Condensers

Cathodic protection has also been applied to shell-and-tube condensers. Here the anodes consist of steel plates positioned on the ends of insulated pipe couplings which protrude into the condenser shell. An installation of this type was reported to have been in operation for 15 months without a tube failure[3] whereas, previously, failures occurred every three to six months.

Submarine Pipe Lines

Cathodic protection is used successfully on submarine pipe lines. The Southern Counties Gas Company has such an installation on their Cerritos Channel pipe line crossing where rectified current is used. Tests were run in 1939 to ascertain the amount of current needed, and it was concluded that the average potential required for protection of bare steel in sea water was 0.5 volt, with the average current about 15 milliamperes per square foot of pipe surface. It was also found that a bare steel surface receiving cathodic protection in sea water becomes coated with a fairly hard salt which gradually reduces the current density needed for complete protection. Enclosed Selenium Rectifier type units lend themselves readily to water-side installations due to their ability to resist atmospheric corrosion.

Hot Water Heaters

Hot water heaters and similar structures also utilize cathodic protection to eliminate corrosion of tubes and also to decrease the formation of scale. Such an installation is actually an amplification and extension of the idea of hanging zinc plates inside a boiler to decrease corrosion, a practice introduced more than 50 years ago. The anodes need not be inside the structure proper but may be placed in inlet tanks or other containers in direct contact with the water flowing through the structure. Such an installation was made in 1937 at a large New York milk plant which used artesian water high in calcium content. Not only was corrosion checked and further deposit of scale prevented, but the scale already in the tubes gradually disappeared.

Water Tanks

The use of cathodic protection in water tanks for railroads, municipalities, factories and other

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[3] V. L. Nealy, *National Petroleum News*, June 25, 1941.

organizations started about 1936 and, at the last report (1941), there were over 1,000 installations completed or on order. Fig. 8 illustrates a scheme utilizing one or more electrodes suspended inside the tank, the electrodes usually being composed of stainless steel or carbon. It has been determined that, to keep a steel water tank from rusting, a potential must be applied from an external source which is in excess of the natural hydrogen overvoltage potential; also, to maintain this potential, the voltage drop through the water must be estimated so that the proper e.m.f. can be applied. Maintenance of a current flow of three amperes for every 10,000 square feet of submerged surface of metal requiring protection has been found necessary.

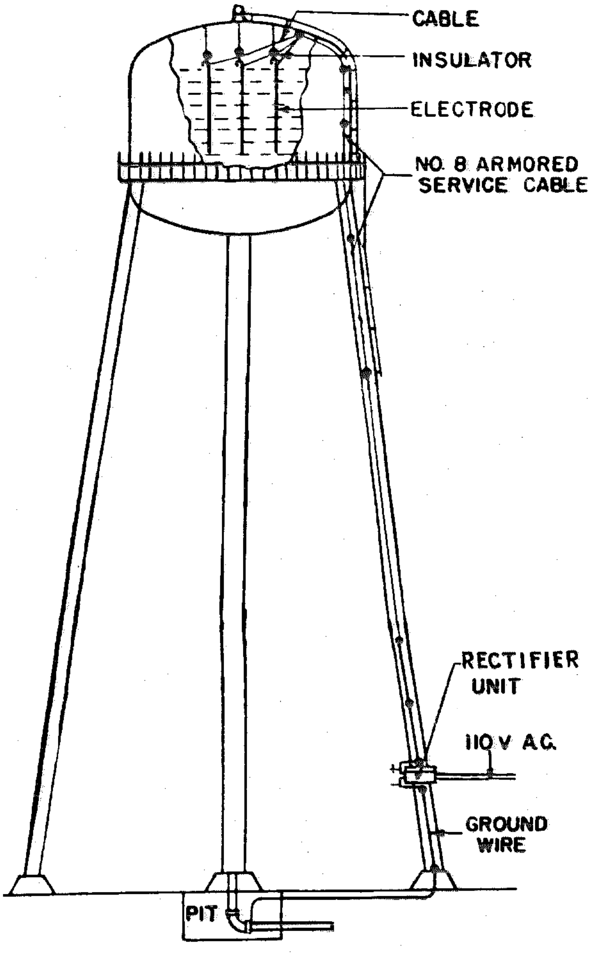

Fig. 8—Cathodic protection applied to water tank.

The cost of installation is usually reported to be less than that of painting the interior of the tank, and operating expenses are low. The high efficiency of Selenium Rectifiers constitutes a factor in keeping current consumption down. A big advantage is the substantial elimination of expensive shutdowns for repainting the interiors of tanks, which may be necessary as often as twice a year for unprotected tanks. Replies to an inquiry sent out by the Pittsburgh-Des Moines Steel Company to owners of all tanks built by them in six years,[4] showed cathodically protected tanks 73 percent fully satisfactory, 13 percent questionable, and 14 percent unsatisfactory.

Future of Cathodic Protection

In general, it may be said that cathodic protection is an effective check to electrolytic corrosion in a wide variety of structures. Its applications have naturally become more highly developed in connection with structures where such corrosion is an economic factor of considerable magnitude, but the convenience and economy of Selenium Rectifiers would indicate that an extension of the field to include many structures where cathodic protection has not hitherto been contemplated is probable. For instance, cathodic protection may be applied with effectiveness and economy to buried gasoline tanks, consumers' oil tanks, etc. Home owners and oil burner manufacturers may adopt this method of combatting the electrolytic corrosion which is almost certain to occur on such structures, especially when aggravated by the various stray currents prevalent in cities.

Eventually, engineers and managers doubtless will find it economical to consider the feasibility of installing cathodic protection on new structures, before corrosion occurs, instead of waiting until preventable electrolytic corrosion has taken its toll.

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[4] *Journal of the American Water Works Association*, Sept. 1941.

Power Transmission Systems

A Review of Progress During the War with Special Reference to Postwar Developments *

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I SHOULD like in the first place to express my deep sense of appreciation of the honour done to me by the members of this Section in electing me Chairman. The more so since in studying the proceedings of the Section during the preparation of this Address I was reminded that the current session marks the end of the first decade of the Section's existence. There is also reasonable hope that during this session the first stages of peace may be reached, some slight relaxation of the grim conditions under which we have been living achieved, and a further stimulus given to post-war planning and preparation for the arts of peace. It is a sad thought that by the end of this session exactly one-half of the Section's proceedings will have taken place under war conditions—five Chairmen will have held office under such conditions as against five who held office before the war.

I am tempted to theorize concerning what differences there might have been in our proceedings this session had there been no war. Even a hasty survey of the situation, however, convinces me that there have been gains as well as losses and that, bearing in mind the comments of several war-time Chairmen regarding the impracticability in these days of publishing all details of progress, there has been built up a substantial reservoir of knowledge to aid us in rapid progress as soon as normality is again the order of the day. While the slogan of this war has certainly not been that of the 1914–1918 war, namely "business as usual," nevertheless many precious hours of leisure have been employed by transmission engineers in "keeping things running," so that the inertia to be overcome in starting-up technical studies after the war has been minimized. In some cases war effort has naturally synchronized with normal progress—has even accelerated progress—and in other cases the war has actually stimulated progress which otherwise might have been tardy or moribund.

I feel, therefore, that the most appropriate subject for an Address at this stage in the Section's history is a review of progress during the war, with special reference to the post-war developments arising therefrom. Such an attempt in so far as it involves prophecy is extremely dangerous, and I have tried to be reasonably cautious in that direction, while at the same time venturing a little boldly in certain other directions in order to bring out interconnected aspects.

1. The Economic Aspect

In his Address at the outbreak of the present war,[1] Mr. Purse drew attention to the outstanding weaknesses in our supply and transmission systems revealed during the previous war. He traced the legislation which ensued (1919–1936) and which left as definite milestones the establishment of the Electricity Commissioners and the Central Electricity Board. I am certain that no Chairman taking office in October 1918 could have prophesied with any exactitude the course that events would take. Much more, in 1943, do I feel that discretion is the better part of valour and that I am well advised to leave to a more qualified successor the task of forecasting the trend of such events. Perhaps by that time some further governmental progress will have been made in the field of the Scott and allied Reports which have been drawn up during the war. Judging by the columns of the technical Press in recent months, he will also have at his disposal in compiling his forecast the views of most sections of the electrical industry. They may be divergent at present, but no sound plan has ever

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* I.E.E. Transmission Section: Chairman's Address (delivered 20th October, 1943). Reprinted from *Journal of The Institution of Electrical Engineers*, Vol. 91, Part I, No. 37, January 1944.

been evolved without much preliminary discussion and even controversy. I shall content myself with a few remarks about the economic aspect.

Both Mr. Purse and Mr. Ryecroft have drawn attention—in different ways—to the two key-points, namely the demand for cheaper electricity and expediency engineering in respect of the equipment installed. Mr. Purse made his point in connection with the installation of minimum sizes of mains, switchgear, transformers, etc., instead of the planned economic sizes; Mr. Ryecroft [2] made his in connection with underground cables and low maintenance cost instead of overhead lines and high maintenance costs. Doubtless the effect of expediency engineering has shown itself during the war when the purchase of new equipment is controlled and difficult and the fruits of lack of foresight are reaped amidst arduous conditions. The demand for cheaper electricity will without doubt be strongly stressed as soon as hostilities cease. It therefore does not require a prophet to foretell that transmission economics in the broadest sense will be prominent in the post-war proceedings of this Section. This is a subject which well merits several papers devoted entirely to the main theme, and I am unable this evening to do more than draw attention to its importance and to point out several allied subjects which profoundly affect economics in our particular sphere of action.

2. *Standardization*

Midway between the economic aspect and the purely technical aspect lies standardization. Two war-time Chairmen have had something to say on this subject, namely Messrs Allcock [3] and Melsom.[4] Significantly enough both were cable makers. Mr. Allcock advocated the revision of B.S. 480 (1933). This is one of the tasks which transmission engineers have found time to undertake despite the war: B.S. 480 (1942–3) has made its appearance, and the majority of Mr. Allcock's points have already been cleared. These dealt mainly with the reduction of the numbers of types and sizes called for in paper-insulated lead-covered cables. A similar plea for all types of wires and cables may be necessary after the war in view of the probable growth of a large number of alternatives. Economies in wires and cables can only be achieved by a trend towards mass production. Mr. Melsom for his part made a plea—as I interpreted it—for the application of economic and scientific principles to standardization, so that on the one hand development would not be cramped, while on the other hand standards would be constantly renewed to keep the number of standardized types at a minimum and so aid the economists in their work.

If the difficulties of the future were apparent in 1941 when Mr. Melsom addressed you they are doubly so to-day. Technique, particularly in wires and cables, is liable to change rapidly after the war; and the greatest care will have to be taken with regard to standardization, otherwise chaos will ensue and true economic solutions will not be found.

Meanwhile we are obtaining plenty of practice in the art of standardization, in compiling, absorbing and using the numerous War Emergency Specifications which are forced upon us by the existing conditions. Many of these are somewhat controversial in that they are naturally not backed by that wealth of experience which characterizes the fundamental specifications. One lesson that we are learning from these war-time specifications is the necessity of the user being able to compile a "performance specification" which lays down as precisely as possible the desired characteristics of the cable, etc., irrespective of the materials used in manufacture. Too often in the past the specification has been written round the characteristics of *the* material which was to form the main constituent of the specified product. Thus we had specifications for *rubber* cables and for *paper* cables. This was a logical development from the days of the original B.S. 7, but war time has introduced the complexity of *substitute* materials. Peace will undoubtedly continue the complexity with alternative materials. The scientific aspect of standardization will have to be carefully studied here if distorted economics are not to arise. This aspect is referred to later in this Address.

One of the best aids to economic and scientific standardization is the public study of the technical aspects, and no better method can be suggested for the transmission items than the presentation of papers before this Section with resultant vigorous discussions. Your Committee is mindful of this point; already papers bearing on some items have been read, and others are under consideration.

All in all we can claim, I think, that as the result of the war years we shall emerge into peace with a better understanding of the correct mechanism of standardization.

3. The Rating of Transmission Systems

Turning to technical matters, I must first make some reference to the rating of transmission systems. Two aspects of the cable-loading problem have been receiving attention, namely current-carrying capacity and short-circuit capacity. The former may be considered very largely an effort at present to squeeze the last ampere, consistent with safety, into systems which cannot easily be duplicated in war time or which have to carry additional load because of the war-time redistribution of industry. The latter comes under the category mainly of steady, although of necessity leisurely, progress in the face of the heavy demands made on engineers by war-time development work. Here also, however, there is a distinct war-time flavour in that enemy action has in certain cases brought to our notice the considerable effects of unexpected and irregular short-circuits and has given us some practical demonstrations to aid our investigations.

The Americans in their usual brisk fashion have already issued a report [6] on the effects of increased loadings brought about by war-time emergencies, and it is felt in the United States that this and subsequent reports will have a considerable bearing on the standardized ratings that will be agreed for peace-time conditions.

The progress in this country in the last few years, if somewhat slower and more conservative, has at least tended to clarify methods of calculation and estimation. The paper published recently in the *Journal* by Mr. Waddicor [7] has helped to simplify these methods.

Economic planning depends largely on a firm basis of factual knowledge concerning items such as cable current-capacity and on simplified calculations which enable the economic aspect to be worked out in detail with the minimum of effort.

Short time-ratings have also become a matter for more serious consideration. Here the rating of the cables has to be considered in conjunction with other equipment in the system, e.g., transformers and current- and fault-limiting devices. With our well-known conservation and resultant comparative freedom from faults, we have perhaps not paid enough attention in the past to the accurate short-time rating of lines and equipment, but there are signs that this is being remedied.

4. Technical Development

The subjects discussed above are logical outcomes of normal transmission studies and researches, albeit specially directed and guided by war-time requirements and experience. It is inconceivable, however, that the very vigorous research development and production expansion in other fields during war time will not react in some measure—in some cases slight, in others large—on the transmission field. Although, as I have said, the role of prophet is never a comfortable one, I would venture to-night to direct your attention to three items which may have considerable reaction on the transmission field. I refer to:

(*a*) Gas, particularly at high pressure.
(*b*) Vacuum.
(*c*) Synthetics.

4.1 HIGH-PRESSURE GAS IN CABLES AND SWITCHGEAR

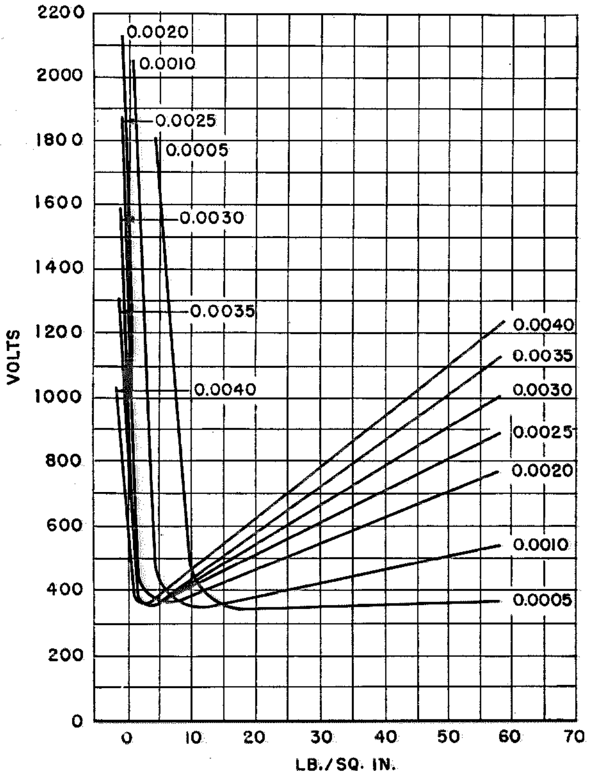
The first of these may be considered as a border-line case or a connecting link between the established transmission items discussed above and those to be discussed below, which are more novel in their impact on the transmission field.

During the last session or two we have had papers on high-pressure gas as applied to cables [8] and switchgear.[9] This session we anticipate a paper on joints and terminations for gas-pressure cables—in some ways a complement to last session's papers. None of these studies is purely of war origin; they mark mainly the steady war-time development of a pre-war novelty. There are, however, auxiliary items which are being stimulated during the war. For example, the production of helium [10] has been studied. This ranks as a strong competitor of nitrogen and has already been successfully applied in the fire-proofing of switchgear where rapid dispersal of heat and freedom from corrosion of contacts are of importance. In inertness, high specific heat and high co-efficient of thermal conductivity, helium is superior to nitrogen but hitherto has been scarce and costly. The intensive examination, however, of the potentialities of natural gases associated with petroleum deposits in certain regions (Texas, Ontario, Alberta, etc.) has tended to increase production and decrease cost. Already one Texas plant is producing one million cu. ft. of the gas per annum at a cost of \$12 per 1000 cu. ft. Since this output is only 3½% of the potential output and since cost is very closely associated with output, we may look forward to a relatively plentiful supply of helium at a price which is not founded on a "scarcity" basis.

Other useful contributions to the gas technique may be expected from similar developments in other fields.

4.2 Vacuum Phenomena

It is not too much to claim that the greatest technical advances of the war have been associated with electronics. Radio, radar (radiolocation), etc., have made immense strides, and these advances have been closely associated with developments in the vacuum tube. This is likely to have four main effects on power transmission work. There will be first some definite reaction on communication systems associated with transmission networks. Secondly, protective systems may have certain relay problems solved or alleviated by thermionic devices. Thirdly, vacuum-tube technique for high-voltage transmission may receive an overdue stimulus and some of the long-talked-of methods of transmission may be brought within the realms of practical politics. Recent information from the United States mentions a 20-million-volt Rheotron and a 100-million-volt X-ray equipment, both of which are products of the (American) General Electric Company. The lessons learned in these developments must undoubtedly have repercussions at transmission voltages.



Air breakdown between parallel plates. Figures on curves give spacing in centimeters.

The fourth effect is more speculative. It has long been realized that hard vacuum is a good insulator. In fact the patent associated with the paper by Beaver and Davey on "The High-Pressure Gas-Filled Cable" [8] was published almost simultaneously with a patent [11] filed by these authors on an equivalent cable working at extremely low pressure instead of high pressure.

If we examine the dielectric strength, or spark breakdown, in relation to pressure (see Figure) we see that some interesting points arise.* At ordinary atmospheric pressure (15 lb. per sq. in.) and just above and below this point, there occurs the worst state of affairs dielectrically (from a breakdown point of view). As the pressure is increased improvement is effected, particularly for large spacings, so that for spacings above 0.002 cm. the dielectric condition is quite reasonable as soon as, say, 4 atmospheres (60 lb. per sq. in.) has been attained. In the region of 10 to 15 atmospheres—the region dealt with by Beaver and Davey last session—the condition is good. Similarly as we approach zero absolute pressure the breakdown voltage rises rapidly. With hard vacuum we therefore obtain results equivalent to, if not better than, those obtained with high gas pressure.

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* In the accompanying Figure, which is based on an illustration in Reference No. 12, liberties have been taken with the curves in the region of zero pressure for the sake of clarity.

One significant point is, however, often overlooked although the practical effects of it are manifest in ordinary impregnated-paper cable phenomena. If we examine the curve marked 0.0005 cm., we see that for very small spacings, whereas the effect of an increase of pressure above atmospheric is comparatively slight, the effect of a reduction is very marked. In ordinary oil-impregnated-cable technique it is commonplace that the breaking-up of voids or gas spaces into small bubbles prevents ionization even if the pressure inside the lead sheath falls below atmospheric owing to the absence of compensating devices.

Since the avoidance of large gaseous spaces is fundamental in the practice of high-voltage insulation engineers, and since engineering technique is steadily progressing towards the elimination of large spacings, the high dielectric breakdown effects produced in small voids by relatively soft vacuum may become of increasing importance, and the use of vacuum devices instead of pressure devices may receive an impetus.

The practical objections are, of course, the difficulties of making vacuum-tight equipment and of exhausting it in the factory and/or in the field. One would expect, however, that with the mass production of vacuum tubes on the scale required by the war, there must have been tremendous advances in these techniques. There is every reason to believe that this is so and that the industrial production of reasonably hard vacuum is within reach.

4.3 SYNTHETICS

My third choice for major development in the future is synthetics—I definitely stress the broad term synthetics as opposed to the narrower terms plastics and synthetic rubber. Mr. Melsom in his Address in 1941 referred at some length to the prospects of these two classes with particular reference to cable insulants and sheaths. Within one month of his address Japan entered the war, 90% of the world supply of rubber was rapidly cut off from the United Nations, and the U.S.A. commenced one of the most ambitious "build-ups" of synthetic and plastic manufacture that the world has ever seen; Canada followed suit to the extent at least of her own requirements; and Britain in a smaller way made preparations to give the chemist a chance to justify his laboratory and pilot-plant findings on a really large production scale. It is inconceivable that industries of this magnitude can disappear after the war with the regaining of the major sources of rubber supply. Moreover, the world will undoubtedly have become plastic- and synthetic-minded and will demand these products or their successors. In fact, there are signs of over-enthusiastic welcome to plastics and synthetics in the belief that they will solve all problems. In my opinion the engineer will benefit greatly from this large-scale addition to his reservoir of materials, but only if he studies the new problems in detail and applies the materials judiciously.

There is a tendency, I think, to overrate the dielectric or insulation aspect of these materials and to underrate the influence they will have on structures, preservatives and other more routine and unexciting parts of the engineering field. I would strongly deprecate the idea that synthetics are mainly of interest to the cable-making and cable-using members of this Section.

Elsewhere in the proceedings of The Institution this session I hope to say a few words regarding thermoplastic cables, with particular reference to polyvinyl chloride. I may be excused, therefore, from commenting here on that particular aspect of the broad picture. Instead, I will try to present the synthetic situation, not merely in terms of production of polyvinyl chloride, polythene, Neoprene, Buna-S, etc., and the substitution of these for rubber, but as a marked step forward in the scientific control of materials and in the economic planning of the use of material resources.

About twenty years ago I remember reading a series of articles by a well-known scientist—I cannot check the reference—in which the suggestion was made that in the years to come engineers would design the materials necessary for their projects on atomic principles, with particular reference to crystal structure and similar aspects. More recently, during a visit to the Massachusetts Institute of Technology and the laboratory of Dr. Von Hippel, I had a glimpse of the future ways in which dielectric phenomena would be explained and interpreted in terms of atomic and molecular arrangement.

While both these atomic ideas have yet to be developed to a stage at which they may be employed as practical engineers' tools, we are at least on the threshold of one more elementary but nevertheless very practical stage, i.e., the design of materials on the basis of molecular arrangements—chains, for example. This applies particularly where plastics, synthetic rubbers and allied materials—in fact synthetics as a class—are concerned.

It has been clear for some time that the best chemical explanation of the molecular behaviour of materials, such as cellulose, silk, rubber, is on the basis of long threads or chains formed by molecules joined together. Another example is the explanation of the transition from petrol through lubricating oils to paraffin waxes by the difference in chain length from 5–10 carbon atoms (petrol), 10–20 carbon atoms (oils), 20–50 carbon atoms (waxes). The study of polymerization, upon which the synthetic industry is founded, has intensified the study of this chain formation of molecules. From single molecules, which may be gaseous, polymerization builds up a chain, the number of molecules in the chain determining the molecular weight of the polymer and influencing, often pronouncedly, the other characteristics of the material. A low-molecular-weight polystyrene, for example, produced by rapid polymerization at high temperature, is brittle and "glassy" and has a comparatively low temperature range of usefulness. If the liquid monomeric styrene is polymerized slowly at room temperature, a high-molecular-weight (say, 750,000) material is obtained which is "tough-rubbery" and has an extended range of temperature between softening point and cold crack. The normal (i.e., generally employed) styrene has a molecular weight of about 100,000 and is midway in characteristics between these two extremes.

Similarly the gaseous monomeric ethylene can be converted into a range of polymers of differing molecular weights and characteristics.

Some monomers polymerize into long-straight-chain polymers—vinyl chloride is an example—and it can be forecast that such polymers will in general be easily processed and will produce flexible plastic materials.

In addition to controlling the characteristics by controlling the polymerization and the length of the chain, a second variable can be introduced, namely the polymerization together of two differing monomers. This is called co-polymerization, and the resultant product is called a co-polymer. Well-known examples are co-polymers of vinyl chloride with vinyl acetate or acrylic ester. The latter produced the co-polymer which when plasticized was called Mipolam; the former is one of the most useful P.V.C. polymer families. Another valuable example is Buna-S, formed by the co-polymerization of butadiene with styrene. This example affords an excellent subject of study of the changes in co-polymeric characteristics brought about by variation of the proportions of styrene to butadiene in the co-polymer.

While, as mentioned above, certain monomers tend to produce long straight chains, others tend to branch and still others tend to form 2- and 3-dimensional chains. The latter class tend to produce materials which become plastic only at high temperatures and then decompose slowly, increasing in plasticity in the meantime. They have no definite softening zone of temperature. They exhibit much greater resistance to abrasion, impact and heat than long-chain polymers. Perbunan and Neoprene are typical examples.

Cross linking between straight chains or branch chains further changes the characteristics of the polymer. The general tendency of this arrangement is to increase brittleness. If controlled, however, it can be beneficial in some cases. Thus a styrenated cable-termination[13] immersed in a transformer which used chlorinated naphthalene or diphenyl instead of oil to minimize fire risks would be softened and eventually degraded by the interaction between the chlorinated material and the styrene. Judicious cross-linking of the styrene can, however, reduce this effect to a negligible value.

Cross-linking is probably also a prominent feature of the curing treatment of bakelite resins and of rubber during vulcanization.

While it may be undesirable to use cross-linking in the production of the material which has to be processed during the fabrication of the article required, it may be reasonable, or even desirable, to bring it into play for the final "setting" of the fabricated product.

If the chemist is not satisfied with the materials obtained from the polymerization of straight hydrocarbons, i.e., carbon and hydrogen, he can set to work on the monomer and substitute the hydrogen atoms attached to the carbon atoms by elements and radicals. The halogen elements, particularly chlorine, are at present especially favoured in this direction, and the acetate radical may also be mentioned as prominent. In addition to varied polymerization and co-polymerization effects, the introduction of these elements can directly influence the characteristics of the polymer. Resistance to oils and solvents may be improved. The introduction of elements such as chlorine will increase the resistance to burning.

While these improvements may be effected by the replacement of hydrogen by other elements or radicals, the chemist must bear in mind the possible adverse effects on other characteristics. Pure hydrocarbons, of which carbon and hydrogen are the only constituents, are electrically inert, i.e., non-polar, but the introduction of other elements such as chlorine or oxygen may introduce polarity with consequent degradation of the electrical characteristics. Thus the ethylene polymer, polyethylene is non-polar, whereas the substitution of one atom of chlorine for one of hydrogen in ethylene results in vinyl chloride and, in polymerization, polyvinyl chloride. The contrast between polyethylene and polyvinyl chloride electrically is well known. On the other hand, polyvinyl chloride possesses certain fire-resisting and other non-electrical characteristics which render it somewhat superior to polyethylene.

Sufficient has been said, I think, to give an elementary but definite picture of the new technique which is rapidly reaching the point where materials may be "designed" in the laboratory with a fair assurance that the product obtained will be endowed with certain foreseen characteristics.

A very interesting series of articles on synthetic rubbers and plastics has been published in the 1943 issues of *Distribution of Electricity*.[14] In particular the first two introductory articles give a simplified and clear picture of polymerization, co-polymerization, vulcanization, cross-linking, replacement of hydrogen by chlorine, etc.—the processes by which the chemist adapts his primary base to give the grouped characteristics of the material required by engineer or designer. For those interested in a more detailed discussion, I would suggest Dr. Barron's book on "Modern Synthetic Rubbers." [15]

When this structural arrangement of materials is considered in conjunction with an increasing knowledge of plasticizing and compounding materials—which may be loosely taken as materials packed into the interstices, molecular and larger, of these designed materials to modify or correct their characteristics—and with a similarly increasing knowledge of the state and aggregation of matter, it will be seen that the immediate future holds hope for scientific selection and even design of the ideal material for the engineering purpose in mind—not only in the insulation field which is of particular interest to the transmission engineer, but also in the structural aspects.

It should be noted that the introduction of plasticizing materials to a synthetic base not only induces or increases plastic qualities, not only brings into play the added characteristics of the plasticizer, but may also introduce other features which at first sight might not be expected.

In an article on the "Diffusion of Water Through Insulating Materials" [16] Taylor, Hermann and Kemp quoted the diffusion constant of cellulose acetate as 159, whereas plasticized cellulose acetate exhibited a constant of 1.18. A hundred-fold increase in resistance to water diffusion is thus obtained by the introduction of the plasticizer for other purposes.

More recently it has been shown [17] that asphaltic materials, which have naturally low diffusion-constants and are largely used for waterproofing purposes, may be still further improved by the addition of small percentages of polybutenes, which are synthetic materials originating in the manner discussed above.

If we assume equal success in designing such secondary materials, e.g., plasticizers, and assume further success in coordinated design of primary and secondary materials in combination, it must be agreed that improvements in engineering materials of this type must accrue rapidly.

This science of material design has not, of course, sprung up overnight; it has been laboriously developed over years. The more important aspect that the war is bringing into the picture is the mass production of the basic materials on which the chemist can work to obtain his finished products having ideal characteristics.

The mass production of butadiene, styrene, etc. has not only resulted in the immediate mass production of Buna-S, Neoprene, etc., but has put on the market for post-war use fundamental materials at relatively low cost from which in due course the chemist will evolve even better products.

In the early stages of the preparation of this Address, I had hoped to reproduce in a modified form a most interesting diagram published recently by Dunstan[18] in the *Journal of the Institute of Petroleum*, dealing with the synthetic materials produced by the cracking of petroleum. Starting with the gases:

ethylene,
propylene,
butene,
butadiene,

the diagram showed some 50 synthetic products which already have definite applications in the industrial field. They included such insulating or allied materials as:

Thiokol
polyvinyl chloride
plasticizers for lacquers
styrene
cellulose acetate
polyisobutylene
butyl rubber
Buna-S
Buna-N

The study, however, seemed to take one into a field which required more time and space than were available. I turned, therefore, to the allied question of alternative methods of preparation of these materials. After all, this country has negligible resources in all aspects of the oil industry; we depend on imports. But we must, I sincerely hope, look forward to a time when this country from its own natural resources will be capable of producing its own synthetic materials to aid in keeping it in the forefront in electrical insulation and mechanical structures. In the popular mind this is a question of putting up plants for the manufacture of synthetic rubbers and of plastics. If I have made my point about the method by which the ideal materials will be designed by the chemist in conjunction with the engineer in the future, we must specify that what are required are the basic raw materials which can be manipulated and transformed into these ideal materials. The petroleum aspect as outlined above indicates the vast array of synthetics which can be derived from four gases, assuming of course the availability of auxiliary materials such as sulphur and chlorine.

Confining our attention for the moment to the mineral world, we have in this country a large and important coal industry. Ethylene, mentioned above, is a by-product of the coke-oven and, as can be seen by the growth of the production of polyethylene, it has already been used in this country for the manufacture of synthetics.

It should be realized, however, that there are many ways of arriving at the final molecular structure desired by the engineer. The choice of the starting-point is largely determined by the availability and cost of the raw materials and the relative costs of the processes.

Acetylene, which is not one of the four gases mentioned above, is an excellent starting-point. Not only can it be combined directly with hydrogen chloride to produce vinyl chloride, leading to P.V.C., but, by transformation to acetaldehyde, butadiene can be produced and the way laid open to the families of synthetic rubbers discussed above. The essentials for the production of acetylene are coke or anthracite, limestone, and cheap and abundant electric power. Two of these are already available in this country and the third, as already stated, may be one of our primary considerations after the war—it should, in fact, be always a matter of endeavour among generation and transmission engineers.

To my mind this question of the production of calcium carbide, and hence acetylene, can lead to a most fascinating economic study. Reduction of the price of electricity to the consumer is largely influenced by the economies effected in transmission systems, which can in turn be brought about by using better and cheaper materials. Among such materials synthetics must undoubtedly be considered. The cost of synthetics can be largely determined by the cost of electricity. Here, therefore, we have an economic problem, the solution of which can benefit all users of electricity, and, in addition, can benefit the coal industry with potential reactions on the thermal generation of electricity.

A further source of synthetics is the vegetable world—potatoes, beets, etc.—through the formation of alcohol. For the time being this method of derivation seems to have been eclipsed by the oil and carbide methods, but in the world of chemistry changes in viewpoint may take place overnight, and it would not surprise me if this aspect became very important. Here again we have in this country a large agricultural industry which could undoubtedly benefit by an industrial outlet for its products. Such a change in the agricultural outlook would undoubtedly react on the rural transmission and distribution of electricity.

5. *Conclusion*

I must apologize for having led you this evening into a very speculative forecast. I feel, however, that we in the Transmission Section should realize the interconnection between our work and that of physicists and of synthetic chemists, coupled with the possible reaction of the chemists' work on the prosperity of other industries such as the coal and agricultural industries and the subsequent or co-ordinated reaction on our own work.

The utilization of these products of the chemists' effort will entail on our part serious study of economics and of standardization. One drawback of a plentitude of potentialities is that, without judicious standardization, mass production cannot be set up and the economies gained may be seriously lessened or even entirely lost.

It is clear that the tasks which lie ahead of us at the conclusion of our first decade of existence are no less arduous than those we have undertaken in the past. It is also clear that despite the handicaps of war our progress over the last five years, although largely unpublicized, has placed us in a position to look forward to extraordinary progress during the next five years.

In one aspect I find some lack of progress: as far as I can ascertain the membership of this Section has remained practically stationary over the last few years. This may be a natural outcome of the war—or it may be, as has been suggested to me, that we have reached an approximate saturation of the "cream" of transmission engineers. We need, however, in the years ahead all the assistance we can obtain in developing transmission systems in every detail of their make-up, and I myself would welcome a further influx of suitable members to strengthen our hands in this task.

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Developments in the Field of Cable and Radio Telegraph Communications*

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and

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Editor's Note: Since this paper was presented before the A.I.E.E., commercial transatlantic telegraph service was resumed between France and the U.S.A. through the inauguration of "Station 25" in liberated France by the Mackay Radio and Telegraph Company. The 20-kilowatt high-frequency transmitter provided for this station, and constructed by the Federal Telephone and Radio Corporation, affords facilities for the twenty-second radio telegraph circuit established by Mackay Radio since the attack on Pearl Harbor on December 7, 1941. Until released by the military authorities the service will be limited to press and Government telegrams.

FOUR record communication operating organizations constitute the far flung system of the International Telephone and Telegraph Corporation which provides telegraphic connections between the continental United States and the outside world. These companies are:

All American Cables and Radio, Inc.
The Commercial Cable Company
The Commercial Pacific Cable Company
The Mackay Radio and Telegraph Company

and operate as a group under the management of the American Cable and Radio Corporation. A brief historical review of each of these follows.

All America Cables and Radio, Inc.

It was as early as 1865, upon the termination of our Civil War, that the first American company was formed to connect the United States by cable with any of our neighbors to the south. The Company was the International Ocean Telegraph Company. It laid a cable between Punta Rassa, Florida, and Havana via Key West, which was first opened to the public in 1866. It is interesting to recall that the first tariff over this short cable was $10 for a message of ten words and $1 for each word in excess.

The leading spirit of this enterprise was Mr. James A. Scrymser, who later withdrew from it. In 1878 control of the Company was obtained by Mr. Jay Gould, and the capital was increased from $1,500,000 to $3,000,000. The Western Union Telegraph Company then leased the Company for ninety-nine years and guaranteed six percent on the increased capital.

Although Mr. Scrymser's part in the International Ocean Telegraph Company ceased when the control of the Company passed into other hands, his interest in cable communication between the United States and the other American republics was to continue throughout a long and active life. He organized the Mexican Telegraph Company, which was formed in 1878, as well as the Central and South American Telegraph Company, which opened its lines to the public in 1882. These were the foundations upon which the All America Cables and Radio system of today was built.

The Mexican Telegraph Company was created with a view to meeting the international telegraph requirements of Mexico. The first cable terminus in the United States was at Brownsville, Texas, and the cable was laid in 1881 to Vera Cruz and Coatzalcoalcos in Mexico. From these points landlines were constructed to Mexico City and Salina Cruz respectively. The Central and South American Telegraph Company's first cable was laid in 1882 south from Salina Cruz, Mexico, through the republics of Central America and thence down the west coast of South America as far as Chorillos near Lima, Peru. In

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* Paper presented at the A.I.E.E. summer technical meeting, St. Louis, Missouri, June 26–30, 1944.

connection with this extension two facts are worth recording: (1) in laying its lines through the Central American area, where population in comparison to the large South American cities was small and where the volume of traffic was relatively inconsiderable, the Central American republics were provided with excellent international telegraph facilities at a comparatively early date, and this fact cannot fail to have been a most favorable factor in the development of their foreign trade; (2) the Central and South American Telegraph Company is responsible for rate reductions which the extension of its lines to Lima in 1882 rendered possible. Prior to 1882 the rate between the U. S. A. and the Argentine Republic—to give a single example—was $7.50 per word and the service was by way of Europe. In 1882, via the Central and South American Telegraph Company's lines to Lima and over connecting lines beyond Lima, a rate of $1.85 per word was established between the U. S. A. and the Argentine Republic—a most drastic reduction, the advantages of which to commerce in general and the users of telegraph communications in particular are obvious. Among such advantages was the existence of a competitive service between South America and Europe via the United States. Innumerable reductions of the basic tariffs have been introduced since then, as well as the cheaper classifications of service now familiar to all.

In 1891, following the termination of a traffic agreement with the West Coast of America Telegraph Company, a cable was laid from Chorillos, Peru, to Valparaiso, Chile, by way of Iquique, so that thenceforth the companies were able to serve the entire west coast of South America over their own lines. There still remained, however, the need of an independent connection between the United States and the east coast, and to secure this the Transandine Telegraph Company, which operated 1,200 miles of landlines between Chile and Argentina, was purchased in 1891. The addition of this important link made possible the inauguration of a through cable service from Galveston, Texas, to Buenos Aires and established the foundation for the ultimate extension of the system to Uruguay and Brazil in 1920.

It is not the purpose of this paper to enumerate the various cables laid or the points which they connected.

In 1917 the name of the Central and South American Telegraph Company was changed to All America Cables, Inc.; in 1926 All America Cables sold a majority interest in the Mexican Telegraph Company to the Western Union Telegraph Company.

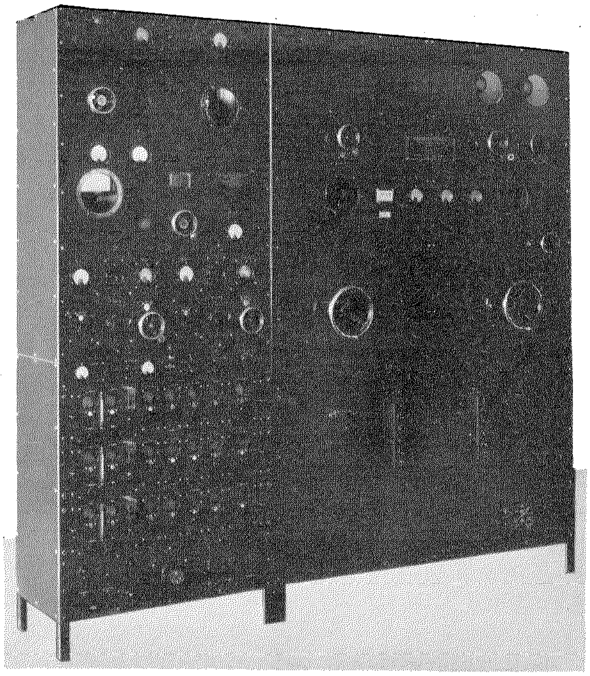
The Company's principal radio telegraph and radio telephone stations are at Lima, Peru, and Bogotá, Colombia. Smaller radio telegraph stations are operated at other points in Central and South America. It owns or operates under lease 29,208 nautical miles of submarine or subfluvial cable and 3,577 statute miles of telegraph landlines in connection therewith. It maintains one or more offices at 68 different points in 24 countries or islands of the western hemisphere.

In 1927 All America Cables became an associated company of International Telephone and Telegraph Corporation and in 1938 the name was changed to All America Cables and Radio, Inc.

The Commercial Cable and Commercial Pacific Cable Companies

In the beginning of the 1880s the telegraph facilities between the United States and Europe were preponderantly foreign and included the cables of the Anglo American Telegraph Co. Ltd. and the Direct United States Telegraph Co. Ltd., both British, as well as those of the French Cable Company. The American Telegraph and Cable Company had two cables leased by Western Union. All of these companies had entered into an agreement for pooling their receipts and fixing rates.

In order to break this communications monopoly and to enable American interests to benefit from more reasonable rates, Mr. John W. Mackay and Mr. James Gordon Bennett entered into a partnership which resulted in the formation of The Commercial Cable Company and the laying of its first two cables in 1884 between Canso, Nova Scotia, and Waterville, Ireland, with extensions to the United States on one side and to England and France on the other side. The reduced rates offered by The Commercial Cable Company resulted in a prolonged rate war between that Company and the foreign controlled pool, which had theretofore maintained a charge of 50 cents per word across the Atlantic. Despite the pressure brought to bear upon



Type of high frequency radio transmitter now being employed at "Station 25" in liberated France by the Mackay Radio and Telegraph Company. This transmitter was designed and built for Mackay by the Federal Telephone and Radio Corporation. Behind the smaller panel at the left are the three crystal control units and the driver; at the right is the 20-kilowatt power amplifier. The transmitter may be switched instantly to any of three preset frequencies from 300 kilocycles to 24 megacycles.

it to join the existing pool and maintain the higher rates, The Commercial Cable Company insisted upon applying lower rates with the result that 25 cents a word was finally adopted by all Companies.

In 1894 the third main cable was laid across the Atlantic and subsequently three other trans-Atlantic cables were added to The Commercial Cable Company's system, together with a number of coastal cables on the American seaboard and on the European side. These provided an adequate network which gave the Company not only an efficient outlet for its cables on both sides of the Atlantic, but also provided alternate routes in case of interruption.

During the first years of this century, The Commercial Cable Company moved into the Pacific. The Commercial Pacific Cable Company was formed and, after formidable difficulties had been overcome, a cable was laid from San Francisco to Honolulu in 1902 and thence to Midway Island, Guam and Manila, with extensions to China and Japan. Some idea of the physical obstacles encountered may be formed from the fact that not only was the cable longer than any previously laid—for example, the distance between San Francisco and Shanghai is in the neighborhood of 9,000 miles—but greater depths were met than any in which cables had ever been laid, reaching over 5,000 fathoms, or more than five and a half miles. The cable has been successfully raised for repairs from a depth of over 4,000 fathoms. With the completion of the Shanghai extension in 1906, telegraphic encirclement of the globe was achieved and on July 4th of that year President Theodore Roosevelt and Mr. Clarence H. Mackay, President of The Commercial Cable Company, exchanged the first telegraph messages that ever travelled entirely around the world. The message from President Roosevelt was delivered to Mr. Mackay in nine minutes after it was filed.

The inauguration of service over the Pacific cable resulted in immediate rate reductions between San Francisco and China from $1.72 per word via the Atlantic to $1.10 via Commercial Pacific, the Philippines from $2.47 to $1.00 per word, and Japan from $1.88 to $1.21 per word. Subsequently, these have undergone further substantial reductions.

In the following years, The Commercial Cable Company expanded its communication network in the Atlantic to 23,177 miles and in the Pacific to 10,068 miles—a total of 33,245 miles of submarine cables, and established its own operating stations in various strategic points providing direct connections between New York and London, Paris, Antwerp, Brussels, Rotterdam, etc. It has at present one or more cable offices in 16 of the most important points in Great Britain and Ireland.

In 1928 The Commercial Cable Company became an associated company of International Telephone and Telegraph Corporation.

TECHNICAL DEVELOPMENTS IN THE OPERATION OF CABLES

Submarine cables have always been very expensive ventures and great hazards were involved in the beginning when the difficulties were still unknown. After a few cables had been laid, the conditions and risks limiting them began to be known, but the general engineering in connection with the first long cables was so sound that their type has since been altered but very little. The early technique of operating cables was in the hands of a small group of men, who were not engineers or scientists, but who merely tried hard to make the most of what was available.

In 1858 Sir William Thomson introduced the first means of receiving the very weak signals arriving over long cables using a mirror instrument, which was a form of reflecting galvanometer, and the signals were read from the movements of the spot of light. Sir William Thomson also made the first improvement on this method of reception when he invented the siphon recorder in 1867, which recorded the signals on a strip of paper in the form of a wavy line of ink. This instrument gradually supplanted the mirror on all long cable sections so that, when the first cables of the All America system were laid in 1881, the siphon recorder was naturally installed as the receiving instrument.

To prevent friction on the recorder paper, the siphon was maintained a short distance from the surface of the paper and the ink was electrified, which caused it to spurt in dots onto the paper. A great improvement was made in 1884, when one of the All America staff, Mr. G. F. Pescod, devised a method of mechanically vibrating the siphon giving a fine dotted line to the record and still overcoming the paper friction. This system of mechanical vibration was soon adopted by every "recorder" telegraph station throughout the world.

As the All America system to South America was made up of a long series of cables forming a chain, linking the cables by relay was obviously necessary. Successive stages of development over the years have brought about the present day fully automatic synchronous regenerated relay chain.

The first method employed the human relay where the operator at the first station sent his message by hand key. At the other end of the cable, the receiving operator received the message from the tape and it was retransmitted by hand. This process was repeated until the message arrived at its destination. With the "human relay" chain, the transmission time factor was good; however, there were the limitations in the rate of sending and the human element which introduced errors. Development was concentrated in efforts to overcome these two adverse elements.

To increase the speed of sending messages the use of automatic cable transmitters was adopted as these became available on the market. In the early days, the paper transmitting tape was perforated by the hand operated "stick" punch which itself imposed a limit on the transmitting speed per operator, as each signalling hole in the tape had to be individually punched. This limit was raised by the keyboard perforator, which punched a complete letter group of holes with one depression of a key on a keyboard similar to that of a typewriter.

The speed problem also depended on conditions at the receiving end. The amplitude of the incoming signal depends on the electrical constants of the cable and so is a fixed quantity for given sending conditions. To care for the smaller amplitudes associated with the higher sending speeds magnifiers were used as they became available. The first of these experimented with were light sensitive cells, but subsequently the familiar Heurtley magnifier was adopted; it depends for its action on the change of resistance with temperature of a very fine platinum wire. As might be expected, electronic valve methods constitute the ultimate in magnifiers, but these have not as yet been adopted by this system.

Since the start of the system in 1881 these cables have been duplexed, permitting simultaneous operation in both directions, and every speed increase has called for improvements in the "balance" involved in the proper adjustment of the special circuits used. This is where long experience and individual skill give results. Obtaining a good balance is still largely a trial and error empirical problem.

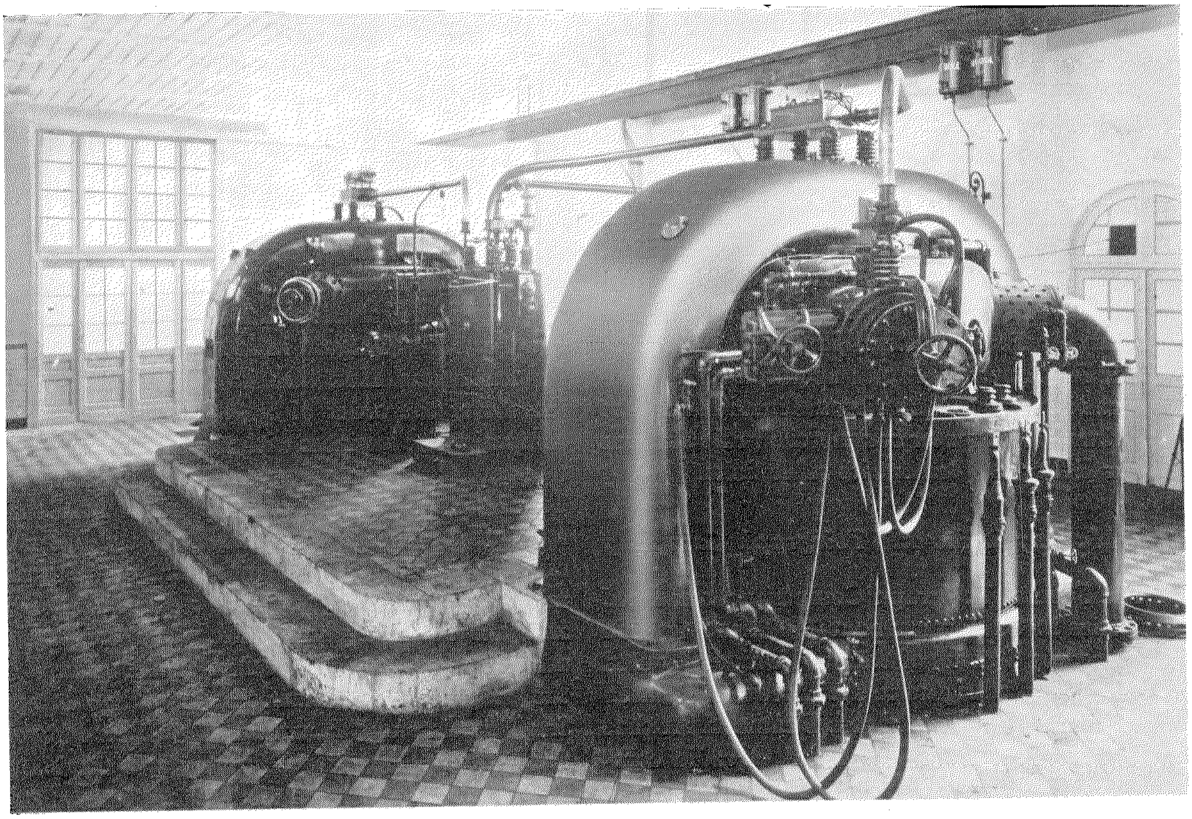
Progress on the problem of reducing the human element paralleled the efforts to increase the speed of transmission. The first thing to be done was to obtain a cable relay that was reliable and this was only possible after automatic transmission had been installed at all sending stations. The Muirhead gold wire relay proved the most suitable after it had been changed somewhat from the original design. First there were single relays between two cables and then extension was possible, linking two and finally three cables in tandem to form a chain.

Each relay, however, retained and passed along some of the distortion accumulated on previous links. To overcome this handicap we developed an automatic reperforator to punch a new transmitting tape automatically from the relayed signals. This gave the means of setting up complete chains from station of origin to station of destination without any human retransmission, but at the sacrifice of introducing a small time lag at each reperforating point. This step forward emphasized the disadvantages of the variability of the transmitter speed which imposed a limit to the stability of working. This problem was solved by making use of tuning forks to control the speed of the automatic transmitter.

With the advent of the tuning fork speed control came another possibility which was taken advantage of by the development of the synchronous regenerator whereby a new signal could be regenerated and sent directly into the next cable section as a perfect signal instead of punching a whole new tape. Thus the accumulated distortion of the relays was eliminated, as also was the time lag due to punching a new tape.

Thus was evolved the achievement of sending messages automatically from one end of the system to the other without human intervention at intermediate points; and, also, of providing for branching traffic by automatically reperforating a new transmitting tape at the appropriate point. The human error factor was thus reduced to the original sender and the ultimate receiver and, of these two, only the human receiver could be eliminated. This was done by the development of an automatic printer method which takes the signals coming from the cable and automatically records them as regular printed characters on a continuous paper tape or, preferably, as printed characters in page form ready for delivery to the customer.

While landline telegraphs were developing carrier transmission, this principle was not neglected by the cable companies. A form of higher frequency transmission was superimposed on



Historic Lafayette radio transmitter station built by the Federal Telegraph Company for the United States Navy near Bordeaux, France, during World War I—the largest transmitter ever built. The illustration shows the two 1000-kilowatt Poulsen arc generators which permitted efficient and reliable communication across the Atlantic Ocean on long wavelengths.

short cables in order to make use of their extra carrying capacity in excess of that of the long cables with which they were linked.

Due to advances in methods of operation on the old cables and to basic cable design which permitted higher speeds on some of the new cables, it was found possible in some cases to secure transmission speeds in excess of the capacity of one operator to transmit or to receive and, therefore, methods for making available more than one channel per cable were introduced and adopted.

An interesting phase of long automatic chains has been the development of "selectors" whereby the sending station can call the attention of any desired station to a particular circuit or can automatically start up an automatic reperforator and punch a new tape at any required point.

While radio telegraphy over long distances was making use of long waves (10,000 to 30,000 meters—a system which involved very expensive terminal installations at each end), the cable companies showed very little interest in adopting radio methods although The Commercial Cable Company, in 1921, acquired control of the Radio Communications Company, Inc. When short wave transmission was demonstrated as practical, the Mackay Company, at that time the parent company of The Commercial Cable Company, acquired the communication system of the Federal Telegraph Company of California which, with the Radio Communications Company referred to above, led to the formation of the Mackay Radio and Telegraph Company. Meanwhile, All America Cables acquired radio concessions in various countries and installed at first experimental and later commercial radio stations to parallel or supplement its cable links.

The Mackay Radio and Telegraph Company

The Federal Telegraph Company commenced activities in California about 1909, having been organized by a group of Stanford University men who had secured rights to the patents of Poulsen and Pedersen of Copenhagen, Denmark. At that time, the only workable method of radio communication was by the use of damped waves generated by the spark type of equipment. This method was inherently inefficient and the power available at the transmitter could only be partially utilized. Practical application was confined largely to communication with ships at sea, and the use of radio for point-to-point telegraphy was very limited, largely because of the inability to cover long distances reliably, particularly in the daytime, such reliability being necessary to compete with other established communication systems.

The Danish inventors had developed a type of high frequency generator employing an electric arc in an atmosphere of hydrogen which made possible the first successful method of communicating with sustained or undamped waves, giving the Federal Telegraph Company a great advantage over others because this method enabled all the available power to be efficiently concentrated in a single wave and also permitted the full effective use of newly discovered methods of reception which were not particularly applicable to the damped wave, spark type of system. While some of the advantages of sustained wave transmission were known prior to the advent of the Poulsen arc, there was no way of using that method for commercial systems because the only instrumentalities available for generating the required currents were incapable of developing any appreciable power. The Poulsen arc, however, provided a means of generating plenty of power with a relatively simple apparatus not involving intricate or unstable features.

The Federal Telegraph Company promptly established commercial radio telegraph services between San Francisco, Los Angeles, San Diego and Portland (Oregon) in 1911 and between San Francisco and Honolulu in 1912, using wavelengths of the order of 3,000 to 10,000 meters, competing for business with the existing landline telegraph and cable companies at lower rates. This business grew to such a point in 1915 that additional facilities were added for the purpose of providing duplex operation, and extra transmitting and receiving stations at San Francisco and Los Angeles were created to increase the number of channels. The immediate success of the long distance transocean circuit between San Francisco and Honolulu in 1912 encouraged the Federal Telegraph Company and the Navy Department to install a Federal arc transmitter at the Navy Department's radio station at Arlington, Virginia, in 1912, as a result of which the Arlington station was able to communicate with the San Francisco and Honolulu stations during daylight hours, a feat never before accomplished. The success of these and other trials caused the Navy Department to adopt the Federal arc system as standard for its service. An extensive construction program was started in 1913 covering a chain of high power Navy radio stations, connecting Washington, D. C., with the Canal Zone, California, Hawaii, the Philippines and Puerto Rico, ranging in power from 100–500 kw., together with a secondary system of medium power equipments at all important Naval establishments on U. S. A. territory and on ships of the Fleet. The climax to this development was reached with the construction of the large radio station built near Bordeaux, France, during World War I, for which the Federal Telegraph Company supplied two transmitters of 1,000 kw. each.

In 1914 the Company, at San Francisco, entered the marine radio field which enabled ships, plying the Pacific, to secure daylight communication over vast distances theretofore impossible.

Following World War I, the Company constructed a new communication system for itself along the Pacific Coast in 1921, equipped for three complete duplex telegraph channels between San Francisco and Portland and three between San Francisco and Los Angeles, together with other innovations, including remote receiving stations, enabling terminals for both sending and receiving messages to be set up and operated in downtown business offices in the respective cities. Time and expense of handling messages between these city centers and the radio stations, which had to be located on the outskirts, were thus eliminated. An example of such direct handling was the service given for many years between the floors of the San Francisco and Los Angeles stock exchanges where traders could get buy and sell order messages delivered in a matter of seconds.

This point-to-point service continued with the original domestic rate schedules established in 1911, which were similar to those offered by the land wire systems, except that 15 words were permitted as a minimum instead of the usual 10, and 60 words instead of 50 for day and night letters. This general rate schedule continued until domestic radio telegraph operations were discontinued in 1942 due to the war.

As has been stated, Mackay Radio and Telegraph Company acquired the system of the Federal Telegraph Company in 1927. Not long after that, it also purchased the entire Federal Company, thereby securing its manufacturing facilities and other assets. These latter, greatly expanded, are today comprised in the I. T. & T. subsidiary, Federal Telephone and Radio Corporation, with factories located in the Newark, New Jersey area, and development and research laboratories in New York City.

Since 1927 Mackay Radio with Federal Telegraph as its manufacturer embarked on an extensive reconstruction program coupled with new construction employing the new found technique of short wave transmission and expanded its service to many other American cities and internationally to important points in Europe, Africa, Central and South America, New Zealand, Australia and the Orient so that it now directly serves 28 points beyond the continental U. S. A. It has also built up an extensive ship-to-shore radio telegraph service having seven radio stations along the U. S. A. coasts and service contracts covering radio facilities on 1,100 American vessels, with service depots in 17 United States ports and world wide service arrangements with associated companies.

Improved technical means have progressed as this communication system has developed, making possible higher transmission speeds, more effective directive antennas and refinements in apparatus details made available through advances in the radio sciences. Automatic relay methods for interconnecting radio telegraph circuits have also been regularly employed. Transmission speeds as high as 500 words per minute have been successfully employed over long distance circuits. A service for the transmission of pictures and facsimile material has been provided. With the advent of very high frequency wave generation and detection technique in recent years, radio control facilities, employing these very short waves, have been established between the radio terminal offices in city centers and the outlying radio transmitting and receiving stations associated with them. Such radio connections are now used to a large extent in lieu of wire lines.

A Proposal for A Global Shortwave Broadcasting System*

Editor's Note: The following article, in non-technical form, originally was published by the Federal Telephone and Radio Corporation to aid in the materialization of adequate international broadcasting facilities on the part of the U.S.A. In view of the interest evoked, this article is reprinted in "Electrical Communication."

LEADING nations of the world long have recognized powerful shortwave broadcasting as essential to international relations. The United States, less pressed by its neighbors, has not in the past stressed international broadcasting, but World War II and its repercussions obviously necessitate presenting American events and ideas to the rest of the world in the most rapid, direct, and effective manner possible. For this purpose, global broadcasting clearly ranks as the foremost of the available media. Thus, a basic problem now confronting the nation is how best to provide completely effective world radio coverage.

The utilization of numerous broadcasting stations powered at 50 or 100 kilowatts represents an approach that is demonstrably inadequate from the viewpoint of efficiency, clarity and reliability of reception, and reasonable freedom from "jamming" by unfriendly stations. Studies by the Federal Telephone and Radio Corporation in collaboration with International Telephone and Telegraph Corporation engineers, on the other hand, show that a superpower broadcasting system, comprising 12 stations individually powered at 200 kilowatts and grouped in an east coast area and in a west coast area, would effectively meet the requirements for world coverage.

The basic idea of a plan for such a superbroadcasting system was originally presented to United States Government authorities in September, 1941, by the Federal Telephone and Radio Corporation, an affiliate of the International Telephone and Telegraph Corporation. The present description, it is felt, will aid in visualizing this sizable and necessarily complex proposal and thus contribute towards the realization of an American international broadcasting system commensurate with the position of the United States in world affairs.

High Power, Directional Beams for Global Range

While the power of each of the twelve 200-kilowatt transmitters in the proposed superpower broadcasting system would be about double that of any transmitter now known to be in operation, efficient radiation of this energy would be imperative for world-wide coverage. The signals, moreover, would be radiated from highly directive antennas, thus concentrating the energy into sharply focused beams in order to cover given world areas or zones with signals of maximum intensity. The signal strength on the path of any zone, in fact, would be the same as that produced by a five million-watt broadcaster with a conventional non-directive antenna. Since twelve simultaneous transmissions of equal power to separate zones would be possible—all on frequencies most suitable for reaching a particular area at a specific time of day and year †—the effective output of the entire system would be greater than sixty million watts broadcast from a single transmitter with non-directional radiation such as is generally used with broadcasting stations operating in the intermediate frequency broadcast bands.

Signals of this magnitude would make possible regular reception of programs in the most distant areas despite occasional jamming by unfriendly stations. Jamming, it should be explained, is accomplished by transmitting noises or tones to prevent normal broadcasts from being heard. It can be overcome either by broadcasting signals powerful enough to override the jamming signal or by shifting frequency. The proposed system would provide transmitters so powerful and

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* Article compiled by F. J. Mann of the editorial staff of *Electrical Communication.*

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† See appendix.

capable of operating on so many different frequencies that radio broadcasts from these American stations would be largely free from any interference of this type likely to be encountered.

Not only would a broadcasting system of the size proposed permit direct reception of clear, steady signals capable of overriding all types of interference, but it would also provide programs ideally suited for rebroadcasting by foreign networks. Rebroadcasts of this character are made after the programs are picked up with a special high quality radio receiver and distributed over telephone lines to the various local network stations. Since the rebroadcasting transmitters operate on the local intermediate frequency, persons in distant countries not equipped with sensitive shortwave receivers may also listen to the programs on their present intermediate frequency radios.

I. T. & T. Pioneer Builder of High-Power Broadcasters

For more than ten years, International Telephone and Telegraph System companies have acquired valuable and extensive experience in the design, construction, and operation of large broadcasting centers similar to the one proposed. Due to the continuous demand from many European sources for increasingly greater power, these companies carried high-power radio research and development well ahead of what was deemed necessary in America in past years, so that they are now well equipped to produce large transmitters.

Out of more than 100 powerful transmitters supplied by I. T. & T. associate companies, the following are of interest as establishing the record of progress during the past decade or more, here and in Europe.

PRAGUE, CZECHOSLOVAKIA: medium wave—1 transmitter of 120 kilowatts—1930
DAVENTRY, ENGLAND: short wave—2 transmitters of 80 kilowatts—1937
ROME, ITALY: short wave—2 transmitters of 100 kilowatts—1939
ISSOUDUN, FRANCE: short wave—4 transmitters of 120 kilowatts—not completed
BRENTWOOD, NEW YORK: short wave—3 transmitters of 50 kilowatts—1942

Further, for more than ten years, I. T. & T. associate companies have manufactured or developed vacuum tubes capable of 100-kilowatt output and, more recently, vacuum tubes capable of 250-kilowatt continuous output on short waves and others for continuous 500-kilowatt operation on medium waves.

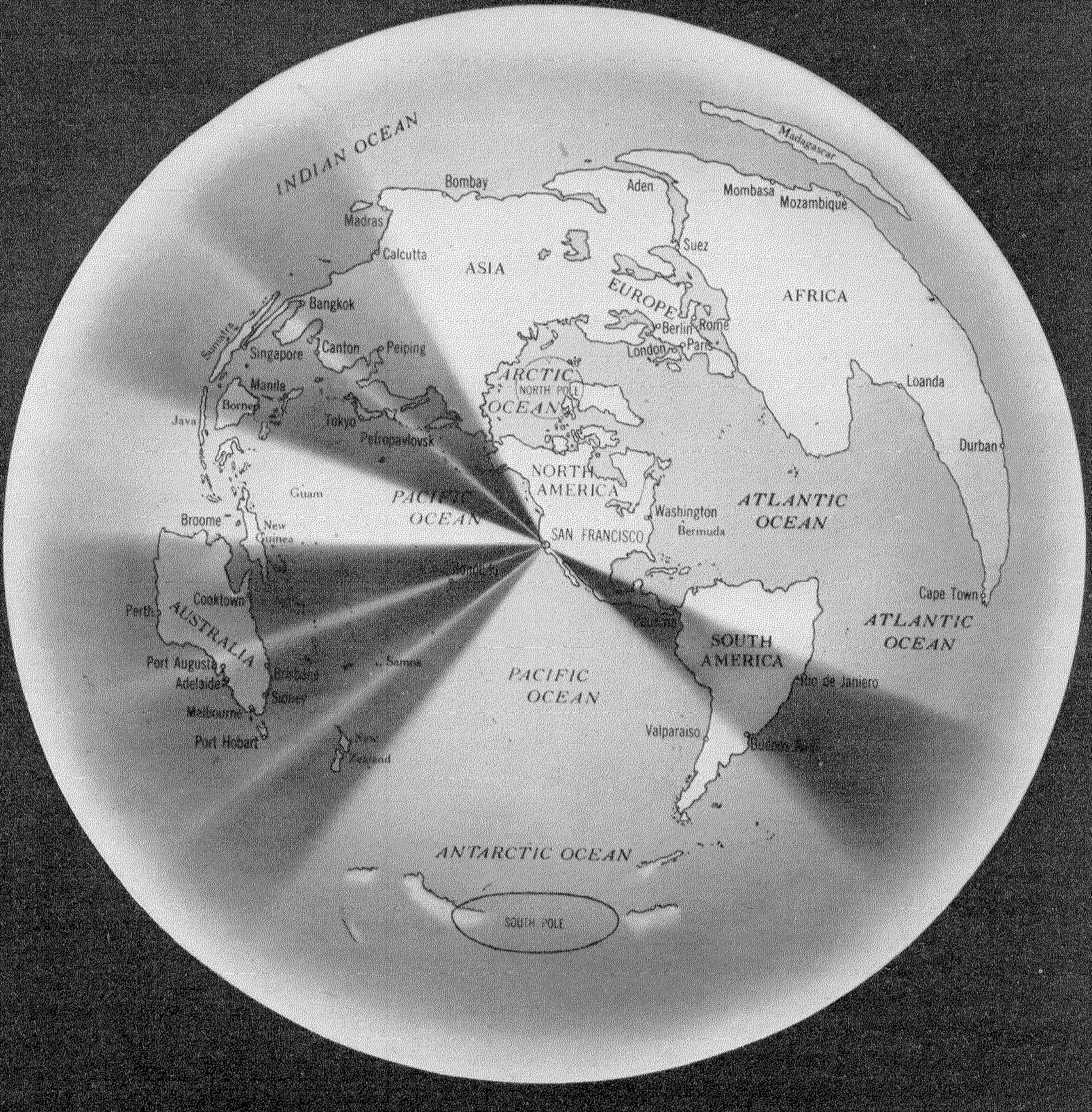
Operating Flexibility

Not only does this proposed design follow sound experience and principles developed by the I. T. & T. System in the past, but it provides for flexibility of operation of each center that should meet new demands likely to arise in the next few years. This flexibility, ample for all requirements, would be provided as follows:

1. One or more programs could be transmitted on several frequencies in any zone or any desired combination of zones.
2. Transmitters would be designed so that they could operate on the same frequency into separate halves of an antenna to give the equivalent of a 400-kilowatt transmitter in a given zone.
3. Antennas would be constructed to serve in any desired zone and on all frequencies suitable for a given zone or area.

If, after completion of the proposed broadcasting system, we should fly over the east coast center, the imposing number of antennas arranged in a semicircle—thirty-two antennas in all—would first attract our attention. They would cover, with the transmitter buildings and power input substations, an area of flat land approximately two miles long and one mile wide—the area to be unsettled and free of nearby hills and mountains.

Some of the antennas would be supported from wooden poles and some from steel masts, depending on the lengths of the wires and their heights from the ground. There would be a great variety of sizes of antennas, but only two shapes or patterns would be noted. The rectangular-shaped antennas would be the multi-element arrays for use on specific frequencies in the shortwave broadcast band. These would be the antennas normally used. The diamond-shaped, or rhombic, antennas would provide for operation on any frequency in the shortwave broadcast band. Thus, efficient operation would be achieved



World-embracing zones: Radio programs would cover world population centers in twelve zones, assuring maximum reception in these areas. But even in adjacent areas satisfactory reception would be possible, since zone edges merely mark portions where signal strength would be less than full intensity. Zones shown on the maps are by no means fixed. They might easily be shifted or broadened to compensate for changes in population or centers of interest.


Java
Sumatra
Singapore
Borneo
Manila
Bangkok
Canton
Calcutta
Madras
INDIAN OCEAN
Bombay
Broome
Perth
Peiping
ASIA
Tokyo
Guam
New Guinea
AUSTRALIA
Petropavlovsk
PACIFIC OCEAN
ARCTIC OCEAN
NORTH POLE
EUROPE
Aden
Berlin
Suez
London
Paris
Rome
Cooktown
Mombasa
AFRICA
NORTH AMERICA
Honolulu
Port Augusta
Brisbane
San Francisco
Mozambique
Madagascar
WASHINGTON
Adelaide
ATLANTIC OCEAN
Loanda
Sidney
Melbourne
Panama
Durban
SOUTH AMERICA
Cape Town
ATLANTIC OCEAN
Port Hobart
New Zealand
Rio de Janeiro
PACIFIC OCEAN
Valparaiso
Buenos Aires
ANTARCTIC OCEAN
SOUTH POLE

with the multi-element arrays on the specific assigned frequencies of the station, while the rhombic antennas would ensure frequency flexibility necessary to avoid jamming from other stations, or provide for special broadcasts on frequencies not regularly assigned.

Array-type antennas have been chosen as the principal radiators for this global shortwave broadcasting system since they are the most efficient type of antenna structure for high-power, shortwave, directional transmission. This type of antenna has been perfected to a high degree by International Telephone and Telegraph System engineers who have engaged in extensive research and development of antenna equipment for the many radio telephone and telegraph installations of the I. T. & T. System throughout the world. Research has made it possible to formulate design data required to control the specific direction as well as the angle of radiation within extremely close limits.

Arrays are usually designed for operation on a specific frequency. Each array antenna also would operate in a particular direction. This accounts for the large number of antennas that would be needed for regular multiple-frequency operation in the various zones. It should be pointed out that a small group of complicated and expensive rotatable antennas would not provide the required flexibility and multi-frequency operation necessary for a successful system. Moreover, they would be expensive and require more maintenance than the proposed antennas.

Ability to operate two transmitters tuned to the same frequency into a single array is an important feature of the proposed antenna system. This would result in 400,000 watts equivalent carrier output concentrated into the zone served by the antenna thus connected—an effective power output eight times greater than most broadcasting transmitters now operating in this country and about four times greater than any operating in this country or elsewhere. Such operation would make increased hours of service possible when conditions are adverse.

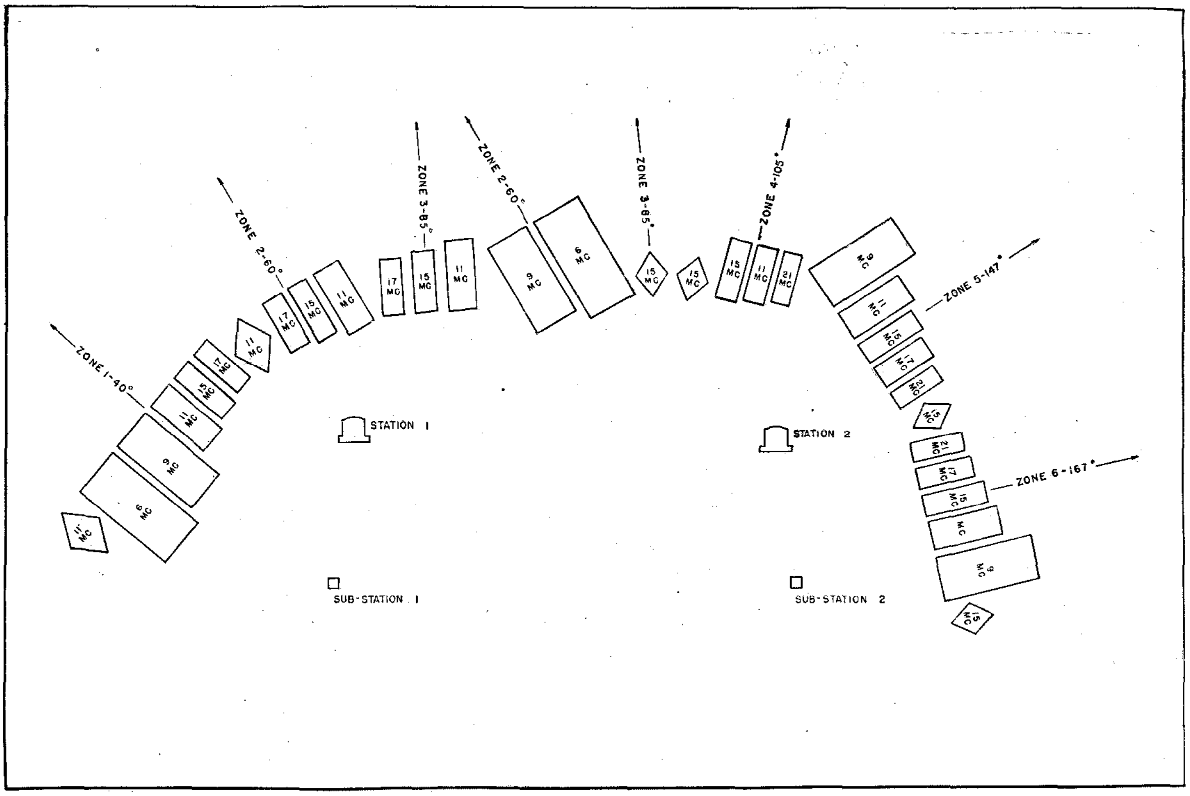
Rhombic antennas, while not so efficient as the arrays, are simple to construct and may easily be adjusted to any frequency within the shortwave broadcast band. They would be included only for use under emergency conditions or when it might become desirable to operate a transmitter on a frequency for which no array is provided.

Transmitter Buildings

Instead of the usual single transmitter building, there would be two modern concrete and glass buildings, identical in size and appearance at each site, making a total of four buildings for the system. They would be located within the area of the semicircle and spaced a good distance apart. By dividing the equipment between two separate buildings, shorter leads to the antennas would be practicable. Then too, the arrangement would provide a safety factor not possible with a single building since damage to one building would affect only half of the equipment. The undamaged building could still continue operation of half the station. A decorative pool with spray fountains (providing water to cool the equipment) would be located in front of each building.

Entering one of the transmitter buildings, we should find ourselves in an attractive foyer. A short distance to the left of the foyer would be a door labeled "Frequency Control Room." This room, containing all the radio frequency control equipment, would be a unique feature of the proposed transmitting stations. Here the high or radio frequencies for all the transmitters in the building would be generated by accurate, temperature-controlled, piezoelectric crystal oscillators. The regular fixed frequencies assigned to the stations would originate from these piezoelectric crystal oscillators. Continuously variable master oscillators would be provided also to permit operation on frequencies between the fixed, crystal-controlled frequencies officially assigned to the transmitters.

Included in the frequency control room would be an accurate frequency standard to assure that the transmitters would be kept exactly on their correct frequencies. This would be the "Bureau of Standards" of the station, where close supervision would be maintained over the steadiness of these initial frequencies, which later would be amplified many times and radiated from the antenna system as powerful radio signals. In fact, with the special attention which would be given to the accuracy of frequency control and the ease of picking up their steady signals on any part of the earth, these stations could serve another useful purpose, quite aside from broadcasting, by enabling the signals to be utilized for setting



Antenna disposition.

world-wide standards of frequency measurement.

To the rear of the foyer, doors would lead to the main transmitter room. Passing through these doors, we would come into the brightly lighted area housing the more powerful transmitter equipment. (See illustration on page 161.)

Panels for the transmitters would almost cover the surfaces of three walls. Directly facing us would be a console closely resembling a console of a huge theater organ. On it we should see neat rows of switches, plugs, knobs, meters, and colored lights. Seated at the console would be an operator who, by means of the many controls, would coordinate the functions of the entire station. At his fingertips would be the means of starting up power supplies, turning on transmitters, changing to different frequencies, switching in various programs coming from studios in nearby or distant cities—and, as each operation was performed, a different light would go on or off to indicate the status of a transmitter or power supply. At the same time other colored lights in other parts of the building would go on and off to indicate that some remote operation had been completed. The illusion would be complete—the operator would truly seem like a musician playing a giant color organ—only this instrument, while silent in the room itself, would have a radio voice loud enough to be heard around the world.

How Radio Signals are Broadcast

While the scene before us would be impressive, to those of us who were not radio engineers the array of panels, colored lights, switches, and meters could easily become a confusing jumble. The plan of the building indicates specific names and locations of the major pieces of equipment, but without basic knowledge of the functions of the various apparatus, this information might not be specifically helpful. However, the purpose of the apparatus may be understood from the following description of how radio signals are broadcast. First we must note that a large radio broadcasting station is in reality a huge amplifier of two types of feeble electric currents.

One type is a steady alternating current whose alternations change millions of times a second, i.e., at radio frequency. We have already seen how these radio frequency currents would be generated at the proposed station by oscillators in the frequency control room. From there they would be conducted to the RF (radio frequency) drivers.

An RF driver in a transmitter amplifies the feeble radio frequency currents several times. After amplification, they pass to the much larger final power amplifiers where the RF energy is again boosted many times until it reaches its full output and can be connected to an antenna to be radiated into space.

Amplification between the oscillator and the antenna is of the order of millions. At each stage of amplification, the apparatus for handling thi greater power must be increasingly larger, provided with higher voltages, and equipped with more and more intricate apparatus to control the greater powers generated.

The resulting electromagnetic waves so generated then carry the radio signal to distant points. When tuned in, it can cause an electric eye tuning indicator to operate on a radio receiver thousands of miles away, but, alone, it produces no audible response in the receiver's loudspeaker. The name "carrier frequency" given to this signal describes its important function of acting as a means of carrying the voice or music of the broadcast program through space. The carrier, therefore, may be compared to an invisible telephone wire connected between transmitter and receiver over which sound currents can be transmitted.

The other type of electric current which must be amplified by the transmitter originates at the microphone in the studio. This current varies in frequency with the vibrations of the speech or music reaching the microphone as sound; it also varies proportionately to the loudness or softness of the sound. When these audio frequencies, as they have been named—generated by the microphone from the sound waves—reach the transmitter, they possess only the strength of a whisper in a telephone receiver. But in the audio frequency section of the transmitter, the final stage of which is called the modulator, they also must be amplified millions of times before they can be made to modulate the carrier frequency—amplification that must be effected without distortion of the signal frequencies.

While the audio frequency currents are unchanged in form as they are amplified, they are enormously increased in power. When they have received their final boost through the modulator, it would be possible to connect them directly to a loudspeaker. A loudspeaker large enough to operate on the full power of a broadcast transmitter modulator would have a voice louder than the sound emitted from a large squadron of four-motored bombers and would be many thousand times as powerful as an average large home loudspeaker.

Even with such great power, the sound produced would be heard only a few miles away while, if equivalent energy is utilized to modulate a powerful radio frequency carrier, the distance sound may be heard through a radio receiver capable of being tuned to the carrier frequency is practically unlimited.

For complete modulation, the audio power from the modulator actually must match the power of the radio frequency amplifier so that a single 200-kilowatt radio transmitter would require two 200-kilowatt amplifiers—one for audio frequencies and one for radio frequencies. Each would be very different in function, but the vacuum tubes used in both would be much alike and power supplied to each would be similar.

We see therefore that, while the high frequency or radio carrier itself cannot be heard in the ordinary radio receiver, the variations imposed upon it through modulation are at audible frequencies which enable the loudspeaker of the distant receiver to reproduce the sound. We see also that the problem of constructing a large radio transmitter is the problem of producing equipment capable of amplifying infinitesimally feeble currents millions of times.

The radio frequency, while being amplified, must be kept steady, free from interference, and must not be allowed to radiate before it is connected to the antenna. The audio frequencies also must be kept free from interference and confined to their respective channels, and they must be amplified faithfully, that is, without distortion.

The proposed main transmitter room on the opposite page shows the two-level arrangement of transmitters and power supply panels.


Charles DuBose

Both tasks become increasingly greater as the power of a transmitter is increased. The first amplifier stages of a 200-kilowatt transmitter might be very similar to the first stages of any other transmitter. But the final stages, the 200-kilowatt power amplifiers and modulators, would be quite unlike those of a 50-kilowatt transmitter, not only in size but also in the specialized design and construction necessary to handle this greater power.

Layout of a 200-Kilowatt Broadcasting Station

Returning now to the station plan, we note that the various amplifiers are segregated in relation to function and to power. At the left of the console are the audio racks containing amplifiers to give an initial boost to the program material coming in on the telephone lines from the studios. These racks would be provided with patchboards to permit any program to be connected, by means of lines running from the racks, to suitable switches on the console. Operation of these switches would permit connecting separate programs to each of the four modulators located toward the rear of the building; or a single program might be connected to all four.

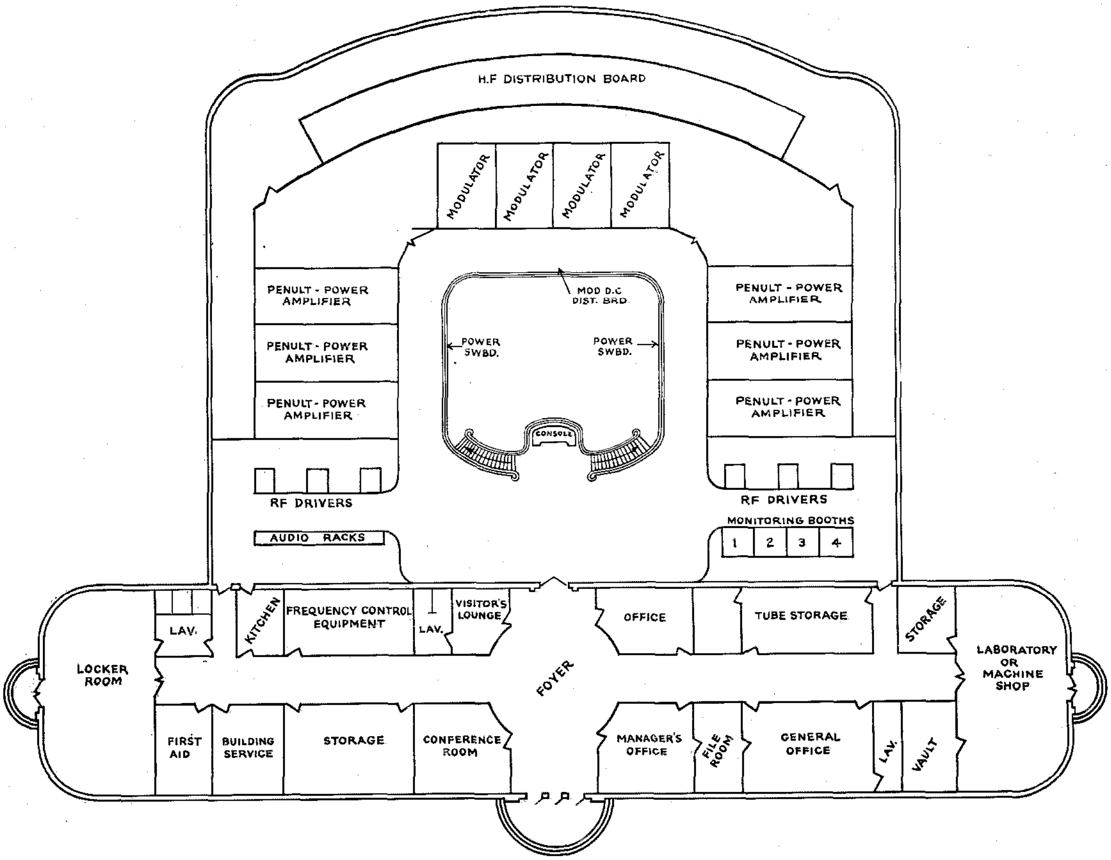
Three RF drivers are shown located in cabinets on either side of the building, making a total of six drivers to connect to the six penultimate and final power amplifiers located in rows behind them. These drivers and amplifiers would step up the radio frequency currents generated in the frequency control room, previously described, to the power necessary for reliable long-distance broadcasting, that is, to the full 200 kilowatts output.

It should be noted that fifty per cent more radio than audio frequency equipment would be provided. This ratio would exist in all the transmitter buildings. Four programs could actually be transmitted simultaneously from the single transmitter building shown since there would be four modulators. The additional radio frequency equipment would enable the operators to preset the frequencies of the two radio frequency sections not in service while the other four sections are in operation. Two of the program channels could then be switched by means of controls on the console to the two idle radio frequency sections, thereby permitting instantaneous change of frequency. Thus, all switching and control operations necessary to change an RF power amplifier and its pre-amplifier stages from one frequency to another could be performed with the power off and without taking a transmitter off the air.

Ready access to all heavy power transformers, rectifiers, power control equipment, and air conditioning and water cooling machinery in the basement would be provided by stairs on either side of the console. This power equipment would have panels fronting on an open area arranged so that meters, controls, tubes, and warning lights would be visible to the control operator at the console above—another unique feature of station design.

The monitoring booths would be equipped with special insensitive radio receivers which would pick up the programs from the air and make them audible to the monitor operators. Complete, permanent recordings of all programs broadcast as received by the monitor radios would be made in these booths. Each booth also would include a microphone and a transcription turntable, both connected to the audio racks, so that, when necessary during an emergency or when adjustments were being made, programs could be originated at the station itself.

The high frequency distribution board at the rear of each building would carry the total power output of the transmitters to the antennas at radio frequency. The purpose of such a board is to permit instant connection of the output of any transmitter to any antenna. Since there would be sixteen antennas for each transmitter building to operate with six radio frequency power amplifiers, a total of 96 switching functions must be possible on the switchboard, not counting switches to permit operating two amplifiers on the same antenna. The design of this switchboard would be especially complex since the board must handle high voltages at extremely high frequencies—a difficult problem of insulation and design of components, not only to prevent breakdown, but also to assure minimum power loss. Power reaching such a switchboard would necessarily be in its most expensive and usable form so that waste at this point would be particularly undesirable and relatively very costly.



Building plan showing the arrangement of station components. Each building would be equipped to provide for the comfort of operating personnel as well as for administration of the station.

After lengthy study and many experiments with dielectrics and switch designs, I. T. & T. System engineers have perfected a design for a high frequency distribution board that is ideally suited to the task.[1] Such a board was installed at the CBS International Broadcasting Station on Long Island, where it is now in operation, and has completely solved the difficulty of providing means for instantaneous interchange of radio frequency amplifiers among the various antennas.[2] In practice, this switchboard not only provides an efficient and fast means of switching from one antenna to another, but it also makes the operation foolproof. Switches are equipped with warning lights and interlocks to guard against the possibility of connecting transmitters

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[1] "Radio Frequency High Voltage Phenomena," by Andrew Alford and Sidney Pickles, *Electrical Communication*, Vol. 18, No. 2, 1939; *Electrical Engineering*, Vol. 59, March, 1940.

[2] "New 50-Kilowatt CBS International Broadcasters," by H. Romander, *Electrical Communication*, Vol. 21, No. 2, 1943.

to antennas already in use or of disconnecting an antenna while power is being fed to it. The antennas of the world broadcasting system would be similar to those used at the CBS station and the same type of board would be employed.

Giant-Sized Vacuum Tubes

In the final power amplifiers and modulators, giant-sized vacuum tubes would be used. On short waves, it is not practical to parallel a large number of medium-powered tubes to obtain high power as has been the practice on intermediate and long wave transmitters. Hence, the power tubes in a 200-kilowatt shortwave transmitter must be capable of carrying the full output of the station under normal conditions of continuous operation.

Design of tube structures of the size proposed is in itself a major problem. The larger elements employed not only create new mechanical difficulties but, as their size increases, the problems of design for high frequency operation mount in even greater proportion. As previously mentioned, I. T. & T. associate companies have been building high-powered vacuum tubes for many years so that the chief obstacles to the production of vacuum tubes of the highest power have been overcome. Tubes suited to the purpose, in fact, have been manufactured; they were of the sealed-off type and were over four feet long. They are the largest tubes of their kind ever manufactured.[3] A new design permits smaller elements and a slightly smaller overall size, resulting in improved efficiency without loss of power. This newer tube design would be employed in the proposed transmitters.

Tubes of this size are water-cooled to permit efficient dissipation of the enormous heat developed in them. Distilled water conducts the heat from the tubes to large heat exchangers which are, in turn, cooled by water circulated through spray type fountains in front of each building. The water in these fountain ponds cannot be applied to the tubes directly, since even slight impurities would cause a current leakage.

Power Requirements

Enough power to supply a city of about 20,000 persons would be the total power input requirements of the two sites. Substations on the east and west coast sites would have a capacity of 3500 kilowatts and 2000 kilowatts, respectively—a total of 11,000 kilowatts. Both sites would be provided with two substations supplied from standard commercial power lines. Each substation would be connected to a different source of power so that failure of one source of supply would not cause shutdown of the station.

Despite this enormous power capacity, the overall efficiency of the stations undoubtedly would exceed that of smaller stations; for, as station size increases, the efficiency tends to improve. The proposal actually makes possible a tremendous saving in power cost compared with a large number of stations of lower power—inadequate for world coverage. Other costs also would be appreciably lower since personnel, buildings, land, and control equipment could all be utilized more effectively with the higher-powered, centralized system.

High power and high efficiency would be attained in the proposed transmitters without lowering standards of performance. Quality of modulation, frequency response, and noise suppression would be equal or superior to any shortwave broadcast station now in operation. Realizing too, that it is more important to keep the frequency stability of such enormous powers within closer limits—just as it is more important, say, to keep a large ocean liner on its appointed course than a small fishing boat—the designers have provided for a carrier frequency deviation even less than permitted by international law for broadcasting stations operating in the high frequency broadcast range. In all respects, the system would meet or exceed the most advanced design practices.

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[3] "Tubes for High Power Shortwave Broadcasting Stations—Their Characteristics and Use," by G. Chevigny, *Electrical Communication*, Vol. 21, No. 3, 1943; *Proceedings of the I.R.E.*, Vol. 31, No. 7, July, 1943.

Appendix—How Short Waves are Broadcast

Shortwave radio signals travel in a straight line much like the beam of a searchlight. We know that the most powerful searchlight in the world would never reach the earth's surface beyond the horizon because the curvature of the earth forms an impenetrable opaque "bump." But radio waves can skip beyond the horizon and be heard at a great distance, even around the world under favorable conditions.

To understand this skipping, we might visualize an attempt to flash a light around the corner of a building. It cannot be done, because light will not bend that way. But light can be reflected and if we set up a mirror tilted to the correct angle, the light will be reflected around the corner, still traveling in straight lines.

Nature has provided such a mirror for radio waves, high in the sky. It is made up of the particles of the ionosphere, a region in the upper atmosphere where free ions and electrons exist in sufficient quantity to cause radio waves to be reflected. Like light against a mirror, radio waves strike this reflecting surface and bounce back to earth, the angle of reflection determining how far around the globe they will be heard.

Some of the energy of the radio signal is lost from the first reflection, but, if sufficient energy remains, the waves may still be reflected from the earth back to the ionosphere and thence back again to earth where they will be heard much further away from the transmitter. The distances between each area of reception are known as "skip" distances and ordinarily the signals are either not heard in these areas or are of unsatisfactory strength or quality for reliable reception with a minimum of fading or noise.

Reflection determining the skip distance areas is itself dependent on several factors. One is the actual height of the ionosphere, which varies from 50 to 250 miles. It is higher at night than during the day; higher in the winter than in the summer. A second is the frequency of the transmitted wave; a third the antenna design. These factors control the angle of reflection of the propagated waves which, in turn, influences the depth of the transmitted beam.

The longer wavelengths, such as those assigned to local broadcasting stations, have a very sharp angle of reflection so that they require numerous reflections for long range propagation. Thus, tremendous powers would be needed at these wavelengths for reliable reception more than a few hundred miles away. It is true that under unusual or freak conditions, local radio stations on medium waves in New York have been heard in Australia or China, but this happens very rarely. Hence, these wavelengths are not suitable for great distances.

The shortest wavelengths, called ultra-short waves or ultra-high frequencies, have a very flat angle of reflection. The angles are so flat that when the waves hit the ionosphere, they are never reflected back to earth, but keep traveling over the surface of the ionosphere until their energy is dissipated. So the ultra-short waves are said to behave similar to light rays and to travel only in a straight line. And like a beam of light, their range is close to the horizon. The ultra-short waves are excellent for local transmission and are valuable for television and other special broadcast and communication facilities. Their range is ordinarily limited to less than 100 miles.

From actual experiment and operational data, it has been found that radio signals of frequencies from about 6 to 21 megacycles are best for long distance transmission. By changing frequencies in relation to the height of the ionosphere at the time of transmission, it is possible to reflect a radio signal to any part of the world.

Radio waves share another property with light —radio energy, like light energy, can be diffused over a wide area or concentrated into a sharp beam. If the lens and reflector are removed from an ordinary battery flashlight, the light is hardly strong enough to read by in a room with no other light source, but the same amount of light can be focused into a sharp beam that will penetrate with good strength hundreds of feet. In the same manner short radio waves can be concentrated into narrow beams with specially designed antennas and reflectors. Such antenna systems have the property of increasing the effective radiation to a particular segment of the earth's surface so that the signal reaches its destination hundreds and even thousands of times stronger than would be the case without such concentration. The reliable distance range with a given power is thus greatly increased.

Development has progressed to a point where a radio signal can be spotted on a particular area almost as accurately as checkers can be placed on a checker board. Further, it is possible to design antennas permitting the radio beam to broaden or expand so that, after the initial skip of several hundred miles, the signals from subsequent reflections would overlap enough to permit good reception without further skip distance.

Directing and locating a radio wave in this manner greatly increases the efficiency and precision of radio propagation. Without such technique, reliable transmission over great distances would be impossible. Nevertheless, wherever radio waves must travel long distances, they meet barriers over which the radio engineer at present has no control. These barriers may be likened to fog or smoke between a light and its objective, obscuring the light. A radio signal is obscured by unwanted sound or noise. Some of this noise, like fog, results from natural phenomena called static or atmospherics; some of the noise, like smoke, is man-made, the result of the many present-day applications of electricity. *Whatever the cause, its only cure in long range broadcasting is higher power.* It is perfectly possible to send a radio signal to the other side of the world using very little power and, under favorable conditions, this signal will be heard by the far-distant radio listener. If the noise barrier is too great, the signal will still be transmitted as before, but it will be as unintelligible in the radio receiver as a whisper in a noisy room. The effective power of the transmitted signal must, therefore, be raised enough so that the received signal will be appreciably louder than any type of noise coming into the receiver simultaneously with the signal.

Providing a global broadcasting system thus resolves itself into a problem of building transmitters capable of radiating on specific frequencies between 6 and 21 megacycles, capable of concentrating or focusing these radiations for maximum world coverage in relation to population centers and possessing power sufficient to override existing noise and thus produce clear and steady signals at the remotest points.

Addendum, Vol. 22, No. 1, 1944

MARINE NAVIGATION AIDS—THE RADIO DIRECTION FINDER AND THE GYRO-COMPASS

For an account of the Radio Direction Finder from an historical viewpoint, the reader is referred to: "The Radio Direction Finder and Its Application to Navigation" by Frederick A. Kolster and Francis W. Dunmore, Scientific Papers of the Bureau of Standards, No. 428, published by the Department of Commerce, Washington, D. C., 1922. This publication is now out of print but may be found in technical libraries.