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CONTROL ROOM OF RADIO STATION WDOD, CHATTANOOGA, TENNESSEE, SHOWING FRONT PANEL ARRANGEMENT AND CONTROL DESK OF NEW 5 KILOWATT BROADCAST TRANSMITTER DESIGNED AND BUILT BY THE FEDERAL TELEGRAPH COMPANY.

The Evolution of Wire Transmission*

By GEORGE H. GRAY

International Standard Electric Corporation, New York, N. Y.

THE importance of recent developments in telephone wire transmission systems may best be appreciated from a brief historical review of the progress achieved in such systems since the early days of the telephone. Such a review is given herein, followed by a brief discussion of the important economic implications of the newer broad band systems—12-channel carrier and coaxial cable.

The review may be divided conveniently into three periods, plus a fourth now well started. Important additions to available types of plant permitted advances during each period in at least three of the following respects:

1. Conversation distance;
2. Transmission channels obtainable from a pair of conductors;
3. Frequency band transmitted and, hence, improved quality and naturalness of conversation;
4. Reliability of service.

1. 1876–1900

The first period, roughly twenty-five years, ended about 1900. Although conversation then was still limited to one per pair of wires (neglecting the ground return telephone circuit and the simultaneous use of wires for telephone and telegraph purposes), reliability of service and transmitted quality had been improved and the transmitting distance increased considerably. This was accomplished largely by the use of copper instead of iron wire, better insulators, improved line construction and carefully designed transposition schemes. These changes involved no additions to the inside plant and no increased complications in the outside plant other than the necessity for properly maintaining the transpositions.

The restriction in the transmitting distance at the close of this period was largely economic due to the fact that, as the distance increased, the quantity of copper required per kilometer for a given line attenuation rose steeply. This is indicated in Fig. 1, Curve *A*, which shows the weight of copper needed, per circuit-kilometer, for circuits up to 200 km (125 miles) in length with a total overall attenuation of 10 db.

Using 4.19 mm (0.165 inch) copper wire, conversation under favorable conditions was possible by the end of this period over distances of nearly 1,600 km (1,000 miles).

2. 1900–1915

The second period, extending from 1900 to about 1915, was marked by the introduction of phantom circuits (invented earlier but not used commercially until about 1903), loading coils and quadded toll cable. These changes resulted in a 50% increase in the circuit capacity of a pair of wires and in slightly more than doubling the transmitting distance of open wire circuits. The use of underground toll cable of course improved the reliability of service. Unfortunately, the use of loading limited the frequency band which could be transmitted. In some cases this band was confined to frequencies below approximately 1,800 cycles, and this affected the quality of the transmission.

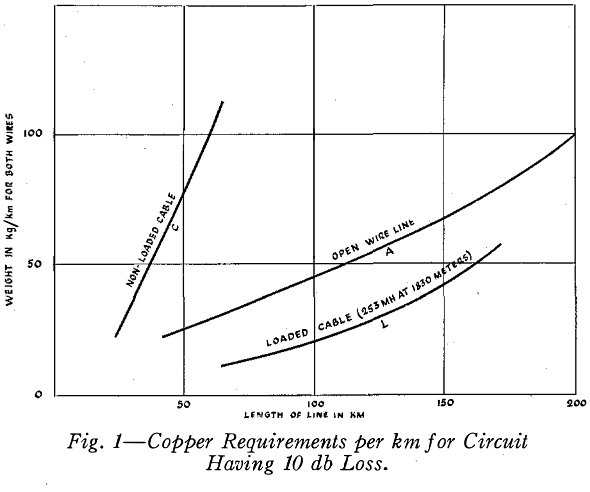

Fig. 1—Copper Requirements per km for Circuit Having 10 db Loss.

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* The material for this article was prepared originally by Mr. S. Van Mierlo while associated with Laboratoires Le Matériel Téléphonique, Paris. It was submitted via London prior to September, 1939, and has been rearranged and amplified by the present author.

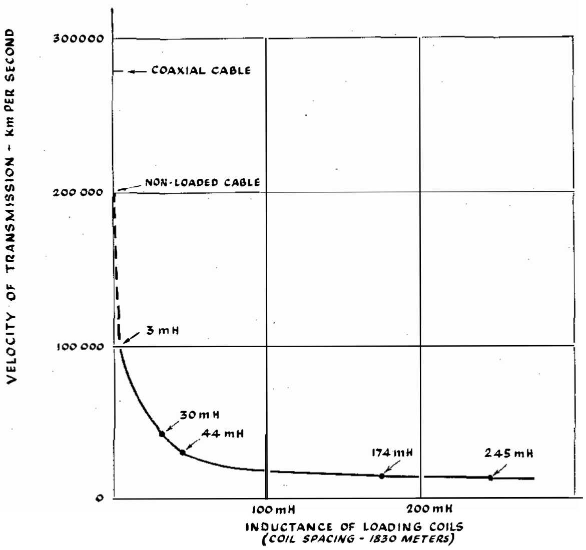

Fig. 2—Speed of Propagation.

The introduction of loading coils also reduced the speed of transmission, thus bringing about potential difficulties from transient and echo effects. However, this was not particularly objectionable at the time since the circuits involved were comparatively short. The change in transmission speed with change in weight of loading is shown by Fig. 2, in which the coils are assumed to be spaced at 1,830 meters (6,000 feet).

Fig. 1, Curves *C* and *L*, respectively, gives the weight of copper needed per circuit kilometer for an overall voice frequency attenuation of 10 db for non-loaded cable and for cable loaded with 253 mh coils spaced at 1,830 meters. The copper requirements of non-loaded cable obviously far exceed those of open wire so that such cables, by themselves, are practicable only for short distances. Loading, as is well known, greatly reduces the amount of copper required; in fact, for the particular conditions assumed, the loaded cable circuit requires only a little more than half the copper necessary for the non-loaded open wire circuit.

With a view to reducing the amount of copper required for a given distance (or increasing the distance for the same amount of copper), a scheme was tried using microphones to control higher power than was practicable with the ordinary carbon microphone, i.e., to increase the total permissible attenuation in the transmission system. Various water-jet microphones were constructed, but high first cost and maintenance expense made such a solution unsuitable for use at subscribers' stations.

The inside plant was made slightly more complex by the phantom repeating coils, and the loading made necessary certain precautions in the maintenance of the outside plant. In general, however, it can be said that this period added little to the plant complexity.

3. 1915–1937

The third period, beginning about 1915 and lasting until perhaps 1937, included the introduction of some radically different and very important types of plant such as the:

a. Vacuum tube repeater
b. 4-wire circuit
c. 1 and 3-channel carrier systems
d. Radio links

During the last few years of the second period (1900–1915) interesting service results had been obtained with "mechanical" repeaters, consisting essentially of combination microphones and telephone receivers. Certain inherent disadvantages, however, were involved and this combination was abandoned soon after the advent of the vacuum tube repeater.

The vacuum tube repeater at once more than doubled the transmitting distance of open wire circuits and, by making possible the removal of open wire loading, permitted the transmission of an increased band width. In cable circuits, repeaters permitted a reduction in the weight of loading and hence an increase in the band width and in the speed of propagation. The 4-wire circuit greatly increased the transmitting range for cable. The 3-channel carrier made it possible

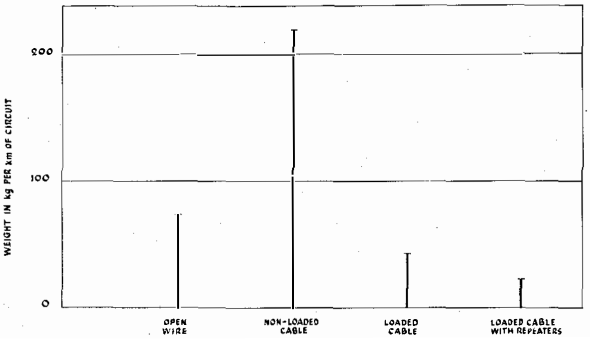

Fig. 3—Comparative Copper for Different Systems. Length: 150 km; Attenuation: 10 db.

to obtain nine circuits from an open wire phantom group where only three could be obtained before—a threefold increase in capacity. And by combining transoceanic radio links with land circuits, the transmitting range was increased to such an extent that a conversation around the world was held in 1935 over a route of approximately 36,000 km (23,000 miles): New York–London–Amsterdam–Java–San Francisco–New York. Obviously, these advances were not obtained without an increase in the complexity of the plant. It became necessary to maintain repeaters, carrier terminal equipment, radio terminal equipment, special transposition schemes, etc.; but, on the whole, no very serious difficulties were encountered. This was due, in no small measure, to special plant personnel training courses conducted at appropriate intervals.

For a circuit length of 150 kilometers (about 90 miles) and an overall voice frequency attenuation of 10 db, the copper required per kilometer is shown in Fig. 3 for open wire circuits, nonloaded cable, loaded cable and loaded cable with repeaters. The relative copper reduction in the case of the repeater systems obviously would be far greater if an overall attenuation less than 10 db were assumed.

Particularly in carrier and in 4-wire systems the total attenuation of a long distance circuit can be maintained at a very low value (often below 3 db) in the transit condition by the use of repeaters. This low attenuation is most important from the viewpoint of economy in regional networks, inasmuch as the total attenuation equivalent between two subscribers (say 25 to 35 db) can then be almost entirely absorbed by these networks.

Summarizing, vacuum tube repeaters and 3-channel open wire carrier systems made possible a practically unlimited increase in transmission range and an improvement in transmission quality. Their introduction, moreover, influenced toll rate decreases appreciably. Nevertheless, outside plant expenditures remained a fairly large factor in the cost of furnishing toll telephone service. Consequently considerable attention naturally was devoted to possibilities of further reductions in outside plant costs.

With near-zero-equivalent circuits already available on conductors approaching the minimum size imposed by mechanical limitations, the most promising solution seemed to be a further increase in the number of circuits obtainable per pair of wires. This, of course, involved an increase in the frequency band transmitted and, unfortunately, greater transmission losses and crosstalk due to the application of higher frequencies.

The negative feedback repeater, special transposition schemes for open wire lines, the separation of the "go" and "return" conductors in cables, special entrance cables, very careful balancing of all circuits, improved filters, dry metallic modulators and demodulators, and many other developments made possible the application of higher frequencies to existing types of plant and paved the way for the next period in the history of wire transmission systems.

4. *1937–*

This fourth period, now well initiated, commenced about 1937 and may be designated as the "broad band" period of wire transmission. The more important developments include:

a. 12-Channel open wire carrier
b. 12-Channel cable carrier
c. Coaxial cable

Although definite predictions would be somewhat premature, present indications are that progress during this period will exceed even that of the previous period.

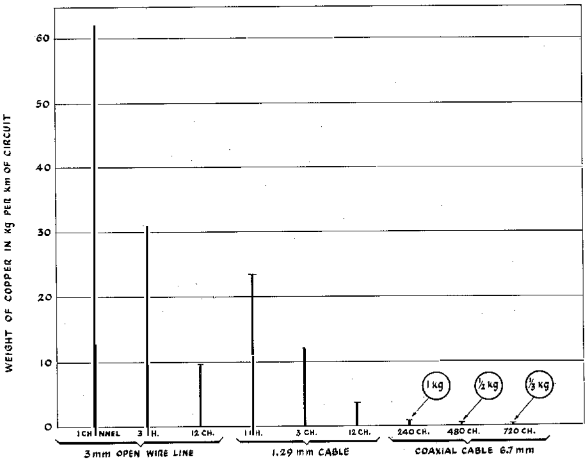

Fig. 4—Comparative Copper for Different Carrier Systems.

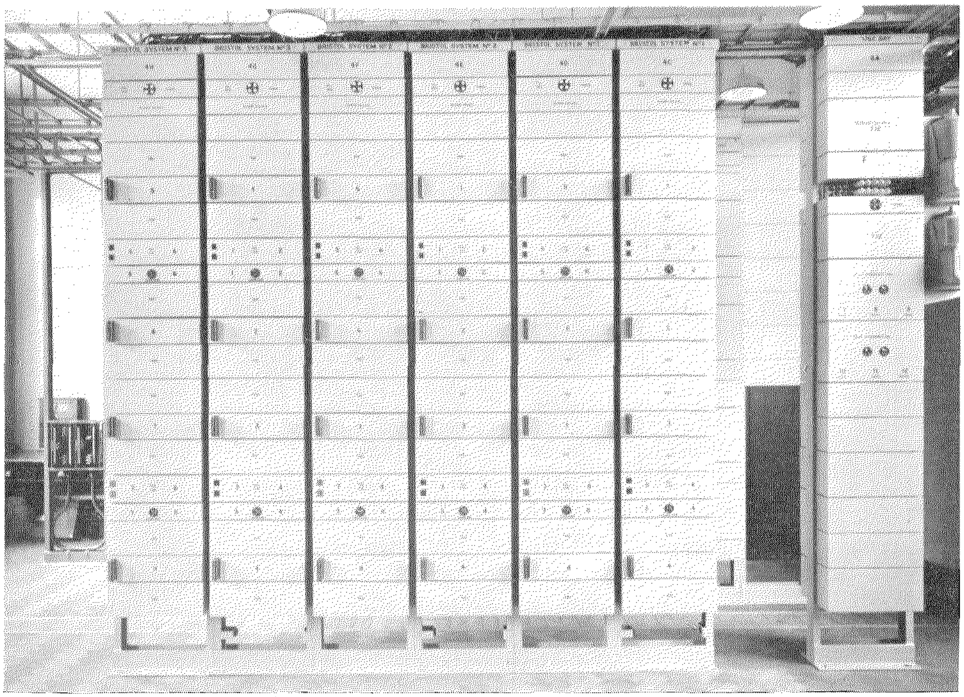

Fig. 5—General View of Terminal Equipment. One of first 12-channel carrier-on-cable installations, showing oscillator, channel and amplifier bays.

An indication of the results obtainable with 12-channel carrier current systems can be visualized from Fig. 4, which shows the copper weight, for both open wire and cable, per unit of channel circuit length (voice plus carrier) in various transmission systems. The copper reduction effected in 12-channel systems is striking.

This reduction must not be taken as representing the relative reduction in *plant costs* since its accomplishment requires a considerable expenditure for equipment (carrier terminal apparatus, repeaters, balancing equipment, etc.); and also, in the case of the open wire carrier, necessitates special transpositions, the installation of new types of entrance cables and other important items.

Loading requirements for cable, it is pertinent to note, have been decreased from 44 mh for voice frequency to 22 mh in the single channel system, to 3 mh in the 3-channel system, and to zero in the 12-channel system. Simultaneously, propagation velocity has been increased radically (Fig. 2).

Loading performed an important service in improving transmission. However, the necessity for transmitting a wider frequency range at higher speeds has now brought about its abandonment for the highest grade of circuits in both open wire and cable.

In the case of 12-channel systems, it might be thought that elimination of loading and the necessity for frequencies up to 60 kc per second would prevent their commercial application. Actually, however, attenuation of 1.29 mm conductors in 12-channel cable systems is about 1.6 db per km (2.6 db per mile) at 60 kc per second, a value which is quite admissible in view of the fact that it is practical in this case to work the channels at an attenuation of approximately 60 db per section with repeaters spaced at intervals of about 35 km (22 miles). Development of these repeaters has progressed to a point where about two out of every three repeater stations can generally be operated on an unattended basis.

The reasons for this high permissible attenuation are very low outside interference at high frequencies and the use of separate cables for the two directions or, alternatively, a single copper-screened cable to reduce interference between the go-and-return channels. As is well known, the limit of amplification, or attenuation, is determined by the signal-noise ratio: low outside interference and low crosstalk result in decreased noise. Speech or transmission signals, therefore, may be correspondingly reduced, i.e., very high level differences between the beginning and end of a cable section are permissible.

An inherent advantage of 12-channel systems, highly significant from an economic viewpoint, results from the importance of installing cables sufficiently large to provide adequately for future growth. Since cable cost represents the greater part of the total outlay for a non-carrier system, the initial investment in cables is ordinarily great and full realization of returns must be deferred until they are worked at full capacity. In 12-channel systems the initial investment, on the contrary, is relatively low, and terminal equipment can be added when required. Moreover, in 12-channel cable systems, the initial investment is not only lower, but a better balance between outlay and revenue can be attained over the entire period of use.

It should be emphasized that no attempt was made to reduce the width of the frequency band when the number of channels was increased. Long experience and extensive research, in fact, have demonstrated the importance of transmitting a relatively wide frequency band (250–3400 p:s, for example). The practical ultimate criterion of transmission quality obviously involves faithfulness of reproduction, as well as the signal level and freedom from noise. The subscriber's choice is the circuit which "speaks best." A wide band width, moreover, makes it possible to reduce the transmission level, especially if the noise is low. Then too, if the transmission loss in a long distance link is reduced to zero, the total allowable losses can be concentrated in the local networks with considerable decrease in their cost. Further, this loss may be increased by several db for the same overall effective transmission, provided the width of the transmitted frequency band is adequately increased. To derive the full benefit from the widening of the band, the subscribers'

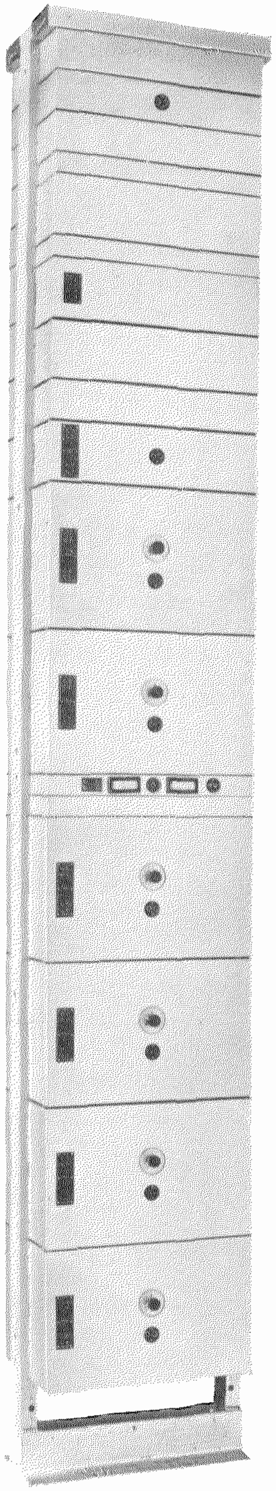

Fig. 6—Later Type of Channel Bay—12-Channel Carrier System. The bay contains complete equipment for one group of 12 channels with the exception of the terminating sets.

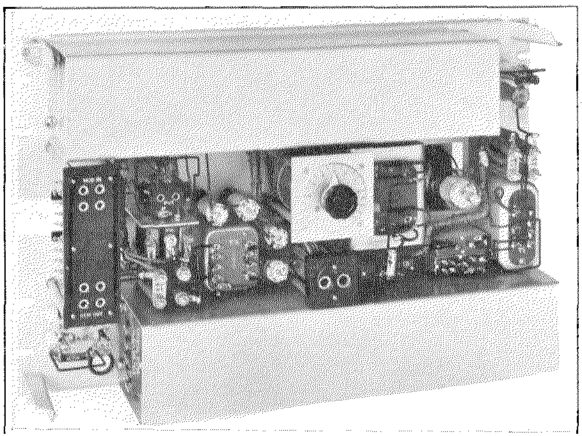

Fig. 7—Modulator-Demodulator Panel—12-Channel Carrier System.

apparatus—transmitter and receiver—obviously must be capable of producing and reproducing this band. Such subscribers' apparatus has been developed and introduced into commercial use.

The propagation velocity over 12-channel cable systems is about 200,000 km/s (125,000 miles per second), i.e., instantaneous for all practical purposes. Even on the longest lines, therefore, speech quality is not appreciably diminished by echoes or other phenomena due to low propagation speed. Consequently, lines may be interconnected at will.

In local networks, the economic advantage to be derived from linking up distribution centers by means of cables is clear. Interconnection of all subscribers, or even all groups, evidently would involve a prohibitive outlay. Similarly, in certain cases, the principle of distribution centers interconnected by cable might be extended to international networks, supplemented by carrier current cables radiating towards the principal regional towns.

It is thus apparent that the 12-channel system, along with inherent economy and improved transmission quality, facilitates the introduction of more economical networks.

Because of the advantages of the 12-channel carrier cable system the British General Post Office immediately adopted it for its principal toll networks; the first of such systems was installed in England even before the close of 1936. Shortly thereafter systems were installed in other countries, including the United States, France, Rumania, Sweden, Finland, Holland and Belgium.

Fig. 5 gives a general view of the terminal equipment of one of the early installations, while Fig. 6 illustrates a later type of channel bay. Fig. 7 shows the modulator-demodulator panel, comprising two crystal filters. Fig. 8 is a view of a crystal filter.

COAXIAL CABLES

For use where very large numbers of telephone circuits were needed and for television (which requires cables capable of transmitting a frequency band of at least 2 mc/s), consideration was given to the application of coaxial cables. Their speech channels, as is now well known, are counted in hundreds rather than in dozens. Even for cables of small diameter, frequencies of the order of several megacycles can be handled; and, since telephone channels are spaced at 4 kc/s, several hundred voice channels can readily be made available. In such cases,

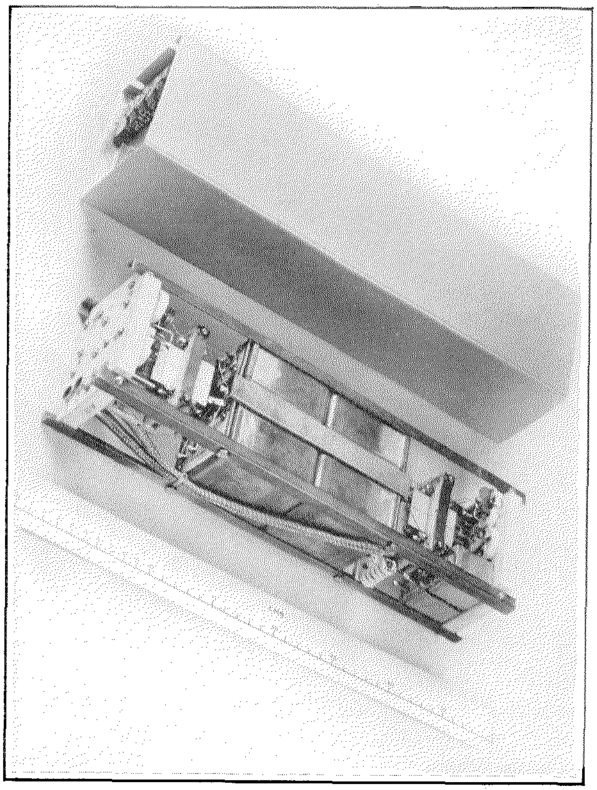

Fig. 8—Complete Crystal Channel Filter Shown in Case and with Cover Removed—12-Channel Carrier System.

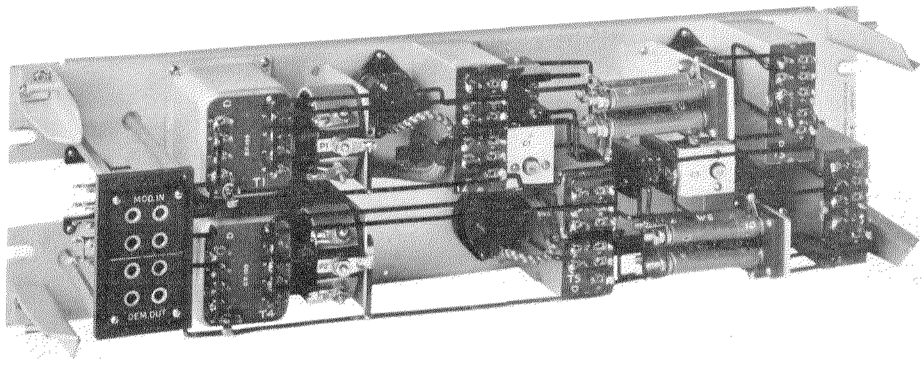

Fig. 9—Group Modulator-Demodulator.

the copper equivalent per speech circuit is extremely low (Fig. 4).

In practice, hundreds of transmission channels between points separated by considerable distances are rather infrequently required. However, if a demand for television channels should arise, this no doubt would result in the installation of coaxial cables and probably additional coaxial units could be added economically for telephone channels. For other installations 12-channel systems appear at present to be more attractive except for long, very heavy traffic routes.

In Europe, coaxial cables have been laid in England, France and Germany. In the U. S. A., a cable containing two 6.7 mm coaxial lines has been installed between New York and Philadelphia (150 km; 90 miles), and another four-line coaxial cable recently was placed in commercial telephone service between Stevens Point, Wisconsin, and Minneapolis, Minnesota (over 300 km; 200 miles).

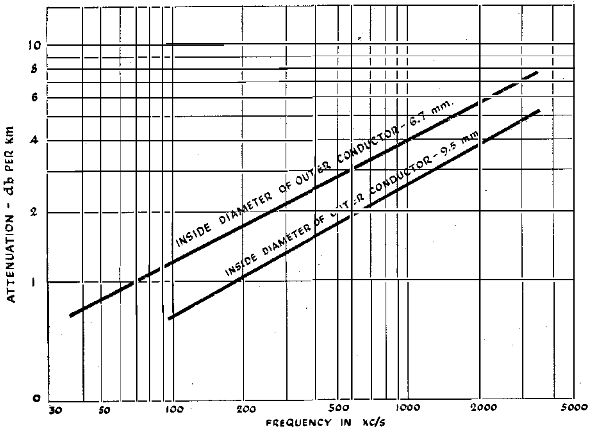

Fig. 10—Attenuation of Coaxial Cables.

The terminal equipment of a coaxial cable system is, in part, identical with that of the 12-channel system. Additional equipment is, however, required to transfer the 12-channel groups into a higher region of the frequency spectrum. Fig. 9 shows a modulator-demodulator capable of effecting this change.

Attenuation values for coaxial cables with internal diameters for the external conductor of 6.7 mm and 9.5 mm are given in Fig. 10. The external conductor, at least above 50 kc/s, serves as a very effective screen against external interference. Hence, very low signal levels, permitting attenuation of 45–60 db per section between repeaters, are acceptable. In a cable of 6.7 mm internal diameter, intervals between repeaters of about 8 km are thus admissible with a frequency band extending up to 3 mc/s. For purposes of comparison, typical repeater spacings and attenuations for various transmission systems are given in Fig. 11, a 240 km (150 mile) line being assumed in each case.

In coaxial cable systems, the total attenuation for a long line is obviously very high. For example, a 1,000 km (625 mile) coaxial cable (6.7 mm), capable of transmitting a frequency band suitable for 300 telephone channels, would have an attenuation of about 4,500 db. Since reception levels must be maintained within restricted limits (about plus or minus 1 db), repeaters must have a high degree of stability. The net result is a permissible tolerance of about 0.01 db per repeater. Furthermore, from the standpoint of distortion and noise, these repeaters must meet stringent requirements. A very satisfactory solution is provided by the application of feedback repeaters.

The attenuation of the cable itself, either of the coaxial or 12 channel type, varies with temperature so that very long circuits, especially if in aerial cables, necessitate the introduction of compensation devices. For underground cables, manual compensation may be used; for aerial cables, automatic compensation is required due to more rapid temperature fluctuations. Recently a simplified regulating method (using devices known as "thermistors," whose resistance varies with temperature in the required manner) has been developed and is expected largely to replace the former rather complicated mechanism.

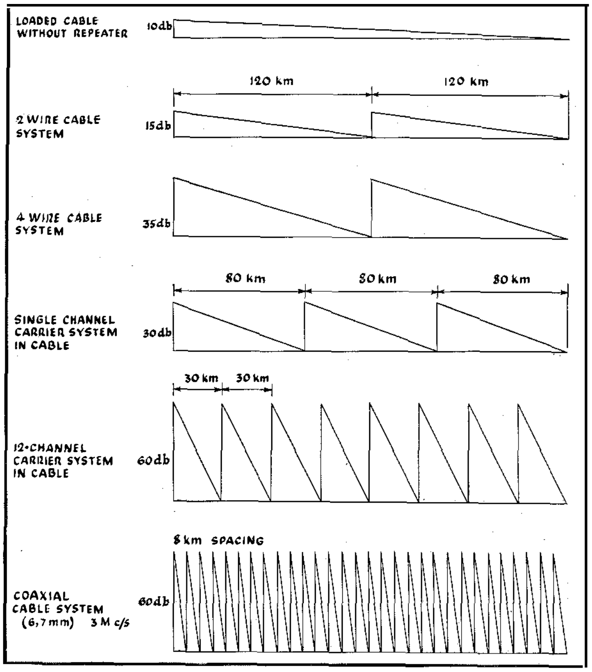

Fig. 11—Typical Repeater Spacings and Attenuations for Various Systems.

Table I and Fig. 12 indicate the results attained in reducing repeater weights and floor space requirements. These show comparative figures, per station, for a group of 240 channels, assuming the use of a 12-channel basic unit for the cable carrier. The results would obviously differ slightly for some of the conditions if a different number of channels had been assumed for the basic unit.

TABLE I

Type of System	Requirements per Repeater Station for 240 Channels		
	No. of Bays	Weight in Kgs	
		Per Channel	Total
Cable			
4-wire Systems—1st type (1926)	64	75	18,000
New type (1931)	28	35	8,400
2-wire Systems—1st type (1926)	64	83	20,000
New type (1931)	44	50	12,000
Carrier on Cable			
1+1 Channel, recent type	10	13	3,000
12-Channel	7	10	2,500
Coaxial	1	1	240

In the case of equipment for coaxial cable, the dimensions and weight (total) of repeaters would not increase even if the number of channels considerably exceeded 240. The equipment, moreover, includes a 100% repeater reserve.

Terminal equipment has been simplified and the weight per channel reduced. In a 3-channel open wire system, three bays were required ten years ago; today, one bay suffices for the principal equipment.

Relative sizes of filters, modulator elements, and complete modulators and demodulators for old and new systems are shown in Fig. 13. In general, the reduction in space required is of the order of 4 to 1.

Conclusion

Although the new transmission systems available in this fourth period of development make use of apparatus which at first glance may appear complicated, there seems to be no reason,

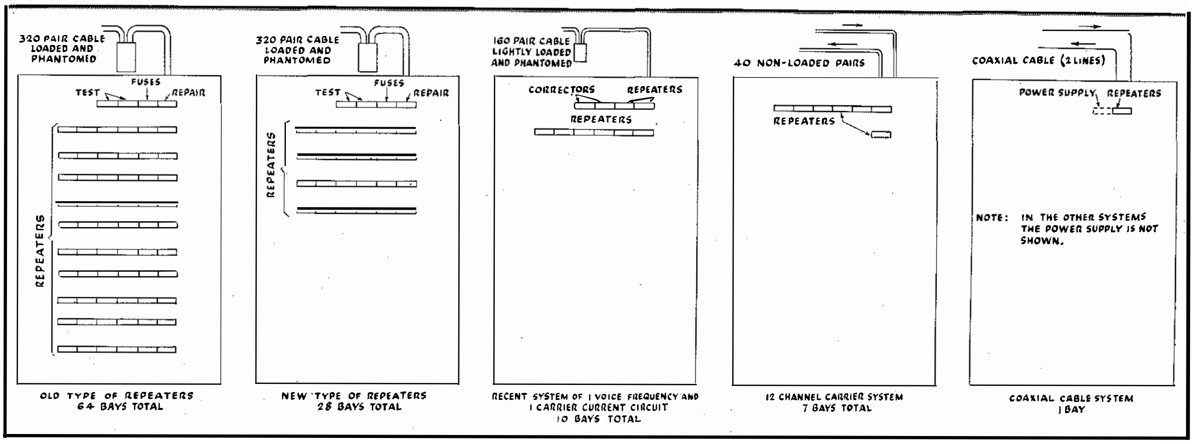

Fig. 12—Comparative Space Requirements for Repeaters.

based on extensive experience to date, to expect any more serious reaction from their application than was encountered with innovations during the other three periods.

The coaxial repeaters, especially, do not require auxiliary equipment. Furthermore, they may be installed in small, simple structures, or be enclosed in metallic housings placed on poles or in underground chambers. The relatively large number of repeaters necessary is no cause for concern. Experience has demonstrated conclusively that the manufacture of repeaters involving minimum risk of breakdown is a practical proposition; and, in addition, arrangements are such that either an individual repeater or a complete cable and repeater section may be replaced automatically by a reserve repeater or a complete reserve section.

The new systems represent a most important advance in long distance communication engineering. Moreover, their development has progressed to the point where they can be considered commercially stabilized to the extent that no radical modification in the structure of cables, repeaters or terminal equipment is to be anticipated. It therefore seems evident that such broad band systems can confidently be taken as the basis for studies of new networks, affording possibilities of rate reductions and of effecting an extraordinary development in high quality long distance telephone communications. Further, their advent makes practical, in many instances, provision for the introduction of television networks on an international scale.

Advances during the first two periods were effected largely with material and apparatus placed in the field, i.e., "outside plant"; those of the third period depended largely on central office equipment. While an important element in progress during the fourth period doubtless must be credited to central office equipment (such as the terminal apparatus for the coaxial and 12-channel systems), it appears that a new essential factor will be the adaptation of apparatus heretofore regarded as central office equipment to utilization in the field. This new apparatus, as previously indicated, has been embodied in unattended repeater stations.

The list of papers appended describes in detail some of the above mentioned developments.

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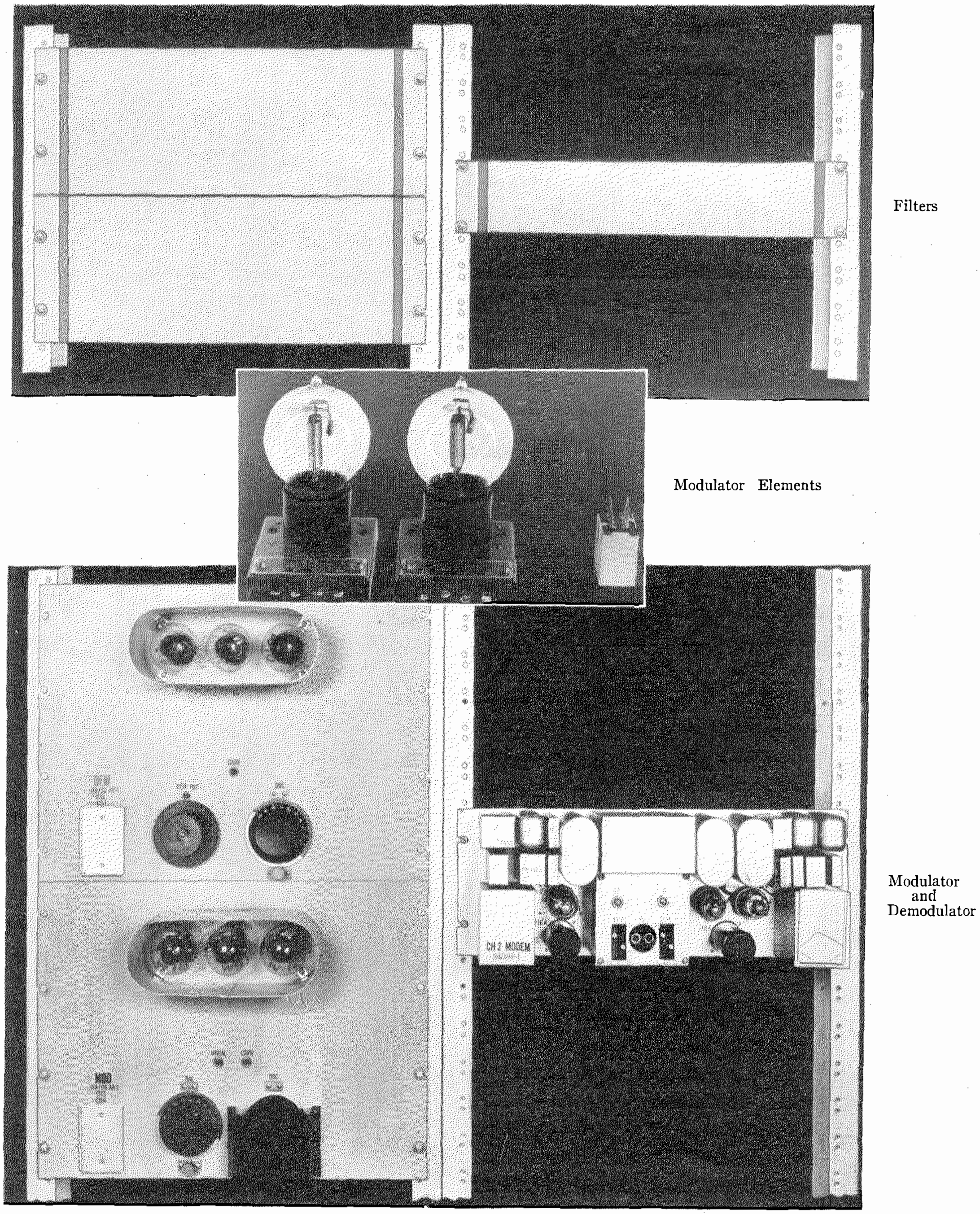

Fig. 13—Comparative Size of Elements of Old and of New Systems.

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Voice-Frequency Signalling and Dialling in Long-Distance Telephony[*]

By W. G. RADLEY,[†] Ph.D.(Eng.), M. I. E. E. and E. P. G. WRIGHT,[‡] M. I. E. E.

During the 21 years between the two great European wars telephone systems of the majority of the cities and large towns of the world have been converted from manual to automatic operation. During the same period notable improvements have also been made to the long-distance telephone service.

The introduction of the use of voice-frequency currents for signalling and dialling represents a stage in a long process of development, and the main portion of this paper describes the problems encountered in the design of a system and the various methods which may be employed for avoiding interference between signals and other currents in the voice-frequency range. Reference is also made to the recommendations of the C.C.I.F. regarding the means of avoiding interference between different signalling systems on international connections.

The interruption in development caused by the present war provides an opportunity for a review of the progress made and for a consideration of future lines of development necessary to keep pace with changes in automatic switching and speech transmission. Therefore, while the paper starts by setting forth the reasons for modern methods of signalling and dialling over long-distance circuits and for preferring the use of voice-frequency currents for these purposes, it concludes by considering the possible trend of future development.

Contents

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[†] British Post Office Engineering Department.

[‡] Standard Telephones and Cables, Ltd., London.

Both authors are members of the Signalling Sub-Committee appointed at the meeting of the C.C.I.F. (3rd C.R.) in 1938.

(1) *The Justification for the Use of Automatic Signalling and Dialling Over Long-Distance Circuits*

MUCH has been achieved in the development of telecommunication systems, and many advances in science have already been transmuted into better service to the subscriber. During the present century considerable improvements have been made in the quality of the received speech, and the distance over which telephone calls are made has been very greatly increased. What is now required is a reduction in the time taken to set up, release and obtain supervision of long-distance connections. Long-distance signalling and dialling by means of voice-frequency currents meet these requirements. By these means the facilities existing in many cities for local calls are extended to the long-distance telephone network. In the present review these facilities will be compared with contemporary practice as operated on modern manual toll switchboards.

Prior to the advent of signalling by more recent methods utilizing voice-frequency currents at 600 and 750 c./s. it had been the practice in Europe to use currents at 500 c./s. for signalling to switchboard operators.[2] This frequency can be transmitted over the normal long-distance circuit with less loss than 16 c./s., which is a customary frequency for ringing a subscriber's bell. The presence of 500 c./s. in speech caused false signals and unnecessary intervention by the operator. In consequence it was found advisable to introduce a time delay and to modulate or interrupt the ringing current by a lower frequency such as 16 or 20 c./s. because the occurrence in speech of the combination of high and low frequencies is of short duration.

Signalling on long-distance circuits by means of 500 c./s. with low-frequency modulation provides a service similar to that of the magneto switchboard which commenced its long journey into obsolescence and obscurity more than 30 years ago. The following processes are involved: The operator at the outgoing end rings down the line —this expression seems more appropriate than "the operator at the outgoing end rings the operator at the incoming end," because frequently the latter is already occupied in setting up a call and, therefore, cannot give immediate attention. The "outgoing" operator then listens on the line and, if necessary, re-rings. The requirements are passed, the "incoming" operator connects the wanted party and the "outgoing" operator reconnects the calling subscriber if previously released from the circuit. The "outgoing" operator monitors to make sure that the conversation starts satisfactorily as regards speech level and correctness of connection and then retires. On receipt of a signal from the calling subscriber, the "outgoing" operator re-enters the circuit, challenges that the conversation is complete, releases the local side of the connection and then rings off over the long-distance line. This signal is duly received by the "incoming" operator, who enters the circuit, challenges, and then releases the remainder of the connection. It will be appreciated that, if three or more operators are necessary to build up a call through intermediate switching points, the complication is increased, due in part to the possibility that the connecting circuits are not available when required and the probability that the three or more operators are not available simultaneously at the moment when it is desired to recall one or other of the subscribers or to take down the connection.

This series of operations conforms precisely to that carried out on short-distance circuits between magneto switchboards and is commonly known as "magneto working." Supersession of magneto working by common battery (C.B.) working on local manual switchboards introduced automatic signalling over short-distance circuits. With automatic signalling supervisory lamps are lit, dimmed or flashed to indicate the condition of the circuit, and events take place in sequence. After the "outgoing" operator has sent a calling signal, a supervisory lamp indicates when the "incoming" operator is connected to the circuit and the call requirements are passed. The "outgoing" operator receives lamp supervision when either party clears and is, therefore, called in automatically if the connection is terminated prematurely. In conclusion, the whole connection is released by the "outgoing" operator without awaiting the assistance of the "incoming" operator, provided that the latter has set up the incoming end of the connection by automatic connecting circuits rather than by cords and plugs. The advantage obtained by automatic signalling lies in the speedier operating because of precise knowledge of the action at the distant end of the line. In addition the "outgoing" operator is saved the distress and delay liable to occur when plugging into a long-distance circuit which has not yet been released from the previous connection at the incoming end. The increase in the speed of setting up and taking down each connection improves the traffic-handling capacity of the line plant. Provision of special recall and transfer facilities, which become possible when a range of different signals is available, simplifies the operating procedure and avoids wastage of time and effort.

The acceptance of the superiority of C.B. over magneto working on local manual switchboards is world-wide, and it is evident from the above considerations that the same reasoning may be applied to long-distance circuits.[3] This generalization applies to exchange areas into which it is impossible to dial. It applies similarly to cases in which dialling over the long-distance line can only be carried out in one direction because one termination is still operating on a manual basis. If the provision of suitable automatic connecting circuits without cords and plugs is inconvenient at the incoming end of the long-distance line, the release of the connection is likely to be under the joint control of both "outgoing" and "incoming" operators with consequential delay. In these circumstances the potential operating advantages cannot be fully realized.

When the long-distance line can be terminated on automatic switches rather than a manual switchboard, the ability to dial the number required eliminates the passing of requirements from one operator to another. As the response of the machine to the calling signal is normally immediate, the saving in service time is considerable. The possibility of an error in transmitting the information is transferred from the human element to the machine, and one operator is eliminated from all but a small proportion of calls, so that operating expenses at the incoming end are avoided by the provision of the additional plant to permit dialling in addition to signalling over the long-distance circuit. The necessary apparatus is not extensive as the voice-frequency receiver must be provided for automatic signalling alone.

The conclusion is obvious that the use of automatic signalling and dialling saves line time, but

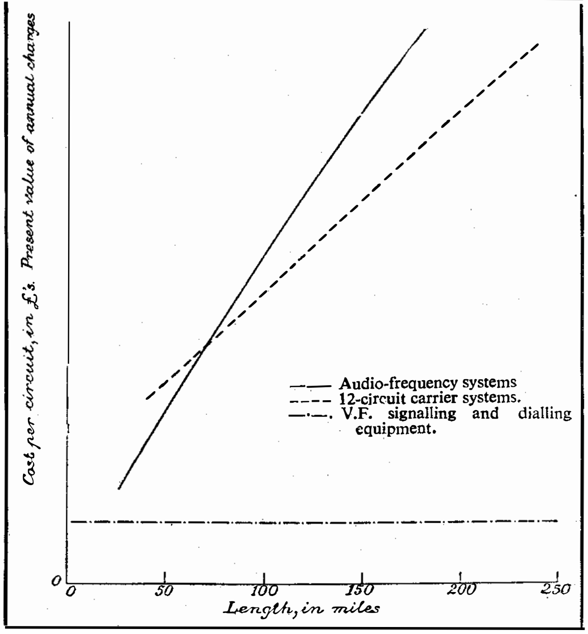


Fig. 1—Comparative Cost of V.F. Signalling and Various Cable Transmission Systems.

it is not so easy to compare the value of the line time saved with the difference in cost between the types of equipment involved. The annual charges for the signalling and dialling equipment are almost proportional to the number of circuits equipped, the length and cost of the line having no bearing on the arrangement or complication of the apparatus. In Fig. 1 comparison is made between the cost of voice-frequency signalling and dialling equipment and that of two types of speech transmission system. The latter has been calculated for conditions in this country and on the assumption that some 300 circuits would be required at the end of a period of 20 years.

To those familiar with the average duration of the holding times of automatic switches it may seem that too much emphasis has been attached in this Section to the reduction of service operating time, but it should be appreciated that this time is often measured in minutes rather than seconds on long-distance calls and that the percentage of ineffective calls is higher than on local connections, due to the fact that the calling subscriber may be asked to leave the telephone and await a recall on account of delay, particularly on personal calls. Table I, compiled from observation records, shows operating and conversation times for demand calls for two cases. Case A is

TABLE I

AVERAGE SERVICE AND HOLDING TIMES

Type of call	Case A*	Case B†
	sec.	sec.
Service time without dialling	94	67
Service time with dialling	—	48
Add for personal calls	64	—
Conversation time (excluding service)	243	183

* British Post Office, January–June, 1939.
† La Plata–Buenos Aires, 1938.

an overall figure for a national network and includes calls with long-distance routes in tandem, while Case B relates to a single route before and after the introduction of long-distance dialling.

(2) *Reasons for the Present Use of Currents in the Voice-Frequency Range for Signalling and Dialling on Long-Distance Circuits*

(2.1) SUITABILITY OF VOICE-FREQUENCY CURRENTS FOR SIGNALLING

Whatever the means of building up a long-distance connection, all the telephone circuits involved must be capable of transmitting voice currents without undue attenuation. In this fundamental principle resides one of the main attractions of voice-frequency signalling. This does not apply to other methods of signalling, such as those utilizing direct current and low-frequency alternating current, which may be suitable for some speech transmission channels but quite unsuitable for others. Fig. 2 shows an example of a built-up connection between the towns A and E. The sections AB and DE are relatively short open-wire lines without amplifiers and are suitable for d.c. signalling. The section BC is operated at audio frequencies, but on a 4-wire basis, and includes amplifiers. Between C and D speech channels are provided by a multi-circuit carrier telephone system. The only frequencies which will pass conveniently over the complete circuit are those in the voice-frequency range. At the time when long-distance signalling and dialling were first being considered it was quickly appreciated that, as the signal receiver could be designed to respond faithfully to a voice-frequency signal, there should be no major difficulty on signalling over any built-up connection.[5] The possibility of developing a voice-frequency signalling and dialling system was technically attractive. The probability of the general adoption for long-distance circuits of speech transmission systems based on carrier-current principles appeared as a further reason for thinking that other methods of signalling and dialling would be less suitable.

(2.2) OTHER PRINCIPLES OF SIGNALLING OVER LONG-DISTANCE LINES

Two other principles for signalling and dialling which have been widely used employ direct current and 50-c./s. alternating current respectively.

(2.2.1) *Direct Current*

A loop resistance of 1,500 ohms approaches the limit over which the simplest method of direct-current dialling can operate. With this arrangement the outgoing end comprises impulsing contacts in series with the line. At the incoming end an impulsing relay is connected in series with the battery. Line leakage tends to short-circuit the impulsing contacts and some improvement is possible with "battery dialling." With this method dialling is frequently over an earth-return path; the battery and impulsing contacts are in series at the outgoing end.

When there are two or more repetitions of impulses the distortions may still be too great to ensure reliable operation without the aid of impulse correctors or impulse regenerators. The former avoid extremes of impulse ratio and the latter are devices which receive, store and retransmit impulses. These additions, whether they are regarded as improvements or palliatives, are all responsible for an increase in annual charges, on account both of first cost and of increased difficulty of maintenance. A rough comparison (Fig. 3) may be made with voice-frequency signalling, which remains at a fixed charge irrespective of distance.

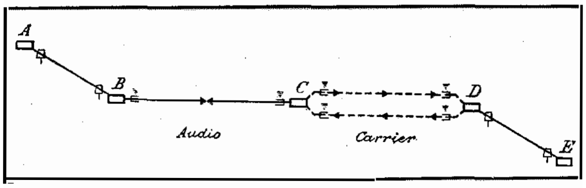


Fig. 2—Typical Built-Up Long-Distance Connection.

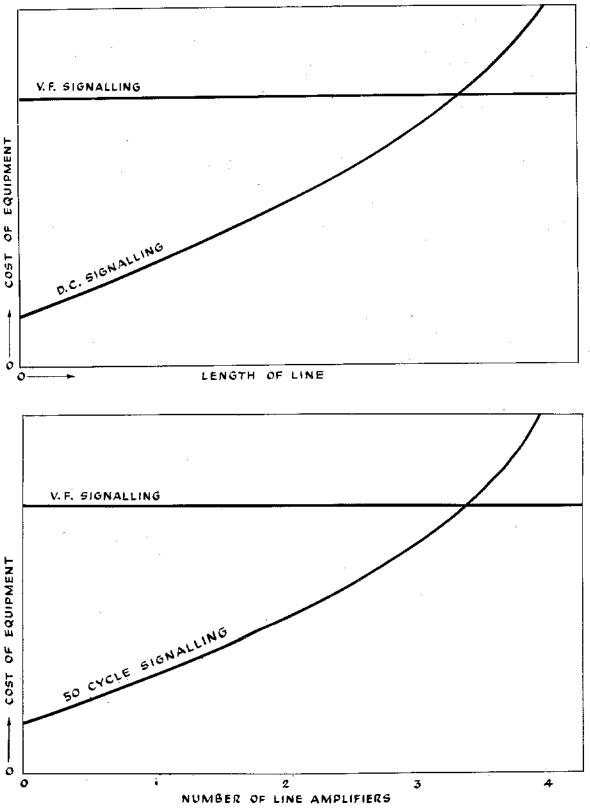


Fig. 3
Fig. 4—*Comparison of Annual Cost of D.C. 50-c./s., and V.F. Signalling Systems.*

Note: The point at which the 2 curves cross in each case will vary considerably according to the facilities provided.

The ingenuity and effort which have been spent in the development of long-distance direct-current signalling and dialling may be appreciated from a study of a system[14] recently designed by the Post Office for restricted application. This system was intended for operation over lines equivalent to 100 miles of 20-lb. star quad phantom circuit. A direct-current loop path is essential. At the incoming end a receiver is connected to the line temporarily for the receipt of impulses by a prefix signal. Transmission of this signal is controlled by a regenerator at the outgoing end which also serves to narrow the transmitted impulse limits. Line equalization over the essential frequency range is obtained by terminating the line in a suitable transformer. The beginning and end of each impulse are marked respectively by positive and negative voltage surges which vary the potential on the grid of a valve controlling a telegraph type relay in order to provide a corresponding direct-current signal. Although this system is likely to prove valuable in providing dialling and signalling facilities over certain loaded circuits, it is not applicable to those on which no direct-current path is available, owing to the phantom being otherwise employed, or to those operated by carrier or radio frequencies.

(2.2.2) *50-c./s. Alternating Current*

Extensive use of a 50-c./s. signalling and dialling system indicates that such a system also has an important field. No loop path is required. The fact that all the necessary signals pass over the two wires forming the speech path without the use of direct current is of importance because it implies that 50-c./s. signals can be employed for both side circuits and phantoms simultaneously. This would be of no advantage with star quad cables on which the phantom circuits are generally useless for speech purposes, but the advantage of using the phantom in open-wire lines or other types of cable is important. One modern 50 c./s. system transmits with no more than 16 volts and uses a telegraph type relay to respond. The relay is probably sufficiently sensitive to receive satisfactorily signals that have passed through a line amplifier, although 50 c./s. is below the frequency band at which transmission can take place without serious loss. It is the practice, however, to fit a 50-c./s. repeater, arranged to pass currents around the line amplifier in either direction. The cost of 50-c./s. systems is, therefore, in part dependent on the number of line amplifiers; a consideration which does not affect the cost of voice-frequency equipment (see Fig. 4).

It is apparent that with 50-c./s. systems the response of the receiving relay is partly dependent on the phase of the supply at the time when the impulse is generated. It should be noted that this circumstance may be more important on systems in which impulses may be subjected to the variations of the subscriber's dial and may be distorted by the telephone circuit, than in systems using machine-generated impulses closely controlled for ratio and speed. The phase mutilation may take place not only on generation of the 50-c./s. current but also at each repetition. However, the portion of the cycle at which the voltage is insufficient is relatively small and, even with all conditions adverse, it is possible to impulse through more 50-c./s. repetitions than are likely to be found in any built-up connection. Public supply systems provide a ready source of signalling current. 50-c./s. signalling and dialling is likely to be cheaper than d.c. methods or voice-frequency for long-distance circuits, but existing carrier systems do not transmit this frequency.[7]

Dialling and signalling between zone centres has been exploited further in Switzerland than perhaps in any other country.[16] It is probable that the geographical arrangement of the country is an influential factor because the principal central switching points at Berne and Zürich are so placed that the average distance of through long-distance circuits is scarcely more than 50 miles, and, in consequence, there are relatively few circuits on which multi-channel carrier systems are installed. The conditions in Switzerland are generally suitable for 50-c./s. operation, and the decision of the Administration to adopt the 50-c./s. equipment was presumably partly due to the economy obtained by using both physical and phantom circuits. This decision has been justified by the service which has been provided during the last 7 or 8 years. 50-c./s. signalling and dialling has also been used for many years in Norway, Hungary and Czechoslovakia, but the greater mileage between centres in these countries makes it appear unlikely that the system can find universal application for long-distance circuits.

(2.2.3) *500- and 2,500-c./s. Alternating Current*

500-c./s. currents have been used for signalling and dialling in a number of countries, particularly in Germany and France, and 2,500-c./s. currents have been used in the Netherlands. These systems can be classed with the voice-frequency systems using 600- and 750-c./s. currents, because the frequencies used fall within the speech band and, therefore, such currents are suitable for use with most speech transmission systems. As will be seen from Section (4), the C.C.I.F. have made various recommendations for the protection of voice-frequency signalling systems from incorrect operation due to extraneous current. These safeguards apply only to 600 and 750 c./s. which are reserved for signalling and dialling, and it would seem that little purpose can be served in contemplating any other frequencies in the audio range.

(2.3) LINE CONDITIONS

Having established that there are good reasons for the adoption of automatic signalling and dialling facilities on long-distance circuits, it becomes apparent on investigation that the requirements may be provided in several ways. The line conditions may be expected to influence decisions as to the most suitable arrangement, and it is desirable to review in general terms the constitution of long-distance circuits. As the length of line and number of circuits increase, the use of carrier transmission systems becomes more economical than separate audio circuits. Several separate carrier systems on the same route may in turn be replaced by multi-channel systems, providing a very large number of channels over

TABLE II

DISTANCES BETWEEN REPRESENTATIVE SWITCHING CENTRES

Country	Switching centres	Distance miles
AUSTRALIA	Sydney — Adelaide	850
	Sydney — Brisbane	500
	Brisbane — Melbourne	1,000
	Sydney — Melbourne	500
	Adelaide — Perth	1,500
	Hobart — Melbourne	400
FRANCE	Bordeaux — Marseilles	330
	Paris — Bordeaux	310
	Strasbourg — Marseilles	400
	Lyons — Bordeaux	280
	Strasbourg — Bordeaux	500
	Lyons — Marseilles	180
GREAT BRITAIN	London — Birmingham	120
	London — Manchester	200
	Leeds — Glasgow	200
	Manchester — Belfast	200
	London — Glasgow	400
	Manchester — Leeds	40
THE NETHERLANDS	Rotterdam — Eindhoven	60
	Amsterdam — Breda	50
	Leeuwarden — Amsterdam	65
	Rotterdam — Arnhem	60
	Maastricht — Groningen	170
	Harlem — Amsterdam	10
RUMANIA	Bukarest — Cluj	220
	Bukarest — Cernauti	260
	Bukarest — Jasi	200
	Timisoura — Chisinau	380
	Braila — Brasov	100
U. S. A.	Los Angeles — Dallas	1,250
	Atlanta — Denver	1,060
	New York — Dallas	1,400
	New York — Chicago	750
	New York — San Francisco	2,550
	Chicago — St. Louis	260

pair- or coaxial-type cable. It is clear that the ratio between the cost of the speech circuit and the cost of the signalling equipment in countries such as the U.S.A.,[1] U.S.S.R., Australia, Canada and South Africa, is very different from the corresponding ratio in the Netherlands, Belgium and Switzerland. Table II shows some typical distances between main switching centres of various Administrations.

The picture is not complete with such a summary of transmission systems, even when allowance is made for the various types of system of the same class, because circuits between adjacent switching centres will not always be of any one type from end to end. In times of emergency extensive patching may be necessary by quite roundabout routes. It would be a considerable restriction to the general arrangement of long-distance lines if the patching depended to any extent on the type of terminal equipment installed.

(2.4) IMPULSING CONDITIONS

Some consideration must also be given to the fundamental switching layout, particularly as regards the repetition of impulses. Most of the permissible distortion is absorbed in switching calls from end to end of a local area. This is roughly equivalent to admitting half the permissible distortion from the subscriber to the group centre. A similar loss may occur in the reverse direction from the group centre to the most distant subscriber and, in consequence, little, if anything, is available for any long-distance line joining the group centres. In register-controlled systems each area is provided with a separate permissible distortion measured from the register itself. In recent years impulse regenerators have been introduced to nonregister systems, performing a similar function to that of the registers, because by their use the subscribers can be isolated from the long-distance line.

An analogy is possible with the design of the corresponding transmission system. In most countries nearly all permissible speech attenuation and distortion from subscriber to subscriber may occur in a local area, and very little is left for the long-distance circuit. Long-distance circuits may, however, be so engineered that the speech impairment is very small. Most designers have accepted the principle that impulsing over the voice-frequency circuit should be achieved with negligible distortion by inter-operation with registers or regenerators.

(2.5) CONCLUSIONS AS TO PRESENT USE OF VOICE-FREQUENCY SIGNALLING AND DIALLING

In Section (3) reference is made to the extent to which regenerators may be used to eliminate possibilities of interference. The restrictions and conditions which the v.f. receiver and the associated code of signals have to face result in an accumulation of protective arrangements needing apparatus and wiring. In consequence the receiving and transmitting relay sets are more expensive than those required for direct current or alternating current at 50 c./s., and this is undoubtedly largely due to the intention to use the voice-frequency equipment for different conditions. Nevertheless, an administration operating a long-distance network of lines chiefly comprising multi-channel carrier systems would feel justified in standardizing the use of voice-frequency signalling and dialling, whereas another administration operating a smaller percentage of carrier circuits might feel justified in using two different systems in the interest of economy in first cost.

The use of voice-frequency currents for signalling and dialling over long-distance circuits has already been introduced in Great Britain,[6] Germany, Eire and large districts of Australia.[17] To a more limited extent it has been used in the Netherlands, Belgium, Italy and Hungary.

(3) *Technical Problems Involved in the Design of Voice-Frequency Signalling Systems*

(3.1) INTRODUCTION

Realization of a voice-frequency signalling system necessitates provision of a group of relays for connecting the voice-frequency current to the line in response to d.c. signals. In addition, a signal receiver is required for the subsequent translation of the voice-frequency line current to d.c. signals. Many problems in telecommunication engineering arise. Their solution is influenced by the following factors:—

(*a*) The facilities required for setting up, supervising and clearing a call.

(*b*) The complications arising from connection to the speech circuit of apparatus, such as echo-suppressors, not associated with signalling.

(*c*) The performance that can be obtained from the voice-frequency signal receiver.

The voice-frequency signal receiver (v.f. receiver) must discriminate currents which represent signals from those of the same frequency due to speech sounds or line noise. The difficulties encountered in doing this lead to the definition of two terms, *signal imitation* and *signal interference* "Signal imitation" describes false operation of the v.f. receiver by a component, or components, in speech or noise of the frequency, or frequencies, used for the transmission of genuine signals. As will be seen later, certain steps are taken to minimize the chance of this happening. In turn these steps may prevent the receiver responding to genuine signals when speech or noise is present. This is known as "signal interference." Designers seek to find a compromise between signal imitation and signal interference.

Voice-frequency systems have not been designed for simultaneous signalling in both directions, but circuit conditions may result in an attempt to pass signals in opposite directions at the same instant. If this happens the operation of echo-suppressors may spoil the passage of the signals. Echo-suppressors are essential features of some types of modern high-grade long-distance circuits and permit only one-way transmission at a time. They may be operated against the signal by speech, tones or signals in the reverse direction.

Further complications arise on built-up connections. These are due to the fact that signals intended for operation within one section may pass to a second section and there cause unwanted switching operations.

Automatic telephone exchanges in Great Britain utilize switching equipment of the Strowger (step-by-step) type. With this type of equpiment the pulses of current used to position selecting switches must correspond closely to the pulses generated by the originating dial. This must be true after they have been transmitted over the line and subsequently translated from alternating to direct current by the v.f. receiver. Somewhat greater distortion is permissible if the exchange equipment is of the register type.

It will be useful to set out the problems referred to above and to indicate solutions before considering each problem and its solution in greater detail. All of these contribute towards the expense and complication which are to some degree inherent in voice-frequency signalling and dialling systems.

(3.1.1) *Signal Imitation*

Since currents at the signalling frequencies also occur in speech, some protection must be provided to avoid false operation of the v.f. receiver. Protection may be obtained by the use of:—

(*a*) Voltage limiter in the receiver.
(*b*) Guard circuit in the receiver (relay or grid-bias type).
(*c*) Signals exceeding a specified duration.

(3.1.2) *Signal Interference*

Precautionary devices necessary to guard against signal imitation may be operated by speech or tone present at the same time as signals, thus giving rise to signal interference. Interference due to currents having their origin at the same end of the line as the v.f. receiver can be reduced by means of a hybrid connection.

(3.1.3) *Interference due to Echo-Suppressors*

Some long-distance lines are fitted with echo-suppressors, which are liable to prevent transmission of voice-frequency signals. This obstacle may be overcome in various ways, of which one is the repetition of signals until their receipt is confirmed by an acknowledgment signal.

(3.1.4) *Inter-System Interference*

When two similar and adjacent voice-frequency signalling systems are associated in a connection, signals may be passed from end to end to avoid the delay and distortion caused by repetition. If, however, this is impossible because there is an intervening link in the connection with some other means of signalling, or because the signalling codes are different, signals from one system entering the second will cause interference. Confusion from this source is avoided by the use of a "prefix" signal and a line-splitting technique which depends on rather accurate timing for its successful operation.

(3.1.5) *Impulse Distortion*

The duration of the dialling impulse normally used is of the order of 60 millisec., and the period between impulses is somewhat smaller. The response time of the v.f. receiver is 10 millisec. or more. In order to maintain the impulse response as accurately as possible, it is desirable to use one frequency only and make the receiver as quick as possible in its response to this frequency.

The solution of these problems lies partly in the design of the v.f. receiver, partly in the design of the signalling system as a whole, and to a great extent in the choice of the signal code.

Related to the signal code it may be useful to define two types of signal element:

(3.1.6) *Simple Signals*

Pulses consisting of either signalling frequency alone are known as simple signals.

(3.1.7) *Compound Signals*

Pulses comprising both signalling frequencies simultaneously are known as compound signals.

(3.2) OPERATING REQUIREMENTS TO BE MET

(3.2.1) *Signalling*

The facilities required vary in different countries. Those regarded as essential usually include the ability (*a*) to seize a circuit and distant terminal equipment, (*b*) to transmit dialling impulses, (*c*) to give information that the called subscriber has answered, (*d*) to give information that the call may be cleared, and finally, (*e*) to transmit a signal to cause the complete release of the circuit and associated apparatus at both ends. Other facilities may be required, and a system should be capable of giving them.

Systems which enable a subscriber to set up a local call by dialling vary considerably in layout and design, but there are certain fundamental principles which are common to all systems and countries. Briefly, these consist of calling by forming a loop of the two line conductors, thus allowing current to flow, dialling by momentary interruptions of this loop, thus generating pulses of direct current which serve to position the selecting switches, and clearing by permanently breaking the loop. It is impossible to model the v.f. system on such principles, as there are many reasons why the audible signalling current should not be applied for long periods. All information must, therefore, be conveyed by coded pulses of the signalling frequency and more apparatus is required. This arrangement also constitutes a slower method of communication than the change-of-condition method used in d.c. circuits. Signal discrimination may be effected by variation of the frequency of the signalling current, of the duration or number of pulses, or by a combination of these variations.

Simultaneous passage of forward and backward signals is often impossible. If a signalling condition, notified from one end by sending a succession of pulses, is to be acknowledged from the other end, adequate intervals must be provided between pulses to permit the transmission of the acknowledgment signal in the reverse direction. This interval is fixed as about 550 millisec. by a combination of factors—the propagation time of the circuit, the change-over time of the echo-suppressor, the response time of v.f. receivers, the time necessary for the recognition of a signal, and various relay release times.

(3.2.2) *Dialling*

The economic advantages to be gained from automatic signalling over long-distance circuits are only fully realized if, in addition to providing for the quick and accurate transmission of change-of-circuit information, the system also enables dial signals to be transmitted with sufficient accuracy to actuate correctly distant automatic switching equipment. Selectors in a step-by-step system will generally respond to impulses at speeds between 9 and 11 impulses per sec. having make/break ratios between 1 : 1 and 1 : 4. Somewhat wider variations are permissible to the impulses which serve to set the switches in a register system. In both cases the tolerances will, to a large extent, be absorbed by variations in operators' dials and by distortion introduced during a number of repetitions when the connection involves several links in tandem, as already indicated in Section (2.4).

(3.3) RECEIVER DESIGN

(3.3.1) *General*

Development and introduction of voice-frequency signalling and dialling have largely awaited the solution of technical difficulties in the design of the v.f. receiver. As a measure of the success that has been achieved, it can be stated that few of the early troubles experienced with the systems now working were due to the receiver.

The initial problem results from the fact that, in order that the v.f. receiver may be ready for the release and other signals, it has to remain permanently bridged across the line when this is being used for conversation. In addition to genuine signals, therefore, it has applied to its terminals speech and noise currents which may contain components at the frequencies used for signalling. To a certain extent currents having their origin on the local side of the receiver may be avoided by insertion of a hybrid transformer between the line and the v.f. receiver. Fig. 5 shows the arrangement of an unequal ratio differential transformer with a balancing network Z having an impedance which is higher than that of the line. This permits the v.f. receiver to be connected with quite a low loss. Currents approaching the transformer from the direction of the local exchange divide unequally between Z and the line and only have an effect on the secondary windings connected to the v.f. receiver due to imperfection of the balance. On the other hand, currents incoming from the line flow through the primary half-windings in such a direction that their inductive effects on the secondary windings are additive. No discrimination by the hybrid transformer is possible between wanted and unwanted currents incoming from the long-distance line.

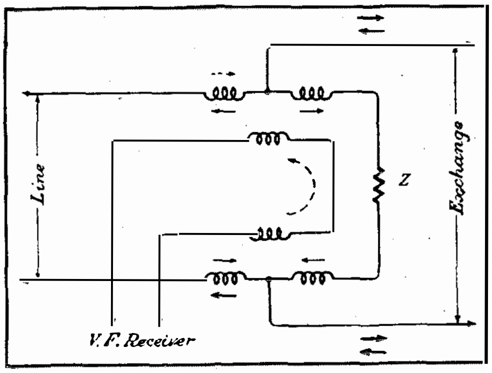


Fig. 5—Principles of Hybrid Transformer Connection.
Currents having their origin on the exchange side.→
Currents having their origin on the line side.- - →

A power of the order of 1 or 2 mW, measured at a point of zero relative level, is usually employed for the transmission of signals, although in order to prevent the over-loading of amplifiers on multi-channel carrier telephone systems it is necessary in some cases to reduce the power when repeated signals are transmitted. Although only small attenuation is to be expected as a result of transmission over a long-distance line directly connecting zone centres, the level of signals received over different built-up connections may vary considerably. Such considerations lead to anticipated variations in the received signal voltage of 22 db., i.e., approximately a 12 : 1 ratio. In order to facilitate design of later stages in which d.c. signalling relays are operated by rectification of the voice-frequency currents, an early stage of the receiver may take the form of a voltage limiter. The output voltage from the limiter stage remains sensibly constant for a wide range of input voltage.

The frequency of received signals may be inaccurate, due either to incorrect speed of the frequency generators at the distant terminals or to actual change of frequency during transmission over one or more sections of a particular long-distance circuit operated by carrier telephony where the modulating and demodulating carrier frequencies are not synchronized. Some allowance for commercial tolerances in the components which are used in building up the signal-selecting elements is necessary. A band-width of ±22.5 c./s. is considered adequate for all these purposes.

As the v.f. receiver must remain permanently connected to the line, its input impedance must be sufficiently high to avoid causing appreciable loss to speech or other transmission. Such loss is usually kept below 0.25 db.

(3.3.2) *Prevention of Signal Imitation*

There is no single characteristic which can be used to distinguish signals from speech and noise. Contemporary design[8] relies on some or all of the following principles:

(i) Tuning the v.f. receiver so that it is more responsive to the signal frequencies.

(ii) Preventing response of the receiver to signal frequencies if other frequencies are present; this may be done in one of two ways:

(ii*a*) By the selection of specific non-signal frequencies to impose an electrical or mechanical guard on the receiver.

(ii*b*) By passing the total input from the line initially through a limiter stage and then making response of the receiver depend on the receipt at its later stages of signal frequency exceeding a predetermined level.

(iii) Imposing time delays.

Attempts have been made to use such distinguishing features as the varying amplitude of speech from moment to moment, but so far no successful design has been evolved. The design of early systems was assisted by the use of greater signal powers than those permissible at present.

Simple resonant circuits to increase the response of the v.f. receiver to the signal frequencies are generally included. The sharpness of tuning depends on a variety of factors, but, as already indicated, the band-width over which sensibly uniform performance is obtained should extend for at least 22.5 c./s. on each side of the nominal signalling frequency.

Use of frequencies other than those adopted for signalling to apply some degree of guard to prevent response of the v.f. receiver is general. Band-stop filters, tuned to the signalling frequencies, are sometimes employed so that the v.f. receiver is effectively made unresponsive should voltages at any frequency differing appreciably from the signalling frequencies be applied to it. Other designers rely on the presence of components at one or more selected frequencies, and the first sub-multiples of the signalling frequencies, i.e., 300 and 375 c./s., may be chosen for reasons which will become apparent later. The choice is useful, as frequencies of this order represent a considerable proportion of the power in voiced speech and also cover many components of the supervisory tones in use in automatic telephony. Whatever the frequencies selected to exercise the guarding function, the voltages in question are amplified and rectified and may then be used to operate a relay, or relays, which render simultaneous operation of other relays by components at the signalling frequencies ineffective, or they may be applied as a disabling negative bias to the grids of valves used for amplifying and/or rectifying components at the signalling frequencies.

Limitation of the voltage passed to the relay operating stages in the receiver assists in preventing speech or other currents containing both signal and non-signal frequencies giving rise to spurious signals. If the sensitivity of the later stages is set so that a voltage at the signalling frequency only just below the full output of the limiter is required for operation, this will not be available when the input voltage contains other components of considerable magnitude.

Nearly all limiting devices produce harmonic distortion of the limited voltage wave. Although ingenious methods have been devised for compensating such distortion by means of wave-form shaping circuits, generation of harmonics by the signalling frequencies and of the signalling frequencies by their sub-harmonics usually occurs. Generation of these components in the limiter stage may influence the choice of non-signal frequencies for guarding the receiver against false operation.

The properties of a limiter add further difficulty to the design of a v.f. receiver which has to respond to compound as well as to simple signal components. With compound signals the available power, determined by the limiter, is divided between two relays. It is therefore restricted in each relay to a smaller value than it has when there is one signalling frequency alone. In addition, as the limiter usually has non-linear characteristics it gives rise to modulation products when passing compound signals. These may be troublesome.

False operation of the v.f. receiver can be rendered ineffective by interposing a time delay between the first reception of current at a signalling frequency and any resulting change of condition in the d.c. circuits controlled by the receiver. If the delay is sufficient, signal imitation can be eliminated almost entirely but the speed of signalling is made slower. The delay is provided by relays.

(3.3.3) *Prevention of Signal Interference*

Application of some of the means of preventing signal imitation just described may render abortive any attempt to signal while speech or tones are being transmitted over the circuit. If signals have to be received in these circumstances any electrical or mechanical guard preventing effective response of the receiver must not operate with a time lag so long that the inhibiting condition will persist throughout pauses in the speech or tones. Further limitation of the effect of the guarding arrangements may become necessary as, in whatever way unwanted operation of the receiver is prevented, the insensitive condition must not occur or persist due to room noise transmitted through the subscriber's microphone or to reasonable amounts of line noise.

(3.3.4) *Reception of Dialled Impulses*

In addition to any added delay which may be introduced to prevent signal imitation, the v.f. receiver itself requires a response time which may be of the order of 10 or 12 millisec. It has already been pointed out that dialling impulses must be converted from voice-frequency to direct current with the minimum added distortion. This makes a short receiver-response time desirable. It is usual to arrange that guards, such as those provided by the addition of time delays, become inoperative when the receiver is in a dialling condition. Relay operations reimpose the guards during periods when the circuit is open to conversation, as otherwise occurrence of the dialling frequency in speech would cause undesirable clicks.

The desirability of the v.f. receiver response time being the minimum possible leads to the invariable use of pulses comprising one signalling frequency only for dialling, as all the power passed by a limiter stage is then available in one relay-operating stage.

If the quality (ratio of reactance to resistance) of tuned signal acceptor circuits is high, frequencies just outside the nominal pass-band will be effectively prevented from causing false operation of the receiver. On the other hand, the higher the quality of the tuned circuit the more slowly will an accepted pulse of current at the impulsing frequency build up to its final value, and it will become difficult to avoid the introduction of impulse distortion.

(3.3.5) *Design Details*

It is not the purpose of this paper to describe any particular design of v.f. receiver for voice-frequency signalling. Fig. 6 indicates in schematic form the principles of four receivers in fairly extensive use. The first and second of these are employed in connection with systems making use of simple signals only. The third and fourth will operate to compound as well as to simple signals. The receivers are mounted on jack-in type baseplates commonly used for automatic telephone switching equipment.

(3.4) SYSTEM DESIGN

(3.4.1) *Interference due to Other Signals, Speech or Non-Signalling Currents*

Signalling becomes more difficult after the connection of supervisory tones or the commencement of speech. Echo-suppressors, if connected to the circuit, may be operated by speech or tones transmitted in the opposite direction to that in which it is desired to signal and bar the signal path. The distant v.f. receiver may be adversely affected by noise or speech and rendered insensitive to genuine signals. Solutions to these problems have been developed in one or other of the following ways:

(i) By repeating signals until their correct reception at the far end of the circuit is acknowledged by a signal sent in the reverse direction.

(ii) By the transmission of pulse signals, stopped only as a result of a further change in the circuit conditions.

(iii) By temporary alteration to the circuit so that access of interfering currents from their most likely source is prevented.

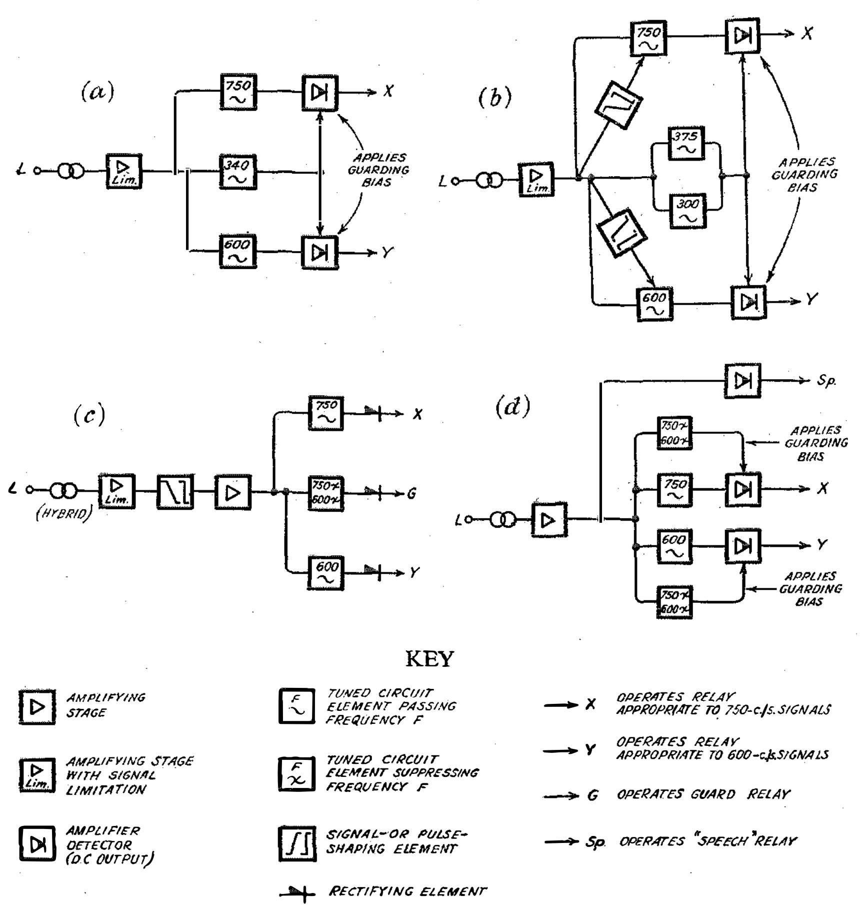
(iv) By testing at the outgoing end for other voice-frequency currents and, if the reception of these indicates that signal interference will be encountered,

(iv*a*) Repeating signals.

(iv*b*) Delaying the transmission of signals.

As an example of the first type of solution, it is necessary to ensure that the forward clearing signal will reach the distant end in spite of echo-suppressors operated by speech in the reverse direction. This is done by repeating signals, separated by adequate pauses, until an acknowledgment signal is received in the backward direction.

The second type of solution, which is somewhat similar to the first, may be illustrated by a particular means of dealing with supervisory signals transmitted from the called subscriber. When this subscriber hangs up, a signal must be sent back to indicate that he has done so. Con-



Principles of typical v.f. receivers.

Fig. 6—Principles of Typical V.F. Receivers

(*a*) *50-V Supply* (*b*) *50-V Supply*
(*c*) *130-V and 21-V Supplies* (*d*) *220-V and 12-V Supplies*

tinual repetition ensures that a signal is successfully received in spite of interference. Cessation of the signals may be brought about by the called subscriber returning to the line or by complete release of the connection, the latter condition being the result of a signal transmitted in the forward direction and operative in the intervals between repetitions of the signals being sent in the backward direction.

Use of a distinctive answer signal indicating that the called subscriber has come on to the line is a feature of the operating procedure in some countries. The steps taken in the British Post Office system to safeguard this signal from loss when it is sent in face of such interference as noise currents generated in the subscriber's or operator's transmitter, speech, further dialling, or switch-hook flashing from the calling end, indicate the third type of solution. An answer signal long enough to exceed in duration such interference is undesirable because of the delay which it would introduce before the commencement of conversation. The difficulty is overcome by the insertion, until the called subscriber answers, of a one-way repeater at the controlling exchange. This repeater enables supervisory tones to be heard by the controlling operator but prevents local disturbance at the calling end from passing out on to the line. The one-way repeater is cut out and the circuit automatically made available for two-way conversation on reception of the answer signal.

The means adopted in Great Britain are not readily applicable in all countries because no speech is possible until the answer signal is given, and with some systems this must be withheld until it is known that the required party is available. The signalling system in use in Eire retains the one-way repeater, but does not necessitate an answer signal, as the circuit is automatically made available for speech when dialling is concluded.

Reference will be made later to the one-way repeater as a means of safeguarding dialling impulses against interference. As the introduction of such a repeater is not uncommon, its uses in a v.f. signalling system may be set down as:

(*a*) To prevent interference to signals from speech, transmitted in the reverse direction.

(*b*) To prevent the v.f. receiver being rendered inoperative by surges generated in a d.c. circuit [Section (3.4.1.1)].

(*c*) A means of protecting the v.f. receiver when it is in a highly sensitive condition for such purposes as the reception of dialling impulses [Section (3.3.4)].

Solutions depending on a test of the circuit for interference listed above as (iv*a*) and (iv*b*) are obtained by means of a "speech" relay connected to the return path of a 4-wire line. The arrangement depends on the introduction of a relay which has a similar sensitivity-frequency characteristic to the echo-suppressor, with sufficient sensitivity to operate before the echo-suppressor but insufficient to operate to line noise. If the speech relay is operated by line currents, transmission of signals is either repeated or delayed. This method is used in Germany to overcome jamming of signals by intermediate echo-suppressors; terminal echo-suppressors are so arranged as to be incapable of causing interference.

Interference caused by terminal echo-suppressors may be avoided if the voice-frequency signalling equipment is connected to the 4-wire portion of the long-distance line. The German system is designed on this principle. Arguments in favour of its use are discussed in Section (5.4).

(3.4.1.1) *The Special Case of Interference to Dialling Impulses*

Various oscillograms illustrating effects which have to be overcome in order that dialling impulses may be transmitted without harmful distortion have been assembled in Fig. 7. In this figure, *a* shows the form of a typical d.c. pulse applied to the relay which controls the application of the voice-frequency voltage to the line. The non-rectangular shape is due to the nature of the local d.c. circuit and must be accepted as an initial disability. Fortunately, dialling impulses are usually transmitted when the line is free from speech or jamming by noise. Superimposed surges, generated in the d.c. part of the circuit and transmitted over the speaking wires, may, however, be troublesome. A typical surge is shown by *b* in Fig. 7. The surge voltage may render the v.f. receiver at the distant end of the line insensitive and prevent its proper response to the subsequent pulse of voice-frequency current and, at the outgoing end, the sequence of operations is such that it is difficult to avoid transmitting forward this surge voltage.

There are various methods of tackling this difficulty. Systems provided with a distinctive "end of selection" signal can be arranged to isolate the outgoing circuit and to connect it for forward speech only when dialling is completed. Conversely, use could be made of a preparatory signal preceding each train of dialling impulses. Insertion of a one-way repeater, previously referred to as the means used in Great Britain of preventing interference with the answer signal, is an effective remedy; so is control of the circuit by means of the German "speech" relay, also mentioned in Subsection (3.4.1). The forward path of the 4-wire line is disconnected from the d.c. impulsing circuit when dialling is taking place and is connected through as a result of operation of the relay by speech or supervisory tones. Use of the dial contacts to control the voice-frequency current, thus eliminating a d.c. to v.f. conversion, or use of a dial key so that the operator controls the disconnection and connection of the speech path, are attractive solutions. Their chief objection lies in the limitations which they impose on the building-up of circuits, since they preclude the possibility of having a d.c. link in front of a voice-frequency link, and this may be a normal requirement. Such solutions would also be unsuitable for subscriber dialling. The use of a regenerator is effective because the delay between pulsing the d.c. impulses into the regenerator and the regenerator pulsing out the corresponding voice-frequency impulses allows the effects of the initial surges to die away before v.f. impulsing commences.

At the incoming end, stepping of the selectors, accomplished by impulsing on the speaking wires, is again productive of surges in the speech and signal path. The introduction of a regenerator is effective as at the outgoing end or, since each surge follows a relay operation, surges may be suppressed from the v.f. receiver by the contacts of a fast relay. Their effect on the receiver may also be reduced by the use of a hybrid connection between the v.f. receiver and the line.

Although noise or other interfering currents may not cause echo-suppressors to bar the transmission path against a train of dialling impulses, the wave-front of the first pulse in the train may encounter a suppressor which is in an intermediate condition. Signalling current will enter the control path of the suppressor and make the transmission path available but, while this is taking place, the initial cycles of the signalling frequency will be suppressed or transmitted forward with considerable attenuation as shown by *d* in Fig. 7. Delay while the transmission path is made available is not so serious with other signals and is also comparatively unimportant during conversation, as clipping of as much as 50 millisec. from initial syllables passes unnoticed. Echo-suppressors located at an intermediate point in the circuit and in poor adjustment have been known to cause trouble due to a backward reflection of the signal from a distant termination competing for control of the suppressor with the forward signal. Partial suppression of the latter may occur temporarily, giving the "waisting" effect shown by *c* in Fig. 7. Terminal echo-suppressors may remain operated in such a way that the required outgoing signal transmission path cannot be established. This occurs when the outgoing signal immediately follows an incoming signal—a condition which does not arise during dialling but which may arise when the connection is being cleared down. The difficulty can be overcome in a straightforward manner by bringing the echo-suppressors under the control of the signalling equipment or by delaying transmission of the signal.

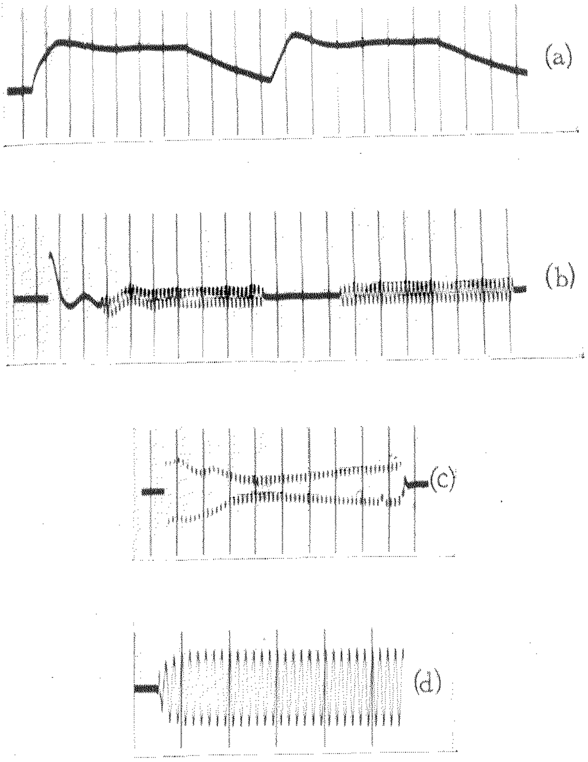


Fig. 7—Oscillograms of Signalling Pulses.

(a) Direct current in relay controlling transmission of v.f. dialling impulses.
(b) Surge transmitted in advance of a train of v.f. dialling impulses.
(c) "Waisting" of a v.f. pulse due to partial operation of an intermediate echo suppressor.
(d) "Wave-front" distortion of a v.f. pulse due to delay in opening up the transmission path.
(Note: Vertical timing lines mark 10-millisec. intervals.)

(3.4.2) *Inter-System Interference.*

The problems which have already been discussed are encountered on lines whose limits are within one national boundary. Whenever two circuits with voice-frequency signalling are joined together within that boundary, signalling and dialling may be extended without retransmission. International calls may, however, have to be obtained by joining together circuits in countries where different voice-frequency signalling systems are in use. If the systems are the same in principle, but signalling codes do not coincide, end-to-end signalling is impossible, as signals will have a different meaning within the foreign network, or on the international line, from that which they have in their country of origin. If the signalling codes are identical, there is still the possibility that signals unintended for end-to-end transmission may cause one section to release prematurely or cause other confusing results. Such considerations made it evident that international agreement was required on fundamental principles of design to ensure that mutual interference between different systems would be avoided. The details of such an agreement had not been fully worked out before the outbreak of war, but it had already been decided that a solution of the problem should be sought by the restriction of the signalling currents to that portion of the line where they were intended to be effective. A similar principle exists in d.c. signalling systems in which signals are restricted to separate sections of a built-up connection by means of condensers or transformers. The two cases are, however, not strictly analogous. Since speech must circulate over the whole of the connection, voice-frequency signals will do so likewise, for it is impracticable to stop them by filtration at points where different systems are, or may be, connected in tandem. Some signal must therefore be introduced which v.f. receivers located at such points will immediately recognize. On doing so they must split the connection, thus trapping subsequent signals to their appropriate section. Such a signal has been given the name of "prefix" signal.

(3.4.2.1) *Use of the "Prefix" Signal*

Use of the "prefix" signal involves general agreement as to the length of time for which the signal must be received before the connection is split.[18] If this time is made too short, false splitting will occur frequently due to signal imitation; although in some cases it can be arranged that false operations result in no more than temporary disconnection of the circuit for a time depending on the duration of the false signal. There is no definite information as to the practical importance of short interruptions in regard to the speech performance of a circuit, but it can be said that those of less than 50 millisec. duration are of no importance. The length of the prefix signal is discussed more fully in succeeding paragraphs dealing with the choice of a signal code. It follows, however, that whatever time period is fixed for recognition of the signal before the connection is split, no pulse of signalling current exceeding this period will be allowed to pass beyond the switching point. If, therefore, durations less than this of the frequency used for splitting are not assigned to significant signals, subsequent sections of a built-up connection will be free from external false signals. The minimum duration of the same frequency, which must be recognized before any operation other than splitting takes place, must be appreciably longer.

In practice response of the v.f. receiver to pulses of signalling current has the ultimate result of operating, or releasing, relays with fixed time-lags. Timing of these relays is, however, subject to inherent variations due to their adjustment. Owing to the effects of line attenuation, incorrect signal frequency and tolerances in the tuning of acceptor elements in the v.f. receiver, some time distortion may accompany conversion from voice-frequency to d.c. pulses. Furthermore, the signal may commence when guard circuits, designed to prevent operation of the v.f. receiver by speech and noise currents, are effective and, until these currents have ceased, response to any genuine signal will be impaired. For all these reasons wide tolerances are necessary on the nominal values of the time set for splitting the line and for the recognition of a significant signal.

Assuming that voice-frequency current at the frequency used for the prefix signal should be applied to the terminals of the v.f. receiver for at least 90 millisec. before the long-distance circuit is split—which Section (3.5.2) will show to be about the minimum time to ensure freedom from false splitting—the receiver and delay elements cannot be adjusted more accurately than will ensure that the maximum period for which the frequency passes the splitting point does not exceed 135 millisec. Any function, other than opening a through connection, depending on the receipt of the prefix signal, is made to follow recognition of the frequency for a minimum period of between 150 and 210 millisec. Response of the receiver itself may, however, be delayed when the prefix signal is sent during a conversation. In order to make allowance for this, the signal frequency is usually transmitted for a period of between 250 and 350 millisec. These times are shown diagrammatically by Fig. 8.

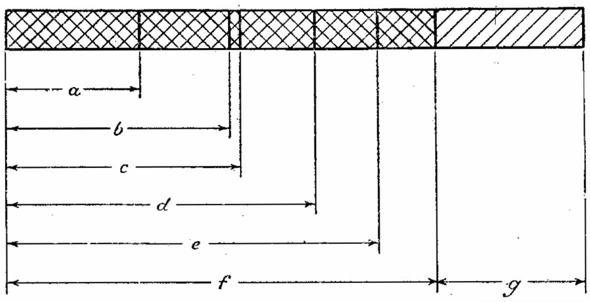


Fig. 8—Constitution of the Prefix Signal.

a = minimum splitting time
b = maximum splitting time
c = minimum prefix response time
d = maximum prefix response time
e = minimum transmitted time of prefix
f = maximum transmitted time of prefix
g = suffix

The duration of the transmitted signals can be accurately controlled. Their timing for purpose of recognition at switching points is not so easy. A pulse-control system is difficult, as the moment of commencement of the signal is indeterminate. Instant resetting is also necessary. Timing is therefore usually determined by means of a slow-to-release relay, and times of the order of 350 millisec. are the longest that can be measured reliably in this way.

It has been emphasized that the primary object of the prefix part of a signal is to divide a built-up connection into separate sections without causing any other change to the circuit. A subsidiary function may be allotted to it. It may be made to prepare the v.f. receiver and associated apparatus for the performance of a switching operation when the subsequent, or "suffix," part of the signal is received. As this will be transmitted after the receiver has been freed from external interference, a short pulse may be used.

(3.5) SIGNALLING CODE

(3.5.1) *General*

A system providing all the facilities usually required could be designed making use of either 600- or 750-c./s. currents only. Elaborate coding to distinguish signals by the number and duration of pulses would be necessary. Utilization of two frequencies provides a second set of distinctive "simple" signals and simplifies the code very considerably, but the signals which are then possible are more liable to signal imitation. There also arises the possibility of introducing "compound" signals to provide a third distinctive set of signal components. It has been found that, when signalling codes comprise both "simple" and "compound" signal components, the available codes are sufficient to enable the latter to be reserved solely for use as the prefix part of signals.

The facilities given by the voice-frequency system now in operation over many long-distance routes in Great Britain are provided by the use of simple signals.[6, 8] The decision not to make use of compound signals was taken at a time when it appeared that there were outstanding difficulties peculiar to the design of a v.f. receiver that would accept these as well as simple signals. These difficulties have largely disappeared as one result of five years' development, so that, although field experience with v.f. receivers which will accept simple and compound signals is small compared with that concerning earlier types, it now seems that such receivers can be made without greatly adding to the complexity of design and without increasing the difficulties of adjustment and maintenance. A code including both compound and simple signal components has since been brought into use in several countries.

It has already been shown that after conversation has commenced it is desirable to prefix that part of any signal designed to bring about a circuit change by another part, the primary function of which is that of splitting the built-up connection at points corresponding to boundaries of different signalling systems. As this common prefix will be the signal component most often occurring during conversation, assignment to it of a frequency, or frequencies, giving the best immunity from false splitting is a proper starting point for the construction of a code of signals.

Signals may consist of a single pulse or of a coded combination of two, or more, pulses. In the latter case the first pulse may constitute the prefix component. On account of the possibility of the required signal transmission path being barred by echo-suppressors or the v.f. receiver being made inoperative by speech or noise, single-pulse signals are chosen for periods when it is known that there will be no speech present, e.g., before dialling commences, or for the transmission of the dial impulses themselves. The latter are subject to interference by busy tone, but only when additional impulses cannot assist to make the connection.

(3.5.2) *Field Tests to Determine the Relative Liability of "Simple" and "Compound" Frequency Components to Signal Imitation*

Prima facie it would appear to be indisputable that a v.f. receiver needing the simultaneous response of two frequency-selecting elements before recording a signal would be more immune from speech interference than one needing the response of one frequency-selecting element only. In practice, however, other factors associated with receiver design enter to prevent the ideal response.

In view of the importance of the matter an extensive series of tests, to check the theoretical conclusion, was carried out in 1938 jointly by the Post Office and three British manufacturers of telephone equipment. The v.f. receivers used were built to a common specification which ensured that, as far as possible, immunity from false operation by speech was not secured at the expense of performance in other directions. These receivers were connected in parallel for some weeks to an inland long-distance circuit in commercial service, the method of connection being such that the speech voltage applied to their terminals could be raised or lowered at will from that normally existing. Later the test was continued using circuits from London to Berlin, Paris and New York, so that the effects of foreign language were also explored. Timing circuits gave a count of the operations of each receiver by speech for periods adjusted to suit line-splitting times of 50, 100, 150, 200, 250 and 300 millisec.

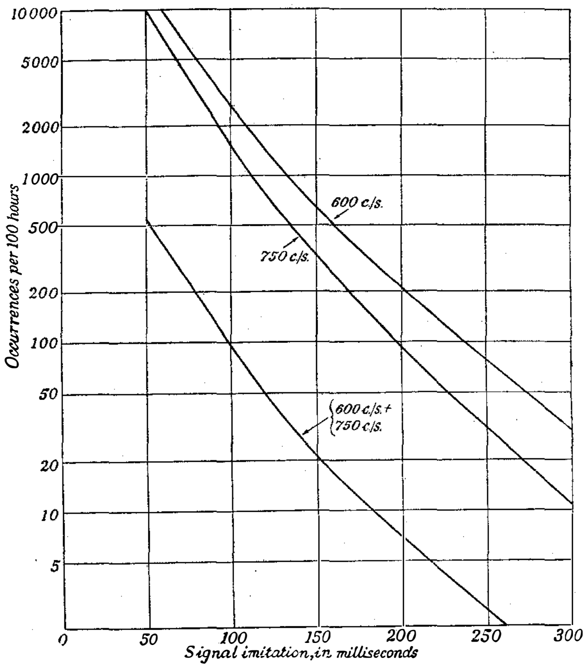


Fig. 9—Speech Immunity Tests of Representative V.F. Receivers Connected to an Inland Trunk Circuit at a Zero Level Point.

It was found that v.f. receiver operations resulting from speech varied in duration, those of short duration occurring much more frequently than those of long duration. From this it follows that a substantial degree of immunity can be obtained by using a time delay which masks false operations of comparatively short duration. It was next confirmed that, with equal time delays, false indications corresponding to the reception of compound-frequency signal components occurred less frequently than those corresponding to the reception of simple-frequency components. Alternatively, simple- and compound-frequency types of v.f. receiver could be made equally immune from speech operation by appropriate adjustment of the time delays. It was found that simple- and compound-signal components were approximately equal on account of signal imitation with v.f. receiver delays of 260 and 90 millisec. respectively. These delays necessitate minimum effective receive times of 400 millisec. for simple-frequency signals and 150 millisec. for compound-frequency signals. Results typical of those on which these conclusions are based are given in Fig. 9, where observations on a number of different receivers have been grouped according to the response concerned.

The results were affected to a certain extent by the level of the speech voltage, and quite wide variations were observed within small groups of v.f. receivers of the same design and adjusted to the same specification. Even wider variations are probable between factory-produced receivers, but the times just quoted should provide adequate margin against frequent false splitting.

(3.5.3) *Typical Signal Codes*

The results of the tests just described confirmed the advantages of a compound-frequency prefix signal, and later in 1938 the proposed standardization of such a signal for use on international circuits was supported by British repre-

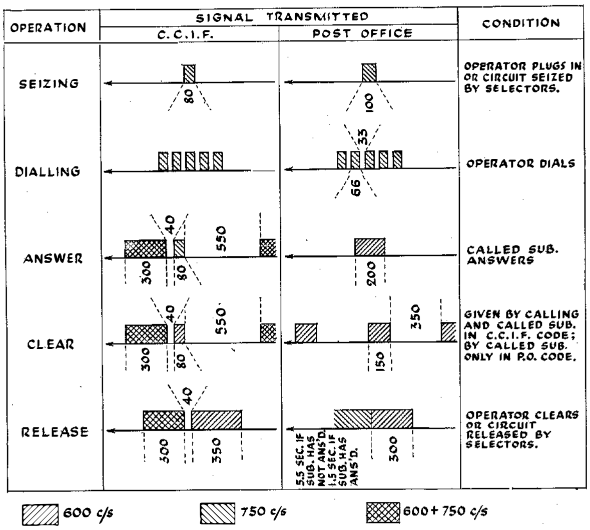


Fig. 10—International and British Signal Codes. (*Codes suitable for systems in which the call is controlled by an operator at the outgoing end.*) *Figures denote mean durations in milliseconds.*

sentatives at a meeting of the C.C.I.F. Use of the compound frequency for other signals is disadvantageous, as the receiver response time is longer. This does not matter with the prefix signal. Most signal codes are therefore based on the use of simple-frequency signals for all signal components other than the prefix. Fig. 10 shows the signals proposed for use on international circuits to give the five essential facilities. The Table also shows how the same facilities are obtained within the British Post Office system by the use of simple-frequency signals only.

(4) *The Recommendations Made by the C.C.I.F. on the Subject of Voice-Frequency Systems*

(4.1) INTRODUCTION

In 1936 the International Consultative Committee on Long-Distance Telephony (C.C.I.F.), representing the major European Administrations and the U.S.A., adopted 600 and 750 c./s. as the frequencies to be reserved for signalling and dialling over international lines. This allocation was made at a time when it appeared that there was insufficient space in the audio range for the various services which were in course of development, and the desirability of earmarking certain bands for particular use was recognized. It was not generally appreciated that international connections would be specially prone to interference due to signal imitation, and in consequence frequencies other than those recommended have been used for national signalling and dialling systems.

To protect the international lines, the C.C.I.F. have recommended a limitation to the duration of pulses of the signalling frequencies which may pass out of the national systems. This recommendation will protect national systems using the recommended frequencies automatically. Use of other frequencies involves the necessity of providing special precautions to avoid interfering currents entering the national system.

The following recommendations were issued after a meeting of the C.C.I.F. held in Oslo in 1938.[12] A further meeting of the Committee investigating signalling and dialling was planned to be held in Paris during September 1939. Various documents representing the opinions of Administrations were circulated in preparation for the discussions. These documents support the recommendations made at Oslo.

(4.2) PREVENTION OF INTERFERENCE ON INTERNATIONAL CIRCUITS

To avoid interference on international circuits, it is recommended that at the end of impulsing a prefix signal, capable of splitting a connection after a certain time, should be transmitted before each signal.

The prefix should be as short as possible, difficult to produce by the human voice, and not liable to result in an incorrect signal if it is abbreviated or interrupted. The purpose of the prefix signal is to divide the connection into separate sections without causing any other operation. It is only the suffix, transmitted after the prefix, which causes other changes to the condition of the circuits. It is obvious that interference can result if the frequency, or the combination of frequencies, used for the prefix signal is connected to an international circuit.

It is probable that the use of a prefix composed of a mixture of the two frequencies (600 and 750 c./s.) will provide the greatest protection against operation by interfering currents. However, the use of this type of signal may introduce additional complexity into the v.f. receiver, so that, before making a definite choice, administrations are recommended to study and make tests to enable them to obtain more experience of systems utilizing both compound signals and simple signals.

Signals

It is recommended that the fundamental signals should be separated from the auxiliary signals. The following are the fundamental and auxiliary signals:

Fundamental Signals

(1) Seizing signal.
(2) Dialled impulses.
(3) Answer signal.
(4) Clear-back signal.
(5) Release signal.

Auxiliary Signals. (The following were listed as examples of what might be required.)

(1) Forward transfer signal.
(2) Offering signal.
(3) Breakdown signal.
(4) Ring forward signal.

Constitution of the Signals

(1) Seizing signal—a single short impulse of 750 c./s.
(2) Dialled impulses—impulses of 750 c./s.
(3) Answer signal—prefix followed by a short signal of 750 c./s. (see remark under "Release Signal").
(4) Clear-back signal—prefix and suffix of 600 c./s. This signal is repeated complete. The interval between signals should be greater than 550 millisec. The signal continues until release, or until the called party returns to the line.
(5) Release signal. There are two cases to consider:
    (*a*) In certain cases the release signal is sent forward from the caller to the called. It is made up of the prefix followed by a long suffix of 600 c./s.
    (*b*) In other cases, a forward signal comprising a prefix followed by a short suffix of 600 c./s. This signal results in the transmission of a release signal which is sent in the backward direction. The release signal is made up of a prefix followed by a long suffix of 600 c./s.

(It was here noted as important that arrangements should be made to ensure that these signals are received with certainty. The Directive with regard to Auxiliary Signals was to have been issued later.)

Signal Length

(1) Short signal: 60–100 millisec.
(2) Long signal: 300–400 millisec.
(3) Compound-frequency prefix: 250–350 millisec.
(4) Simple-frequency prefix: to be fixed later.
(5) Pause between prefix and suffix: 30–50 millisec.
(6) Repeated signals: the pause between two consecutive signals should be equal to, or greater than, 550 millisec.

(4.3) RECEIVER SPECIFICATION

Limits for Signal Frequencies

The admissible variation in frequency for the generation of signals on international circuits should be ±0.5 per cent. The receiver should function with a relatively uniform response over a band of ±22.5 c./s. from the nominal frequency in order to provide for variations at the source and change of frequency due to carrier shift.

Limits for the Power which may be used

(1) *Simple frequency*
2 mW, with a variation of ±1 db., measured at the point of zero relative level and measured as a steady frequency.
(2) *Compound frequencies*
1 mW of each frequency, measured at the point of zero relative level, with a termination of 600 ohms, and measured as a steady frequency with a variation of ±1 db., provided that the voltage of the two frequencies does not differ by more than 0.5 db.

Dialled Impulses

It is desirable to standardize the impulsing speed for international circuits. 10±1 i.p.s. is recommended. It is also recommended that the impulse ratio should be standardized on international circuits, but actually it is not possible to fix this ratio.

Insertion Loss

The insertion loss of the voice-frequency receiver should not exceed 0.3 db. for any frequency transmitted by the circuit.

Receiver Operating Limits

The receiver should be designed for connection to a point of nominal relative level of from 0 to −10 db. and should operate correctly when the actual relative level differs from the nominal relative level by ±5 db.

General

In order to prevent a voice-frequency signalling circuit from being indicated free at an outgoing end before the circuit is free at the distant end, the principle of release should maintain the circuit indicated busy at all points of access until it is actually available at all points.

(4.4) PREVENTION OF INTERFERENCE ON NATIONAL CIRCUITS

It is, in fact, difficult to specify general precautions capable of avoiding interference in national systems which use frequencies other than 600 or 750 c./s. when these systems are connected to an international circuit. The following precautions can, however, avoid interference to national systems utilizing 600 and 750 c./s., chosen by the C.C.I.F., and connected together by international circuits. It is recommended that means should be provided to prevent a voice-frequency current passing from the national to the international circuit if its length exceeds:

400 millisec. for a simple frequency (600 or 750 c./s.), or

150 millisec. for a compound frequency (600 and 750 c./s.).

(5) *A Forecast of the Future Development of Signalling and Dialling Over Long-Distance Telephone Circuits*

(5.1) INTRODUCTION

Before future developments can be forecast, consideration must be given to the requirements which are likely to be made with regard to long-distance signalling and dialling, particularly as a result of more extensive replacement of operators by automatic switching equipment in the setting up of calls. Consideration must equally be given to the type of transmission system that is likely to be used, for it is probable that this may influence directly the form which the signalling system should take.

(5.2) PROBABLE DEVELOPMENTS IN SIGNALLING

One probability is the enlargement of the area over which the subscriber is permitted to make connection without the assistance of an operator. Widespread introduction of subscriber dialling must inevitably be delayed for a number of years. It is likely to be preceded by a period of more limited mechanization during which the densely populated areas become accessible for subscriber dialling from towns at distances up to 100 miles or so. Such calls could be identified by a special 2-digit prefix and would not necessitate the subscriber dialling a total of more than 10 digits.

As the distance extends over which subscriber dialling is permitted, problems concerned with routing the call become more difficult. At present there are operating in this country a large number of multi-exchange areas each using a separate numbering scheme. Group centres and zone centres are arranged to suit the needs of general administration and the existing line plant. A national switching plan must be prepared to enable the various stages of mechanization to be introduced from time to time.

To assist the subscriber and the P.B.X. operator, it will be necessary for the overall switching plan to be based on a national numbering scheme. It is also very desirable that the maximum number of digits for any one subscriber to reach any other should not be large. One step towards achieving this object might be a reduction in the number of zone centres so that a single "zone" digit following the general long-distance prefix may identify the zone required. For example, the country might be divided into zones based on the following switching centres:

(1) London.
(2) Bristol.
(3) Birmingham.
(4) Manchester.
(5) Leeds.
(6) Newcastle.
(7) Edinburgh.
(8) Glasgow.
(9) Belfast.

The tenth digit might be used to obtain access to an operator for international calls.

To extend the connection from the zone centre to any dependent area, it would be necessary to allocate a series of "area" codes which might be restricted to 3 digits as a maximum. The 1,000 combinations so formed would be usually sufficient for each zone, and some of the larger areas with 5- or 6-digit exchange numbers could be allotted 2-digit codes.

In some Continental countries the digit 0 is used as a general long-distance prefix, but in this country there are objections to this arrangement because this digit is well established for providing access to an operator. A 2-digit prefix would be necessary and the numbering plan would then be constituted as follows: 2 digits for long-distance prefix, 1 digit for zone prefix, 3 digits for area prefix and 4 digits for exchange number, giving a total of 10 digits.

Economical provision of line plant requires flexibility in the use of circuits which may be employed to build up long and complicated connections. This will probably lead to the introduction of storage on some calls. The storage period would be utilized, when necessary, for the translation of one or more of the digits dialled by the subscriber into such others as the circumstances required. Storage would be accompanied by regeneration of all impulse trains but, unless storage and regeneration were introduced on all calls, development of the long-distance signalling system would not be greatly influenced.

Prior to the introduction of subscriber dialling, either in part or on a full national basis, it is believed that an intermediate stage of development with an extensive use of cordless switchboards should be expected. Many of the selectors which are provided for the use of cordless switchboards can be utilized without rearrangement for subscriber dialling as mechanization proceeds. These switchboards are more flexible in arrangement and simpler in operation than the multiple type. To compensate for loss of direct access to the long-distance line, facilities will be necessary to indicate to the operators when a circuit in any particular direction becomes available. The indication will enable the available lines to be loaded to the maximum efficiency during conditions of congestion. Thus the succession of events will be a progressive reduction in the number of operators required for each call, tending to the condition when the subscriber is capable of setting up all long-distance connections. Operators must be retained for international calls, for such special services as personal calls, and for assisting subscribers unable to complete their own connections, more especially during periods of congestion.

For large cities and for groups of towns, it seems probable that in place of a centralized long-distance switchboard on which terminate a large number of lines, some decentralized system utilizing a ring main will be adopted (see Fig. 11). With this layout the long-distance lines will terminate at the periphery of the area.

Repeated operation of the subscriber's message register, known as multi-metering, is now used in this country as a means of recording calls up to the value of 4d., corresponding approximately to a 15-mile connection, but it is unsuitable for the more expensive calls, as details are not recorded. Before the subscriber can be allowed to set up expensive calls without the intervention of an operator, automatic equipment might be required to give a printed record of the call and to enable the necessary particulars to be entered on the account as at present. Such equipment has already been installed in Belgium. An example of

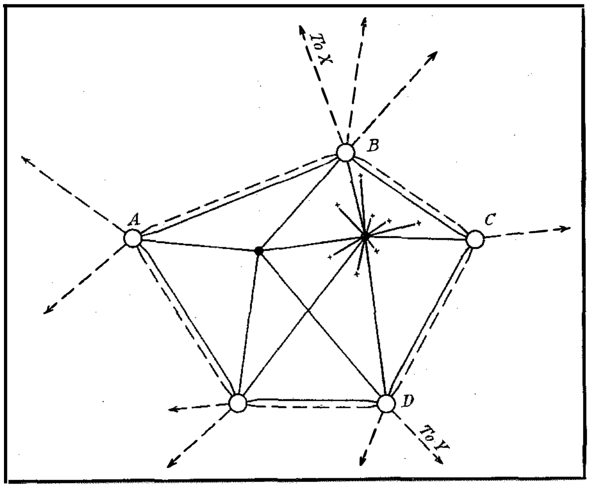
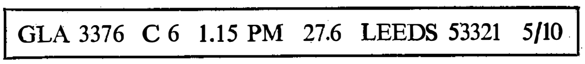


Fig. 11—Decentralization of Long-Distance Switching. (Two only of a number of likely control centres have been shown, and only the local exchanges connected to one of the control centres.)

○ *Ring main switching centres*
● *Control switching centres*
+ *Local exchanges*
——— *Audio-frequency cables*
– – – *Multi-channel carrier cables*

(*Note: A call from X to Y would be switched round the ring via B, C and D.*)



GLA 3376 C 6 1.15 PM 27.6 LEEDS 53321 5/10

Fig. 12—Typical Long-Distance Ticket

This ticket conveys the following information. Subscriber number GLAdstone 3376 has called LEEDS 53321 at 1.15 p.m. on the 27th June. The call was set up on circuit number 3(C), the duration of the call was 6 minutes and the charge is 5s. 10d. The latter half of the ticket represents the information necessary for the subscriber's account.

a ticket from a machine developed for use in step-by-step areas is shown in Fig. 12.[15]

It has been argued that on calls for which the tariff is more than a few pence the subscriber is entitled to the assistance of an operator to check that the speech level is satisfactory and to render any service which is possible. On the other hand the ability to make a long-distance connection without the intervention of any operator would be of importance to many subscribers who would possibly not appreciate the improvements in service resulting from the use of automatic signalling and dialling by an operator. Whatever the limit to which subscriber dialling is eventually permitted, it is certain that an operator will be available to render assistance if required. Subscriber-to-subscriber dialling over large areas is practiced in many Continental countries, notably Germany, Switzerland, the Netherlands and Belgium.[10, 11, 16] Before the commencement of the present war it was intended to provide subscriber-to-subscriber dialling over the whole national network in all these countries, and considerable development had taken place.

The switching requirements which are likely to influence the development of future long-distance signalling systems cannot be enumerated with any degree of certainty, but at the present time it is to be expected that the following factors will be of importance:

(i) The connection will be under the entire control of the subscriber.

(ii) Subscribers must be able to obtain access to an operator for special services and in case of difficulty with the long-distance circuits.

(iii) Speedier switching and release of built-up connections will result in more switching points and shorter lines.

(iv) Alternative routes will be established automatically when needed. Introduction of the additional switching digits may require storage on some calls but not necessarily on all.

(v) The subscriber will be protected from complicated dialling codes by a comprehensive national dialling scheme. Such a scheme and the probability of more switching centres may involve storage and translation on some calls.

(vi) The answer signal must be safeguarded from subscriber interference.

(vii) The ability to use either of two seizing signals, depending on the ultimate destination of the call.

(5.3) THE NATURE OF FUTURE TRANSMISSION SYSTEMS

In April 1937, Col. A. S. Angwin and Mr. R. A. Mack[9] gave The Institution an account of the carrier telephone system then operating between Bristol and Plymouth and affording 12 telephone channels per pair of wires in the frequency range 12–60 kc./s. "Go" and "return" channels were supplied by separate cables. The success of this installation was such that 12-circuit carrier systems were adopted by the Post Office as the premier means of providing additional groups of long-distance circuits. A network of cables was planned interconnecting many of the more important centres in the country. Provision of this network had progressed to a considerable extent before September 1939, and 12-circuit systems have since been brought into commercial service on other routes.

There was described in the same paper a parallel line of development[4] exemplified by the provision of the first British coaxial cable. This was laid between London and Birmingham and was designed to give 320 carrier telephone circuits within the frequency band 0.5–2.1 Mc./s. The cable was equipped with wide-band amplifiers at intervals of approximately 7 miles, and separate coaxial tubes were used for the two directions of transmission. In anticipation of a continued and increasing growth in the trunk traffic, the original London–Birmingham cable was extended to Manchester, Leeds, and Newcastle. It now appears definite that the economies inherent in a wide-band transmission system are such that, even allowing for the considerable cost of the associated terminating equipment, these systems will form a future means of providing large groups of long-distance circuits in this country. Where a large group of circuits is required between switching centres upon long-distance routes the wide-band system may prove economical for distances down to 50 miles due to the saving resulting from the common use of plant and equipment.

It is difficult to forecast the post-war demands for additional long-distance circuits, but in the years immediately preceding 1939 long-distance traffic was increasing in Great Britain at the approximate rate of 25% per annum. Without very great capital expenditure it would have been impossible to provide the additional circuits required, solely by extension of the existing network of audio-frequency cables. 12-circuit carrier and wide-band coaxial systems give means of providing these circuits much more cheaply. It appears, therefore, that the long-distance transmission system of the future will consist of wide-band coaxial systems connecting main centres, with 12-circuit carrier systems as a subsidiary. 12-circuit carrier and wide-band coaxial systems have features in common. The latter are built up from groups of 12 speech channels, and each group, apart from its location in the frequency spectrum, is similar to the group transmitted, in the case of the 12-circuit system, within the frequency range 12–60 kc./s. Adjacent speech channels are spaced at 4-kc./s. intervals. Short links between zone and group centres may be 12-circuit carrier or 4-wire audio circuits. The latter type of circuit will probably not be used except between centres which are sufficiently close together to permit the operation of d.c. dialling systems.

An attempt has been made in Fig. 13 to indicate the probable nature of the links included in a built-up connection of the immediate future.

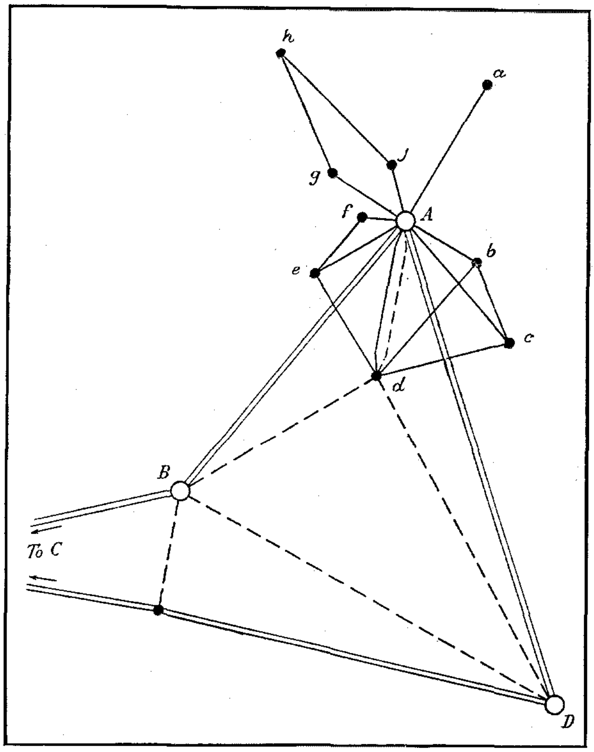


Fig. 13—Schematic Layout of Modern Long-Distance Telephone System. (A few only of the lines have been indicated and the group centres in Zone A only. Telephone exchanges are connected to the group centres and have not been shown.)

A Primary switching centres (zone centres)
○
a Secondary switching centres (group centres)
●
══════ *Coaxial systems*
– – – – *12-circuit systems*
———— *Audio systems*

(5.4) POSSIBLE DEVELOPMENT OF 2-VOICE-FREQUENCY SIGNALLING

Any picture of the future long-distance telephone service should include the provision of automatic signalling and dialling by continued use of voice-frequency systems with possible improvements or modifications. Alternatively, entirely new signalling systems may be introduced for operation over the special types of speech transmission path likely to be employed in the future. Initial consideration must be given to the first of these possibilities.

The power-handling capacity of the amplifiers included in a wide-band coaxial system is decided by the average speech level of the telephone channels. Peak levels may be very much higher, but do not occur simultaneously on all channels. At present voice-frequency signals are sent at levels higher than normal speech and the possibility of some reduction being necessary must be kept in mind.

Whatever the future means of providing connections between switching centres more than a few miles apart, the circuits will almost certainly be of the 4-wire type, comprising separate "go" and "return" paths. These paths may consist of separate pairs in an audio-frequency cable or of separate channels in a multi-circuit carrier or wide-band coaxial system. It has already been shown that echo-suppressors connected to 4-wire circuits constitute one of the major obstacles to the transmission of voice-frequency signals. Although on future high-velocity circuits echo effects will not be troublesome, the retention of echo-suppressors to limit singing currents is possible on some circuits to ensure stability. Such echo-suppressors will normally be connected at switching centres, as with carrier circuits intermediate positions are unsuitable.

Difficulties due to interference by signals enumerated in Section (3.4.1) can be avoided if the voice-frequency signalling equipment is connected to the 4-wire portion of the long-distance line, because in this position the circuit is divided into separate "go" and "return" transmission paths. Such an arrangement eliminates unwanted operation of the v.f. receiver from currents passing in the opposite direction and also provides a means for avoiding the interference due to the terminal echo-suppressors. There is, however, a serious disadvantage in connecting the voice-frequency signalling equipment on the 4-wire side, because it increases the difficulty of passing the received signals to and from the switching equipment. These operations need to be controlled in the d.c. portion of the circuit on the exchange side of the terminating set. Additional conductors may be necessary between different buildings if transmission and switching equipments are located separately.

With manual operation all long-distance circuits have been provided with a 2-wire termination and appear on the switchboard in the same way as junction and local circuits. Although technical difficulties exist with the switching equipment if circuits are connected together 4-wire to 4-wire, it is certain that the possibilities of this method will be studied where long-distance lines are joined in tandem,[13] because with 4-wire switching the number of paths included in the built-up connection and around which singing currents can circulate is reduced. The complication with 4-wire switching does not lie with the transit connection but, more particularly, on those calls which need to be switched to a local line operating on a 2-wire basis. The way in which the connection is to be extended will probably remain unindicated until one or more selecting digits have been received, and this uncertainty may necessitate the transmission, later, of a special signal in a backward direction. This signal may be valuable for other functions, such as inserting an echo-suppressor. The arrangement places the v.f. receiver in the 4-wire side but leaves the position of the terminating set unspecified, and some interesting possibilities arise.

It has been noted that storage and regeneration of dialled impulses at certain switching centres is likely in the future. The introduction of storage will facilitate automatic adjustment to be made of the overall gain on a built-up connection. Without storage, the short inter-train pause between successively dialled digits does not provide the opportunity for the transmission of a signal long enough to determine the automatic setting of the gain of a repeater. Regulation of the overall gain of a circuit may become a greater problem in the future as both the total attenuation and the total gain increase. These two factors are considerable in modern circuits. On a 300-mile connection over coaxial cable (London-Newcastle, for example) the total attenuation is of the order of 2,000 db., i.e., if it were not for the compensating gain introduced by amplifiers at regular intervals along the route the received speech voltage would be reduced to $1/10^{100}$ of that transmitted. It is difficult to give any illustration of this ratio. Comparison of the total power radiated by the sun with the light emitted by a glow-worm is roughly equivalent to the attenuation of the coaxial line between London and Birmingham. Because of the great attenuation and gains involved, automatic regulation appears to be extremely desirable. Hitherto individual links have been set to have approximately zero attenuation, but many difficulties would be avoided could the normal attenuation of each link be increased slightly and the net attenuation of a built-up connection controlled by automatic adjustment of the gain of repeaters at switching points. The signalling frequencies transmitted with 2-voice-frequency systems provide a basis for the automatic setting of the gain of a circuit. It should be noted, however, that the ability to do this is also inherent in other long-distance signalling systems.

(5.5) SIGNALLING AND DIALLING SYSTEMS DESIGNED ESPECIALLY FOR OPERATION OVER MULTI-CIRCUIT CARRIER SYSTEMS

Use of multi-circuit carrier systems, whether of the 12-circuit or wide-band coaxial types, in increasing quantities justifies consideration of the special problem of providing automatic signalling facilities over such systems by the most economical means possible.

Signalling channels operating in a frequency band entirely separate from the speech frequency band have been used to provide automatic facilities on open-wire carrier systems of certain types.[19] Such systems are simple, but the frequency band required might not always be available in multi-circuit and wide-band systems.

The carrier frequency itself has been used for signalling purposes on certain systems in which the signalling forms an integral part of the transmission equipment. This method of signalling increases the difficulties of filter design, and difficulties may be experienced with the precautions which have to be taken to keep the leakage of current at the carrier frequency small. Even so, a fairly high signalling power may be necessary.

(5.5.1) *Signalling Facilities Provided Separate from the Speech Channels*

Suggestions have been made that signalling channels suitable for use with multi-circuit carrier telephone systems could be provided by means

TABLE III

COMPARISON OF VARIOUS LONG-DISTANCE SIGNALLING SYSTEMS

Location of signalling channels	Means of signalling	Method of avoiding speech imitation of signals	Usual or suggested field of application	Facilities provided		Transmission of signals at transit switching centres
				Signalling	Dialling	
1	2	3	4	5	6	7
(1) Within the speech channel						
(1*a*)	500/20, i.e. 500 c./s. modulated at 20 c./s.	By time delay and combination of 2 frequencies	Technically possible on all types of circuit, infrequently installed on short lines on account of cost	Only ringing signals for calling operator	No	Manual repetition necessary
(1*b*)	2 voice-frequencies, usually 600 and 750 c./s.	By time delay and guard circuits	As (1*a*)	Sufficient distinctive signals for full automatic supervision provided by coded pulses	Yes	End-to-end signalling possible, failing which precautions to avoid interference between different sections must be taken
(2) Adjacent to the speech channel						
(2*a*) Sub-audio						
(2*a*)i	16⅔ c./s.	Signalling frequency is below effective speech band	Limited to audio-frequency circuits	Only ringing signals for calling operator	No	Manual repetition necessary
(2*a*)ii	50 c./s.	As (2*a*)i	As (2*a*)i	Full automatic supervision provided by distinguishing pulse signals on a time and sequence basis	Yes	Conversion into d.c. signals and repetition necessary
(2*b*) Super-audio	2,500 c./s. or higher frequency	By low- and high-pass filters to separate speech and signal channels	Open-wire carrier circuits	As (2*a*)ii	Yes	As (2*a*)ii
(3) Carrier, appropriate to the speech channel	Channel carrier frequency	By band-pass filters; additional modulation process sometimes necessary	Carrier systems, in which it forms an integral part of transmission system	As (2*a*)ii	Yes	As (2*a*)ii
(4) Segregated from the speech channel						
(4*a*) Within carrier group	Specific frequencies transmitted over one of a group of carrier circuits, the selected circuit being subdivided as in v.f. telegraph systems	Signalling currents use separate channel	12-circuit carrier and wide-band coaxial systems only	Full automatic supervision provided by continuous signals, or, failing this, by pulses as with (2*a*)ii	Yes	As (2*a*)ii
(4*b*) Outside carrier group	Specific frequencies transmitted over a frequency band, provided outside the carrier group, the selected frequency band being subdivided as in (4*a*)	Signalling currents use separate channel usually in the band below 12 kc./s.	12-circuit carrier systems only	Full automatic supervision provided by continuous signals as with direct current	Yes	As (2*a*)ii

similar to those employed in voice-frequency telegraphy. The proposed schemes envisage the allocation of one speech channel from a group to provide signalling facilities for the remainder of the group, the allocated speech channel being sub-divided by filters to give the appropriate number of signalling channels in the same way as a 12- or 18-channel voice-frequency telegraph system is obtained by sub-division of a speech channel into bands, each having a width of 120 c./s. In order that the complete system should be flexible, it is not desirable that the signalling channels appropriate to more than one, or at the most two, groups of 12 speech channels should be associated. A convenient scheme would be for one speech channel in each 12-channel group to be allocated for signalling and to be sub-divided so that it provides signalling facilities for the other 11. Alternatively, the selected speech channel could be sub-divided to provide many more signalling channels, but with such sub-division, or with cheapened filters, the frequency band-width

TABLE III (*Continued*)

COMPARISON OF VARIOUS LONG-DISTANCE SIGNALLING SYSTEMS

Modifications required to transmission system 8	Remarks concerning nature of signal receiver 9	Comparative space occupied by signalling equipment 10	Comparative first cost of signalling equipment 11	Extent of practical experience 12	General remarks 13
None	Comparatively complex and requires specialized maintenance	0.5	0.5	Large	Signal imitation gives rise to the risk of occasional short-period interruptions
None	Similar to (1*a*) but more elaborate; requires specialized maintenance	1.0	1.0	Fair	As (1*a*)
Bypass signal path, or signal-repeating apparatus at each repeater station	Simple and robust	0.1	<0.1	Large	To the cost of the terminal equipment (Col. 11) must be added that of the units necessary at repeater stations to bypass or repeat the signals
As (2*a*)i	As (2*a*)i	0.5	0.4	Fair	To the cost of the terminal equipment (Col. 11) must be added that of the modifications or additional equipment necessary at each repeater station (Col. 8)
Filters are necessary to separate speech and signal channels, and some speech impairment results	Comparable with (1*b*)	1.5	1.5	Small	A speech transmission system with this method of signalling will not usually meet C.C.I.F. requirements
Design of speech and signalling terminals completely interdependent. Provision of signalling makes channel filter requirements more difficult to meet and additional filters are necessary to separate speech and signal currents	Built into carrier system and requires specialized maintenance	1.0	1.5	Small	
A proportion of the speech circuits must be abandoned to nonrevenue-earning purposes	Follows orthodox v.f. telegraph apparatus design and requires corresponding maintenance	Not developed	1.5 to 2	None	To the cost of the terminal equipment must be added that due to the loss of a proportion of circuits to revenue-earning purposes. It may be economical to make use of a dialling path having a greater band width than the signalling path (e.g. the speech channel itself) in order to cheapen the design of the filters separating signalling paths or to make a greater number of signalling paths available within a given frequency band
Restricts the use of the frequency band below 12 kc./s. for such purposes as music transmission	As (4*a*)	Not developed	1.5 to 2	None	As (4*a*) except that signalling frequency band may not be otherwise revenue-earning

included in each channel would be insufficient for the transmission of dialling impulses without the introduction of distortion exceeding permissible limits. Dialling impulses could, however, be transmitted either over the speech circuit, which is not required for conversation during dialling, or over separate dialling channels which are connected to the circuit only when required. The band-width required for each individual channel to provide signalling facilities other than dialling could be reduced since considerable distortion can be permitted to these signals. Apart from the reduced flexibility of such a system, the reduction in cost of the individual signalling channels would probably more than compensate for the additional complication.

Independent channels are used for the two directions of transmission, and signalling can take place independently and, if necessary, simultaneously in both directions. Signalling is possible during the periods when speech is also being transmitted, and the signalling system is entirely free from interference due to speech currents. The facilities which the system is capable of providing approximate closely to those obtained by d.c. signals in local networks, but this is not necessarily true if the signals have to be transmitted over wide-band coaxial systems, which may in the future contain up to 1,000 channels. In such cases the overloading of intermediate amplifiers would result from the use of continuous signals at levels exceeding that of normal speech. Modification of d.c. signalling methods would therefore be necessary.

The cost of systems employing separate signalling channels has not yet been worked out in detail. It will possibly be more than that of 2-voice-frequency systems, apart from the fact that to it would have to be added the cost of the circuit allocated for signalling purposes and therefore lost for speech. There are apparent advantages of simplification and ease of maintenance, but complications may arise with respect to the transmission of signals over built-up connections. Conversion into d.c. signals will generally be necessary at transit switching centres, apart from the obvious necessity of such conversion at points where different types of transmission system meet. In this respect systems employing separate signalling channels compare unfavourably with voice-frequency signalling. In conditions of emergency necessitating a rapid rearrangement of the routing they also compare unfavourably with voice-frequency systems in which the speech path serves also as the signalling path.

(5.6) CONCLUSIONS AS TO FUTURE DEVELOPMENT

In Table III an attempt has been made to summarize the relative advantages and disadvantages of various possible methods of signalling over long-distance circuits. Methods which have been in widespread use for a number of years, but which give very restricted facilities, such as ringing only, have been included to form a basis of comparison in such matters as cost and complexity. Other methods, which give greater facilities, but which have not yet had the test of extensive practical use, have also been included.

Any review of the means by which long-distance signalling and dialling may be accomplished suggests that 2-voice-frequency systems have certain outstanding advantages as regards their capability of operation over any type of speech transmission path. They alone permit through signalling over a patchwork connection consisting of different types of transmission systems and allow end-to-end signalling when several trunk links are connected in tandem. In view, however, of the interference between different sections of a built-up connection, which is discussed in Section (3), the advantages of end-to-end signalling are problematical. The increasing proportion of long-distance circuits to be provided by means of 12-circuit carrier and wide-band coaxial systems merits, however, the consideration of other means of signalling specially adapted for such systems. Although limited in their application to carrier telephone systems, such means of signalling have the advantages of avoiding somewhat formidable difficulties due to speech interference.

(6) *Acknowledgments*

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Selenium Rectifiers and Their Design*

By J. E. YARMACK, S.B. in E.E.

International Telephone & Radio Manufacturing Corporation, East Newark, N. J.

Editor's Note

This is the third of a series of articles [1,2] *on Selenium Rectifiers recently published in this journal and is devoted to design methods. The present article parallels presentations before the American Institute of Electrical Engineers.*

The design procedures and computations described, as well as the nomenclature utilized, have proved useful in expediting the selection of Selenium Rectifier plates or discs and in consummating designs of complete rectifier units even in cases of complicated field requirements. Insofar as the author is aware, the procedures outlined have not heretofore been applied to the design of metallic plate rectifiers.

Selenium Plates

THE rectification of alternating currents by means of the Selenium Rectifier takes place wholly within the constituent plate or plates, seven sizes of which are shown in Fig. 1. The rectifying medium of this electronic device consists of selenium; the principle of operation is similar to that of other dry plate rectifiers, i.e., low resistance in the forward direction and high resistance in the reverse direction. A metal plate serves as back electrode; over it, a layer of selenium is deposited, thin enough to give minimum internal losses, but sufficiently thick to withstand high inverse voltage. A soft metal of low-melting temperature is then applied over the selenium layer to form a front electrode. Finally, by means of controlled processes, a barrier layer is formed between the selenium and the front electrode.

Fig. 1—Left: Cross-Section of a Selenium Rectifier Plate Showing the Sequence of Various Layers. Right: Seven Basic Sizes of Selenium Rectifier Plates.

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Selenium Rectifier Stacks

Rectifier stacks are produced by assembling Selenium Rectifier plates (40 plates are usually maximum) on a center stud with contact discs or washers interspersed between plates. Series and parallel arrangement can readily be provided as required by inserting insulators between plates and introducing terminal lugs into the stack.

A stack consisting of forty plates may be connected in several different ways; for example, as a bridge circuit unit having ten plates in a series and one plate in parallel (4–10–1), or one plate in series and ten in parallel (4–1–10). The same stack may also be connected as a half wave rectifier having all forty plates in series to take care of voltage and one plate in parallel to take care of current (1–40–1). Further, the forty-plate stack may also be assembled as a doubler (2–10–2), two of which make a bridge circuit rectifier with ten series and two parallel plates in each arm of the bridge.

For the three phase half wave circuit the total number of plates must be a multiple of three to allow a total connection such as 3–6–2 for a thirty-six plate single stack unit. Similarly, this latter stack, if connected as 6–6–1, becomes either a bridge or center tap three phase rectifier.

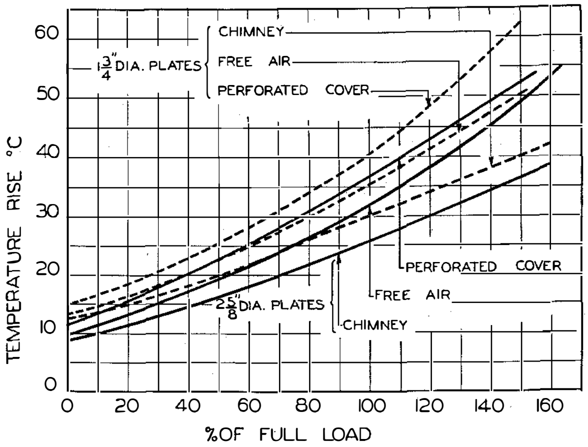


Fig. 2—Temperature Characteristics of Two Selenium Rectifiers Under Three Different Cooling Conditions: (1) in a cabinet with perforated top and bottom covers; (2) in free air; (3) in a chimney-like enclosure fully open at the top and bottom.

Rating of Plates

Current ratings of selenium plates are a function of their effective rectifying areas and heat-dissipating capacities. Table I lists seven basic plates, ranging from three-quarters of an inch to four and three-eighths inches in diameter; it also shows ratings of the basic plates in various rectifier circuits. The ampere capacities shown in this Table are based on an ambient temperature of 35° C., and were determined experimentally. The requirements of a Selenium Rectifier, in respect to current, are always met by selecting the proper size of plates and their number in parallel, if the total rating of the rectifier exceeds the rating of an individual plate.

The ratings of the plates shown in Table I can be increased by providing additional cooling. Doubling the spacing between plates assembled in a single stack increases the heat-dissipating ability of the stack; the rating of plates is then 25 to 50% higher than those shown in Table I. Table II lists six selenium plates having the same

TABLE I

Plate Type No.	Diameter of Plates	Maximum Number of Plates per Stack	Max. R.M.S. Reverse Voltage per Plate	Single Phase Rectifiers			Three Phase Rectifiers			Rating of Plates Used as D.C. Valves	
				Half Wave	Bridge	Center Tap	Half Wave	Bridge	Center Tap		
	Inches		Volts	D.C. Amperes						Amperes	Volts
1	¾	36	18	.04	.075	.075	.10	.11	.13	.06	15
2	1	36	18	.075	.15	.15	.20	.225	.27	.12	15
3	1⅜	36	18	.15	.30	.30	.40	.45	.55	.23	15
4	1¾	40	18	.30	.60	.60	.80	.90	1.1	.45	15
5	2⅝	40	18	.60	1.2	1.2	1.6	1.8	2.2	.90	15
6	3⅜	40	16	1.2	2.4	2.4	3.2	3.6	4.5	1.8	12
7	4⅜	40	14	2.0	4.0	4.0	5.3	6.0	7.5	3.1	12

Current and Voltage Ratings of Seven Basic Selenium Plates When Used in Narrow Spacing Assemblies and with Resistive and Inductive Loads. For battery-charging and condenser loads, these ratings are reduced by 20 percent. Conditions: Continuous Duty; 35° C. Ambient Temperature.

TABLE II

Plate Type No.	Diameter of Plates	Maximum Number of Plates per Stack	Selenium Plate No. Used (See Table I)	Max. R.M.S. Reverse Voltage per Plate	Single Phase Rectifiers			Three Phase Rectifiers			Rating of Plates Used as D.C. Valves	
					Half Wave	Bridge	Center Tap	Half Wave	Bridge	Center Tap		
	Inches			Volts	D.C. Amperes						Amperes	Volts
20	1	28	2	18	.11	.22	.22	.29	.33	.4	.17	15
21	$1\frac{3}{8}$	28	3	18	.23	.45	.45	.6	.67	.82	.34	15
10	$1\frac{3}{4}$	28	4	18	.39	.78	.78	1.0	1.1	1.4	.58	15
11	$2\frac{5}{8}$	28	5	18	.78	1.6	1.6	2.1	2.3	2.8	1.2	15
14	$3\frac{3}{8}$	28	6	16	1.5	3.1	3.1	4.1	4.6	5.8	2.4	12
18	$4\frac{3}{8}$	28	7	14	2.6	5.2	5.2	6.9	7.8	9.7	4.0	12

Current and Voltage Ratings of Six Selenium Plates (Similar to Table I, Except No. 1 Plate Omitted) When Used in Wide Spacing Assemblies and for Resistive and Inductive Loads. For battery-charging and condenser loads, these ratings are reduced by 20 percent. Conditions: Continuous Duty; 35° C. Ambient Temperature.

TABLE III

Plate Type No.	Size of Cooling Fins	Maximum Number of Plates per Stack	Selenium Plate No. Used (See Table I)	Max. R.M.S. Reverse Voltage per Plate	Single Phase Rectifiers			Three Phase Rectifiers			Rating of Plates Used as D.C. Valves	
					Half Wave	Bridge	Center Tap	Half Wave	Bridge	Center Tap		
	Inches			Volts	D.C. Amperes						Amperes	Volts
9	$2\frac{5}{8}$ D.	28	4	18	.58	1.1	1.1	1.5	1.7	2.1	.87	15
12	$3\frac{3}{8}$ D.	28	5	18	.90	1.8	1.8	2.4	2.7	3.3	1.4	15
13	$4\frac{3}{8}$ D.	28	5	18	1.1	2.2	2.2	2.9	3.3	4.0	1.7	15
15	$4\frac{3}{8}$ D.	28	6	16	1.8	3.5	3.5	4.6	5.2	6.5	2.7	12
16	$4\frac{3}{8}$ D.	24	6	16	1.9	3.8	3.8	5.0	5.6	7.0	2.9	12
17	6 × 6	28	6	16	2.7	5.4	5.4	7.2	8.1	10.0	4.1	12
19	6 × 6	28	7	14	3.7	7.4	7.4	9.8	11.1	13.3	5.7	12
8	8 × 8	28	7	14	5.0	10.0	10.0	13.0	15.0	18.0	7.5	12

Current and Voltage Ratings of Eight Selenium Plates (Nos. 4, 5, 6 and 7) Equipped with Cooling Fins of Different Sizes, and Used for Resistive and Inductive Loads. For battery-charging and condenser loads, these ratings are reduced by 20 percent. Conditions: Continuous Duty; 35° C. Ambient Temperature.

effective rectifying areas as those listed in Table I, but their current ratings are higher because of wider spacing.

By providing cooling fins, the forward current carrying capacity of the plates can be raised still further. Table III contains eight additional plates with fins, the current ratings of which are from two to two and one-half times greater than the plates of the same rectifying areas listed in Table I. With the extended ratings of the plates, whether by means of wide spacings or cooling fins, the internal losses of Selenium Rectifiers are greater; consequently, their efficiency is slightly reduced and the voltage regulation is adversely affected.

Tables I, II, and III also give the maximum permissible reverse r.m.s. voltages per plate. The voltages thus indicated have ample safety margin. If, however, the reverse voltage be increased beyond safe limits, the rectifying layer between the selenium and the front electrode alloy breaks down. The maximum specified voltage must not, therefore, be exceeded. Tables I, II, and III include ratings of selenium plates in d-c circuits.

Rectifier stacks with narrow or wide spacing, as well as those with fins, are ordinarily cooled by convection. Large size Selenium Rectifiers, however, often utilize forced draft ventilation in order to save space and to economize in rectifying elements. The normal plate rating can thereby be increased twofold, and sometimes threefold. If, however, extended loading of plates with the aid of forced ventilation is not desired, substantially greater current output, as compared with free air conditions, can be obtained by mounting the stacks in a chimney-like enclosure (Fig. 2). As

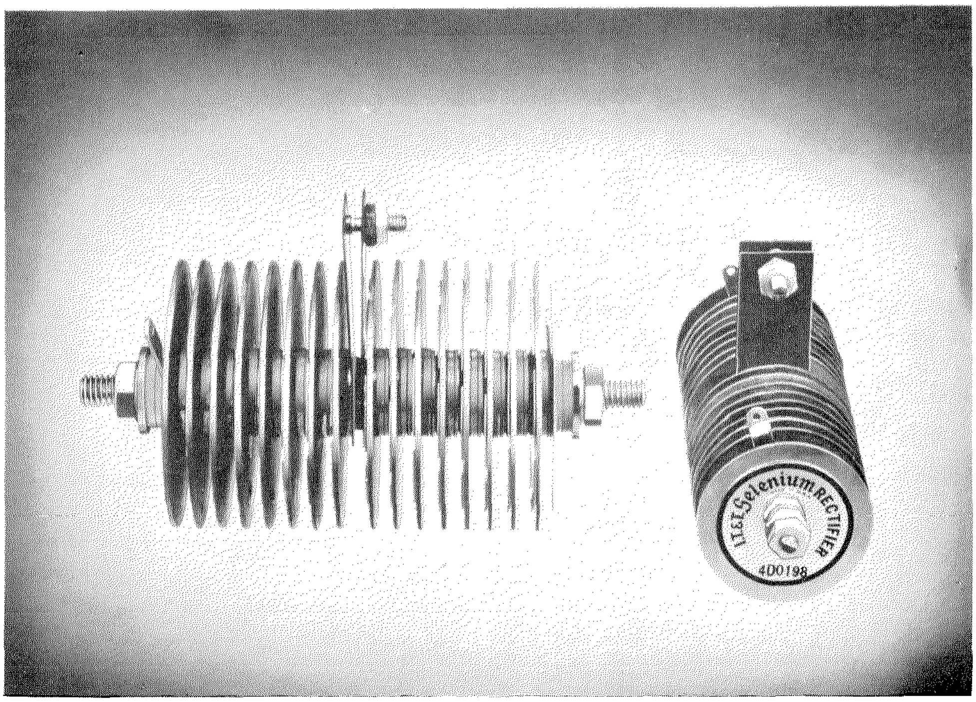


Fig. 3—Two Half Wave Selenium Rectifiers for Operation of Magnets in Business Machines. Both stacks are equipped with bi-metal strips to open the circuit when the plate temperature exceeds a specified value.

will be noted from the figure, the least favorable condition is that of mounting the stacks in a cabinet provided with perforated covers.

The current rating of Selenium Rectifiers is limited only by the final plate temperature resulting from heating. The stacks can be heavily overloaded, provided the maximum safe operating temperature of 75° C. is not exceeded. When this temperature is reached, the load must either be reduced to normal, or provision made for cutting the rectifying elements out of service as in the two half wave rectifiers illustrated in Fig. 3, widely used in business machines. Each element in these machines is equipped with a pair of bi-metal strips connected by means of an adjustable screw. If, by chance, the key-punch or the duplicator happens to be jammed and causes the temperature of the stacks to reach a range of 70 or 80° C., the bi-metal strips separate, thus breaking the circuit. The plates then cool off and the bi-metal strips again close (Fig. 4).

Intermittent Service

Considerable gain in the current capacity of Selenium Rectifiers can be obtained when they are used in intermittent service, in which case, the duty cycles must be definitely established. The variety of these intermittent applications is great and their complete discussion here would be too lengthy. One formula, however, is frequently used for periodic loadings:

$$I_m = I_{\text{max.}} \sqrt{\frac{A}{A+P}}, \qquad (1)$$

where I_m is the continuous current rating, $I_{\text{max.}}$ the maximum current drawn periodically, A the operating period, and P the inoperative interval; both A and P should be in the same time units. Experience has shown that this formula can be used only if A is less than the selenium plate time constant T, which may be defined by:

$$t_1 = t_2\left(1 - e\frac{A}{T}\right) \qquad (2)$$

and which varies from 5 to 8 minutes, depending on the plate size (t_1 and t_2 are instantaneous and final plate temperatures, respectively). When operating periods are separated by inoperative intervals of such length that the rectifier again cools practically to normal ambient temperature, much greater plate overloads are practicable.

Design of Stacks by Direct Values

After choosing the size of plate with proper current-carrying capacity, the internal voltage drop of the plate is considered. Fig. 5 illustrates the average, experimentally determined, internal voltage drop for seven plates in either bridge or center tap, single phase circuits. The voltage drop per plate, designated as dv, is one-half of the difference between the root mean square values of voltages read on the input and output side of the rectifier. These quantities are plotted as ordinates against the arithmetical values of output current in amperes plotted as abscissa.

The output voltage of a Selenium Rectifier is determined by the input voltage V_{ac} less the total voltage drop within the rectifier. The computation of the necessary alternating current voltage to be impressed on the Selenium Rectifier involves consideration of the voltage drop per plate and the number of plates through which the current flows.

Using the data given in Tables I, II, and III, and the internal voltage drop per plate illustrated in Fig. 5, any single phase Selenium Rectifier can be designed and the necessary alternating current voltage computed by the following formula:

$$V_{ac}=k_1 V_{dc}+k_2 n dv, \qquad (3)$$

where V_{ac} is the input voltage, k_1 the form factor to convert the arithmetical value to the root mean square voltage value (Table IV), V_{dc} the required direct current output voltage, k_2 the number of arms through which current must pass in the circuit for each half-cycle, n the number of plates in series per arm, and dv the voltage drop per plate for the circuit employed. The constants k_1 and k_2 vary depending upon whether a bridge or center tap connection, a single or three phase circuit is employed.

As an example, let us design a bridge type unit required to deliver 4 amperes at 16 volts continuously under the maximum ambient temperature of 35° C. in a single phase circuit. Selenium plate No. 7, $4\frac{3}{8}''$ in diameter (listed in Table I and rated at 4 amperes) will serve the purpose. Using equation (3) and corresponding constants from Table IV:

$$V_{ac}=1.15\times16+2ndv.$$

The number of plates in series, i.e., quantity n, necessary at this stage, can be computed by the following formula:

$$n=\frac{k_1 V_{dc}}{V_p-2dv}. \qquad (4)$$

V_p for Plate No. 7 is 14, and dv, as read off characteristic No. 7 in Fig. 5, is 1.29; hence,

$$n=\frac{1.15\times16}{14-2\times1.29}=1.6 \text{ or 2 of No. 7 plates in series.}$$

V_{ac}, therefore, at the start of service, is equal to 23.6 volts. With the aging of the Selenium Rectifier, the forward resistance increases and the inverse resistance also slightly increases. Based on lengthy experience in the design and application of these rectifiers it can be stated that the only variable in equation (3) is dv, which may increase as much as 50% under most adverse conditions. An additional tap, therefore, should be provided in the transformer winding to give the V_{ac} required for the aged condition:

$$V_{ac}=1.15\times16+2\times2\times1.29\times1.5=26 \text{ volts.}$$

Designs by Relative Values

The foregoing example and reference to Fig. 5 characteristics apply only to the single phase, bridge, and center tap designs with either inductive or resistive loads. With condenser and

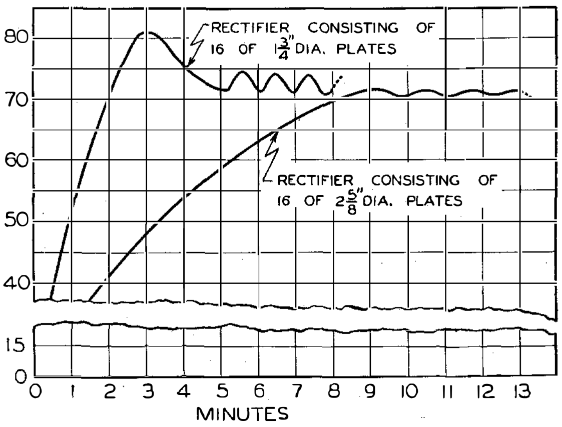


Fig. 4—Time-Temperature Characteristics Illustrating the Performance of Selenium Rectifiers Equipped with Bi-Metal Strips (Fig. 3).

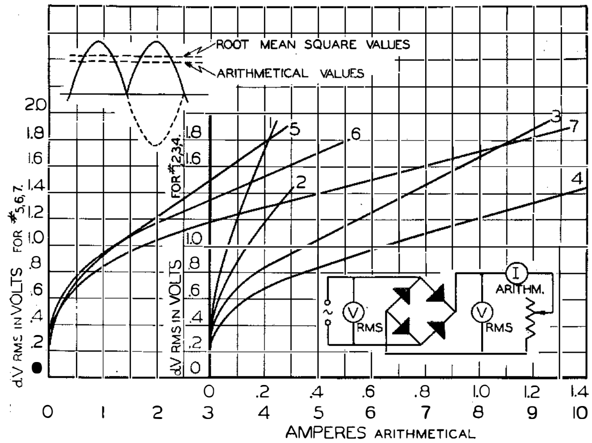


Fig. 5—Rectification Characteristics of Seven Basic Plates (¾, 1, 1⅜, 1¾, 2⅝, 3⅜ and 4⅝ inch Diameter) Used in the Design of Single Phase Bridge and Center Tap Rectifiers for Inductive and Resistive Loads.

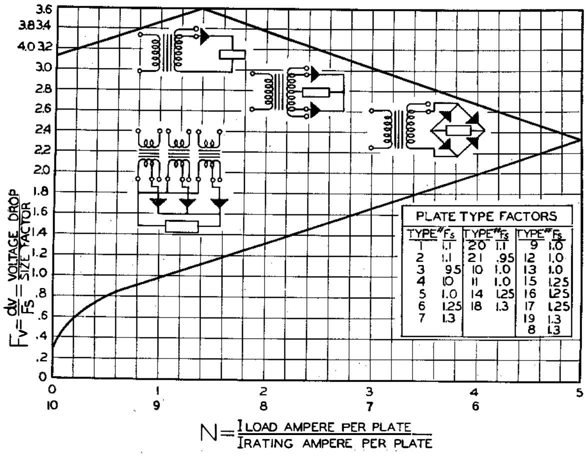


Fig. 6—Characteristic Illustrating the Relation of F_v and N for Single Phase, Half Wave, Center Tap and Bridge Rectifier Circuits with Resistive or Inductive Load; Also for Three Phase, Half Wave Rectifier Circuit with All Types of Load.

battery charging loads, even in the above-mentioned circuits, intermittent loading on the selenium plates occurs with periodic values of the forward current greater than the periodic values for the same d-c output feeding resistive or inductive load; voltage drops per plate are, therefore, greater in the former case. Applications occur, however, where the voltage drop per plate is smaller than the values shown in Fig. 5. An example is the three-phase circuit where the rectified current is practically at the peak value of the applied alternating current. The output current density per plate in these circuits is considerably higher than in the case of a single phase bridge circuit; furthermore, the type of load, whether it be resistive, inductive, capacitive, or battery charging, has practically no effect on the voltage drop per plate.

Inasmuch as a wide variety of circuits and types of loading is encountered, a method for rating the 21 rectifier types according to relative values of output current and voltage drop per plate has been developed. Figs. 6, 7, 8, and 9 illustrate the relationships N and F_v for various types of circuits and loads.

The use of these characteristics involves, first, determination of the value N, which is obtained by dividing the actual ampere load per plate by the ampere rating of the basic plate employed. With this value determined, the value F_v is read from one of the characteristics and then multiplied by the plate size factor F_s to obtain the actual voltage drop per plate, dv, for the plate selected.

Fig. 6 illustrates the relationship of F_v to the value N for half wave, center tap and bridge, single phase circuits when loaded with either resistive or inductive load; also for half wave, three phase circuits for all types of loads. Fig. 7 gives a similar relationship of F_v to the value N for half wave, center tap and bridge circuits, all single phase for capacitive or battery charging applications. Fig. 8 shows the relationship of F_v to N for three phase bridge and center tap circuits for all types of loads. Finally, Fig. 9 shows the relationship of F_v to N for direct current and blocking circuit applications.

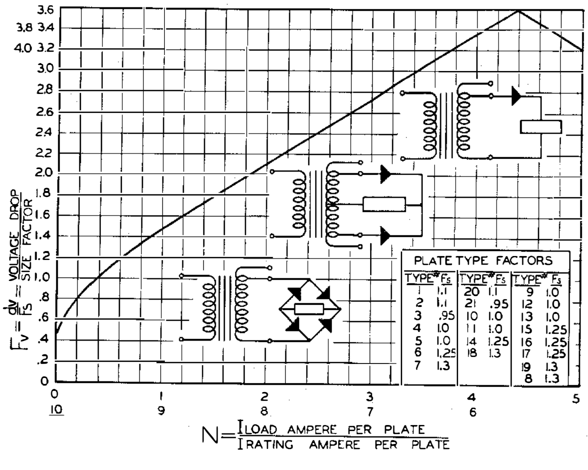
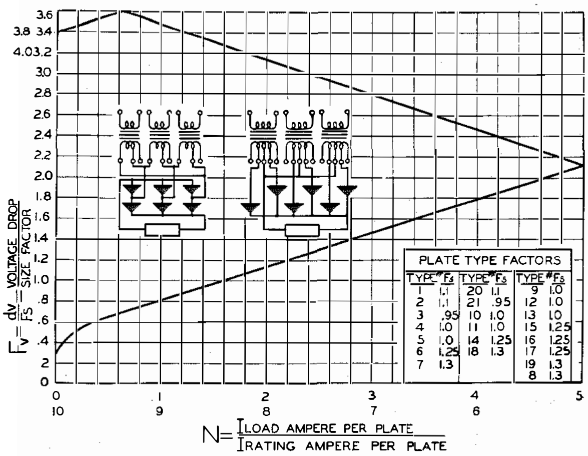


Fig. 7—Characteristic Illustrating the Relation of F_v and N for Single Phase, Half Wave, Center Tap and Bridge Rectifier Circuits for Battery-Charging Application or Condenser Loads.



TYPE #	Fs	TYPE #	Fs	TYPE #	Fs
1	1.1	20	1.1	9	1.0
2	1.1	21	.95	12	1.0
3	.95	10	1.0	13	1.0
4	1.0	11	1.0	15	1.25
5	1.0	14	1.25	16	1.25
6	1.25	18	1.3	17	1.25
7	1.3			19	1.3
				8	1.3

Fig. 8—Characteristic Illustrating the Relation of F_v and N for Three Phase, Center Tap and Bridge Rectifier Circuits for All Types of Load.

To illustrate this method of design, let us compute a three phase Selenium Rectifier capable of delivering 325 amperes at 13 volts for the filament supply of a television transmitter tube. An additional requirement is that the rectifier deliver not more than 488 amperes at approximately 2 volts into the tube when cold.

Several plates in Tables I, II, and III should be tried; however, plate No. 13, rated at 3.3 amperes will be most economical; the total current of 325 amperes can be safely handled by 100 plates connected in parallel.

$$I_{dc} = \frac{325}{100} = 3.25 \text{ amperes per plate.}$$

This plate loading with 1.8 ampere rating for basic plate No. 5 used in type No. 13 will give:

$$N = \frac{3.25}{1.8} = 1.8.$$

From Figure 8, $F_v = 1.07$ and $dv = 1.07 \times 1 = 1.07$.

In aging, the dv value may increase 50%, and thus becomes 1.6. Substituting the known quantities in formula (4):

$$n = \frac{.74 \times 13}{18 - 2 \times 1.6} = .65; \text{ or 1 plate in series.}$$

The foregoing proves that the entire rectifier should consist of a total connection of (6–1–100), where the first number (6) designates the number of arms of the three phase circuit, the second number (1) indicates the number of plates in series, and the third number (100) gives the number of plates in parallel. The total of 600 plates of type No. 13 may be conveniently assembled into 24 stacks, each having 25 plates in parallel.

Using formula (3) and the design constants of Table IV:

$$V_{ac} = .74 \times 13 + 2 \times 1 \times 1.07 = 11.8 \text{ volts}$$

when rectifying elements are new;

$$V_{ac} = .74 \times 13 + 2 \times 1 \times 1.6 = 12.8 \text{ volts}$$

when they are fully aged.

In order to meet the requirements of approximately 2 volts with the current output of 488 amperes:

$$I_{dc} = \frac{488}{100} = 4.88 \text{ amperes per plate;}$$

$$N = \frac{4.88}{1.8} = 2.7;$$

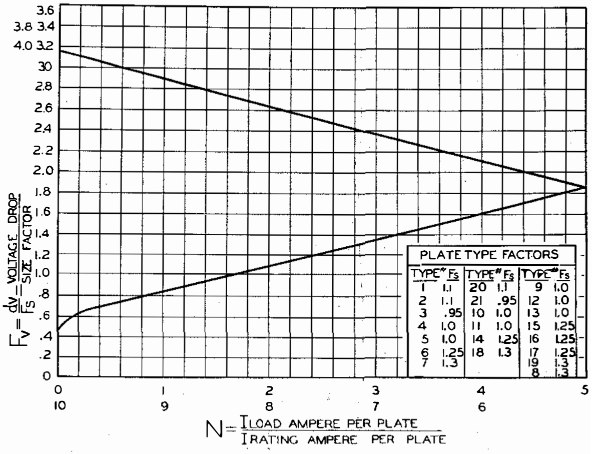
from the characteristic of Fig. 8,

$$F_v = 1.37.$$

For the new stacks, therefore, $dv = 1.37 \times 1 = 1.37$, and for fully aged stacks:

$$dv = 1.37 \times 1.5 = 2.06.$$

Using formula (3) and these two values of dv, the new and aged V_{ac} will be found to be 4.2 and 5.6 volts, respectively. The 50% limit for the current requirement is actually met by the external limiting reactances in each phase of the three phase circuit. The complete assembly of this rectifier is shown in Fig. 10.



TYPE #	Fs	TYPE #	Fs	TYPE #	Fs
1	1.1	20	1.1	9	1.0
2	1.1	21	.95	12	1.0
3	.95	10	1.0	13	1.0
4	1.0	11	1.0	15	1.25
5	1.0	14	1.25	16	1.25
6	1.25	18	1.3	17	1.25
7	1.3			19	1.3
				8	1.3

Fig. 9—Characteristic Illustrating the Relation of F_v and N for Direct Current and Blocking Circuits.

The ordinary single phase bridge type rectifier for resistive loading can also be designed through the use of relative values. Fig. 11 illustrates a 2-ampere, 120-volt Telautograph unit.

With two No. 9 plates in parallel, or one ampere per plate:

$$N=\frac{1}{.6}=1.67;$$

from the characteristic of Fig. 6,

$$F_v=1.2;$$
$$dv=1.2\times 1.0=1.2;$$

hence,

$$n=\frac{1.15\times 120}{18-2\times 1.2\times 1.5}=9.6, \text{ or 10 plates in series.}$$

The total connection of the rectifier is then 4–10–2. Practical considerations suggest four stacks, two of which make one bridge with ten plates in each arm of the bridge. Again, from formula (3), corresponding constants of Table IV and the above **dv** value, V_{ac} is found to be 162 volts when new and 174 volts when aged.

TABLE IV

Number of Phases	Circuit Type	k_1	n	k_2
1	Half Wave	2.3	$\frac{V_{ac}}{V_p}$	1
1	Bridge	1.15	$\frac{V_{ac}}{V_p}$	2
1	Center Tap	1.15	$\frac{2V_{ac}}{V_p}$	1
3	Half Wave	.855	$\frac{\sqrt{3}\,V_{ac}}{V_p}$	1
3	Bridge	.74	$\frac{V_{ac}}{V_p}$	2
3	Center Tap	.74	$\frac{2V_{ac}}{V_p}$	1

Selenium Rectifier Design Constants: k_1=form factor; n=number of plates in series; k_2=circuit factor; V_p=maximum voltage per plate; V_{ac}=phase voltage, except three phase bridge where it is line voltage.

Ratings (Tables I, II, and III) of Selenium Rectifier plates, functioning as blocking valves in direct current circuits, are higher in current and lower in voltage value than they are in half wave alternating circuits. The higher current rating is acceptable inasmuch as the forward resistance ordinarily decreases when only forward current passes through the Selenium Rectifier plates. The reverse current of the blocking unit, on the other hand, is higher and the safe voltage limit is, therefore, more conservatively established than for alternating current circuits. As an example, a 30 volt, 4.5-ampere blocking unit consists of a total connection of 1–2–5 No. 5 plates. The value N for this unit is equal to one, and **dv** is .84 (Fig. 9).

Experience has shown that for constant current battery charging and condenser loading, the current rating should be only 80% of the values tabulated in Tables I, II, and III. In the design of the rectifier for charging a 60-cell battery at the rate of 0.4 ampere, with 2.4 volts per cell, plate No. 4 may be selected. The value of N is .67. The new dv, as read off the characteristic of Fig. 7, is 1.25 and, after aging, it becomes 1.87. The number of plates in series is determined either by

$$n=\frac{V_b}{V_p} \text{ or} \qquad (5)$$

$$n=\frac{V_b/\sqrt{2}}{V_p-2dv} \qquad (6)$$

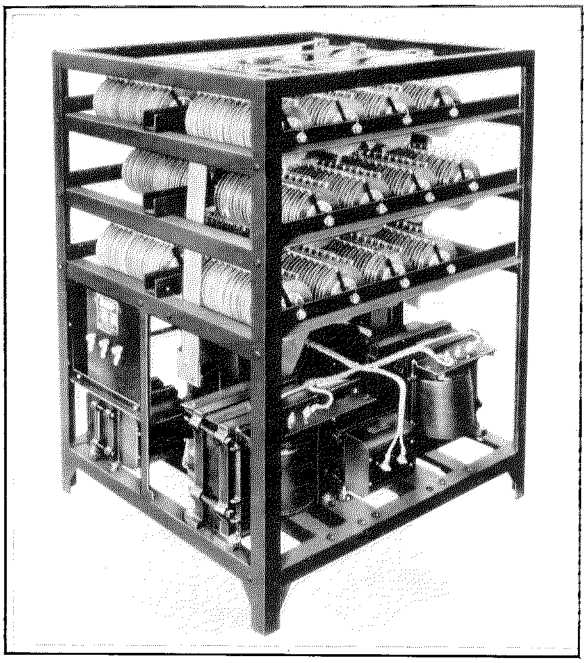


Fig. 10—Rectifier Unit of 325 Ampere, 13 Volt Rating with Reactances Limiting Output Current to 488 Amperes at 2 Volts. A.C. Input: 220 volts, three phase, 60 cycle. Rectifying element consists of 600 plates arranged in 24 stacks, each stack consisting of 25 plates in parallel.

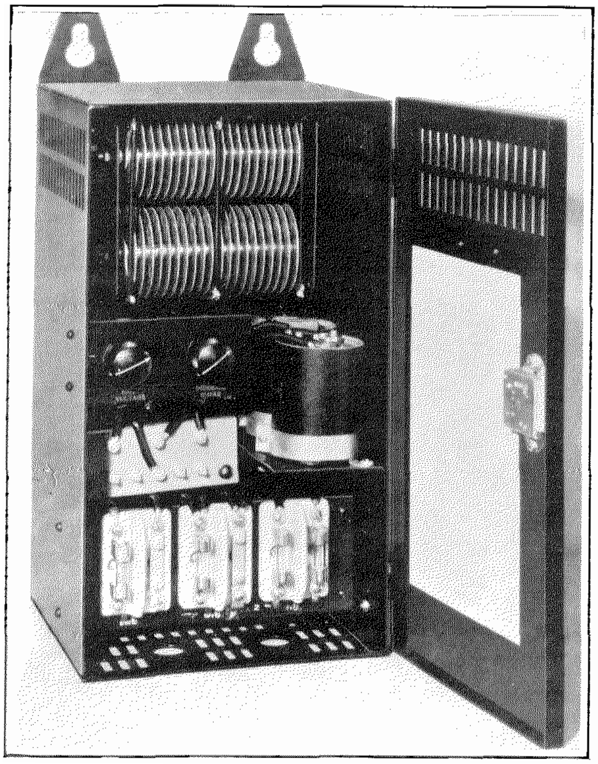


Fig. 11—Selenium Rectifier with Output of 2 Amperes at 120 volts for Powering Telautograph Equipment.

depending on which is greater.

$$V_{ac}=\frac{V_b}{\sqrt{2}}+k_2ndv \qquad (7)$$

$$=\frac{60\times 2.4}{\sqrt{2}}+2\times 8\times 1.25=122 \text{ volts}$$

An additional tap to give 132 volts for the fully aged condition of the stacks should be provided.

Design of Forced Draft Ventilation Unit

The extended current rating of Selenium Rectifier plates with forced draft or fan cooling and the speed of air constituting the forced ventilation require further consideration. A rather conservative relationship of current rating to air velocity has been established and successfully used for the $4\frac{3}{8}''$ diameter No. 7 plate (Table V).

As an example, let us design a three phase, full wave rectifier supplying a d-c output of 600 amperes at 6 volts. Because of the low required output voltage, as compared to the full r.m.s. voltage permissible for the No. 7 plate, the center tap circuit is most economical and gives greatest efficiency. With the fan delivering air at a speed of 120 feet per minute, the 7.5 ampere (Table I) loading of this plate can be increased 2.5 times (Table V), thus making it 18.7 amperes per plate. Practical consideration of possible 10% overload suggests that this unit should have 36 plates in parallel for the total current output of the unit. This makes the value N (Fig. 8) equal to 2.22 and the initial and aged dv equal to 1.6 and 2.4, respectively. The total connection of the rectifier is, therefore, 6–1–36. The new V_{ac} for half of the transformer secondary voltage is 6.1 volts and, for the fully aged condition, 6.9 volts. A view of this equipment is shown in Fig. 12.

Voltage Regulation

The inherent voltage regulation of the Selenium Rectifier is in the neighborhood of 10–20%. In computing the regulation, one must determine the no load value of dv and then the no load output voltage. In the case of the first example of a 4 ampere, 16 volt rectifier, the dv value from Fig. 5 is 0.4. The d-c output voltage, therefore, at no load is:

$$V_{dc}=\frac{23.6-2\times 2\times .4}{1.15}=19.1,$$

$$\text{Regulation}=\frac{19.1-16}{16}\times 100=19.4\%.$$

Similarly, the regulation of the three phase, 325 ampere, 13 volt unit (Fig. 10) is computed by reading F_v for N equal to zero in Fig. 8. Substituting 0.3 for the value of dv in formula (3), and taking 11.8 volts for V_{ac}, the no load voltage is

TABLE V

Multiplying Factor for Normal Plate Ratings, k_3	1	1.5	2	2.5	3	3.5	4	4.5
Air Speed in Ft. per Minute	0	60	90	120	160	200	310	400
Cubic Feet per Minute per Plate	0	.5	.8	1.1	1.4	1.7	2.8	3.7

Relation of Factor k_3 by Which Normal Rating of No. 7, i.e. $4\frac{3}{8}$ Diameter Selenium Plates Can Be Increased, and the Speed and Amount of Air Necessary.

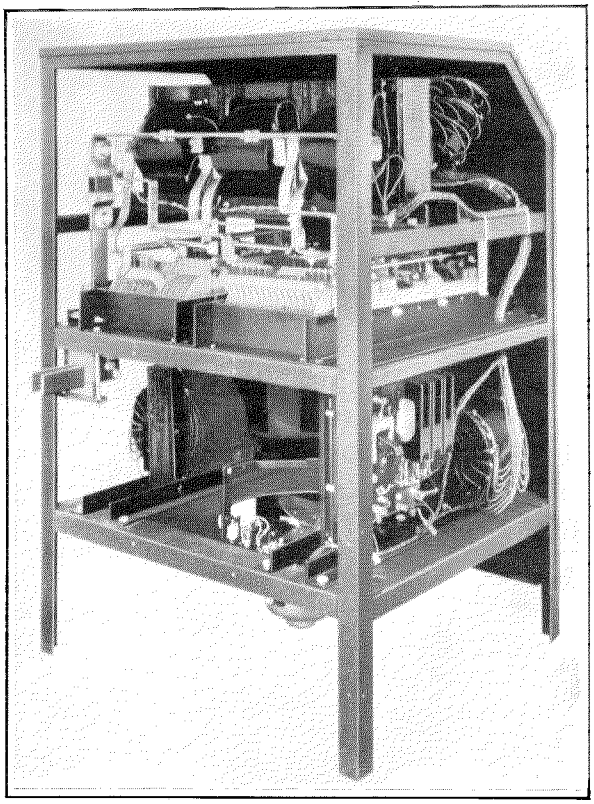


Fig. 12—Three Phase Selenium Rectifier Unit Employing Forced Draft Ventilation for Output of 600 Amperes at 6 Volts. Overall Efficiency: 74%; Power Factor: 94%.

found to be 15 volts, and the voltage regulation is, therefore, 15.4%.

Efficiency

The efficiency of Selenium Rectifiers varies with the type of circuit and the nature of the load. The single phase circuits with fully loaded plates in respect to voltage and current, and when feeding either resistive or inductive loads, give an efficiency of approximately 64%; the same circuits, when used for battery charging, give an efficiency some 14% higher due to the greater value of the rectified voltage. The three phase circuits give efficiency values in the neighborhood of 83% and, for all practical purposes, remain the same irrespective of the type of load. For all circuits and loads, however, the efficiency of Selenium Rectifiers increases with decrease of load down to approximately 25% of full value, and thereafter falls off rapidly. The efficiency itself depends on the combined losses in the Selenium Rectifier from forward and reverse currents, and, in formula form, it is:

$$\frac{V_{dc}I_{dc}}{(V_{dc}I_{dc})+W_f+W_r}\times 100=\%\text{ efficiency,} \qquad (8)$$

where W_f are losses due to forward current and W_r are losses due to the reverse current.

The computation of exact efficiency for all sizes of plates, and various loads and circuits is rather involved and constitutes an extensive subject in itself.

In order to illustrate the simplified method of efficiency computation and the effect of *dv* changes on its value, let us compute the efficiency of the 325 ampere, 13 volt, three phase unit illustrated in Fig. 10.

Forward losses per plate in the three phase bridge circuit are

$$w_f=\frac{\sqrt{2}\,I_{dc}dv}{3},$$

where $\sqrt{2}$ is a conversion factor for approximating the peak value of the a-c wave in terms of effective value of *dv*. Divisor 3 results from the fact that in the three phase bridge circuit each plate is utilized $2\times 1/6$ times in each cycle.

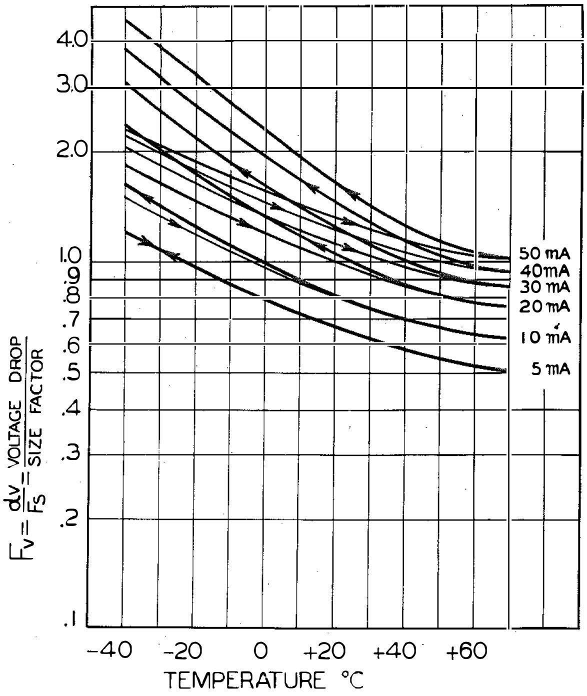


Fig. 13—Relation of F_v at Varying Current Densities to the Ambient Temperatures Throughout a Heating and Cooling Cycle.

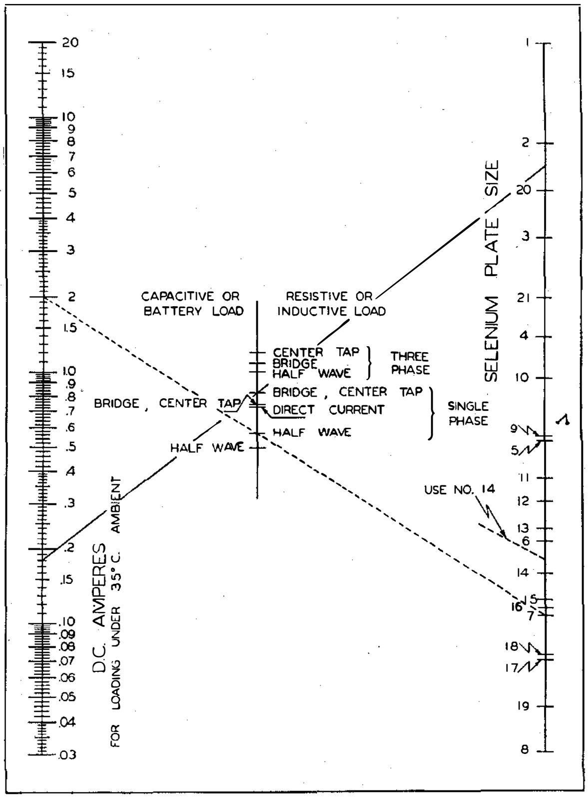


Fig. 14—Alignment Chart for Determining the Rectifier Type Number for: (1) Output Current, (2) Nature of Load, (3) Type of Circuit.

$$w_f = \frac{325/100 \times \sqrt{2} \times 1.07}{3} = 1.64 \text{ watts per plate,}$$

or $W_f = 6 \times 100 \times 1.64 = 984$ watts for all 100 plates in six arms.

The reverse losses are approximately one third of forward losses computed for the normal rating of the plate used in this unit:

$$W_r = \frac{1}{3} \times \frac{6 \times 100 \times .8 \times \sqrt{2} \times 1.8}{3} = 136 \text{ watts.}$$

The new input wattage W, therefore, is:

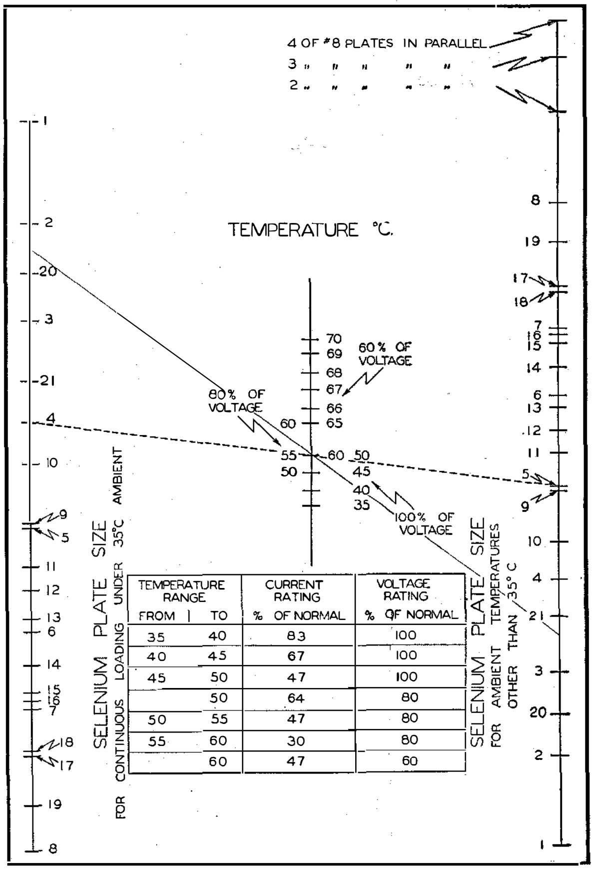
$$W = (I_{dc} \times V_{dc}) + W_f + W_r$$

$$= (325 \times 13) + 984 + 136 = 5345 \text{ watts.}$$

$$\text{Efficiency} = \frac{4225}{5345} \times 100 = 79.2\%.$$

Similarly, assuming a possible 50% change in dv, the efficiency of this rectifier with stacks fully aged is computed as 72%.

The foregoing designs illustrate the importance of the quantity dv, which is dependent on the forward resistance and current density of the plates as well as the ambient temperature under operating conditions. Its changing values under varying conditions greatly influence the efficiency, regulation, and aging of Selenium Rectifiers. The ambient temperature and current density relationships affecting the value of dv are illustrated in Fig. 13. The arrows on the curves indicate that the resistance of the plates decreases with increase of temperature. As the plates cool off the resistance again increases, and dv is greater at the new lower temperatures than during the rising temperature phase of the heating cycle. This phenomenon diminishes with lower current densities to a point where the resistance is the same at corresponding temperatures of the heating and cooling portions of the cycle.



TEMPERATURE RANGE FROM	TO	CURRENT RATING % OF NORMAL	VOLTAGE RATING % OF NORMAL
35	40	83	100
40	45	67	100
45	50	47	100
	50	64	80
50	55	47	80
55	60	30	80
	60	47	60

Fig. 15—Alignment Chart for Determining the Selenium Rectifier Plate Type Number Required in Ambient Temperatures Above 35° C. Also, Table of Percentage of Current and Voltage Ratings at Ambient Temperatures Above 35° C.

Selection of Plate Type for 35° C. and Higher Ambient Temperature

Almost invariably more than one selenium plate type appears suitable for given output requirements. The type of circuit or nature of loading as well as the cost, however, restricts the choice.

The Alignment Chart (Fig. 14) has been found useful in selecting plate types for specified output currents. If a straight edge is laid connecting the required direct current output with the type of circuit and the nature of load, the intersection of the straight edge on the plate size scale gives the type number of the required rectifier plate. If the intersection falls between two plate type numbers, the plate having the higher current rating should be chosen.

For ambient temperatures higher than 35° C., the plate type number for a 35° C. ambient should first be found. Referring to Fig. 15, a straight edge connecting the 35° C. ambient temperature plate type number with the desired higher ambient value of the temperature scale intersects the right-hand scale, indicating the required higher ambient plate type number. Again, if the intersection is between two plate type numbers, the plate type number with the higher current rating should be used. It will be noted that, by decreasing the voltage rating, a small increase in current rating is allowable.

As an example, let us design a high voltage, low current rectifier of the type illustrated in Fig. 16 for either resistive or inductive load. Referring to Fig. 14, the line drawn through the 0.18 reading on the left-hand scale, and the point marked "single phase bridge" in the middle of the chart, intersects the right-hand scale between "2" and "20". Thus, Plate 20 (Table II) would be used if the rectifier is to operate under maximum ambient temperature of 35° C. In order to derate plate 20 for a 60° C. ambient, reference is made to Fig. 15. The line drawn on this chart through the same point (between "2" and "20") of the left-hand scale (as in Fig. 14) and the point marked "60% of voltage" indicates that the No. 21 selenium plate (Table II) should be used for the required assembly. Further computations of quantities N, dv, and n result in the design of a rectifier with total connections of 4–224–1, arranged in 28 stacks, each consisting of 32 $1\frac{3}{8}''$ plates in series.

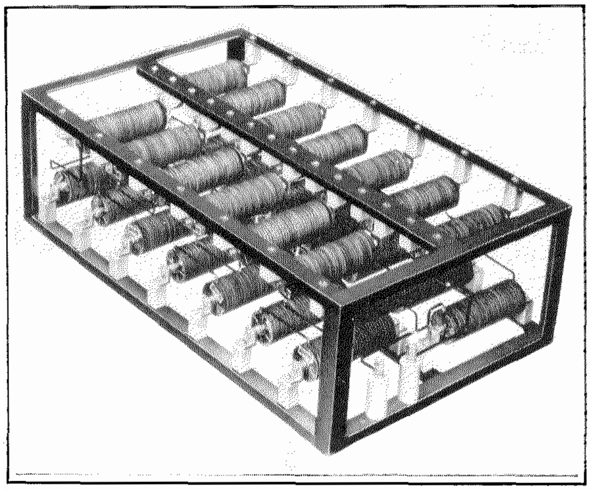


Fig. 16—Single Phase Bridge Connected Rectifier. Output: 180 Milliamperes at 2300 Volts Under Ambient Temperatures from −40° C. to +60° C.

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The Electrical Strength of Nitrogen and Freon Under Pressure*

By H. H. SKILLING, *Member A.I.E.E.*, and W. C. BRENNER, *Associate A.I.E.E.*

Editor's Note

The work reported in this paper continues studies of the electric strength of air for the primary purpose of investigating the electric strength of the gas dichlorodifluoromethane, commonly known as Freon F-12. It was carried on by the Electrical Engineering Department of Stanford University under the sponsorship of the International Telephone and Telegraph Corporation.

Synopsis

Results are given of an investigation of the electric strength of nitrogen, of dichlorodifluoromethane (Freon F-12), and of mixtures of these gases. Sparking voltages are presented as measured between spherical electrodes of brass and aluminum and between pointed electrodes of brass, at various spacings and in gas at pressures ranging from one to several atmospheres. All measurements are for 60-cycle applied voltage. Dichlorodifluoromethane is found to withstand much higher voltages than either air or nitrogen; this advantage is more marked between points than between spheres, which suggests its use in certain types of insulation applications. A small percentage of dichlorodifluoromethane gas in nitrogen produces an anomalously large rise in the electric strength of the gas, indicating practical advantages of such mixtures.

PREVIOUS studies of the electric strength of air under pressure have been reported by the authors.[1,2] The present paper presents data from a continuation of this work for the primary purpose of studying the electric strength of the gas dichlorodifluoromethane, CCl_2F_2, commonly known as Freon F-12. This gas is readily available as a refrigerant and is known to have unusually high electric strength. It was studied both alone and mixed with nitrogen, and to complete the series of tests the electric strength of nitrogen was also determined.

Freon was obtained in liquid form, in a pressure cylinder, and gas from the upper part of the cylinder was released into the test chamber as desired. Nitrogen gas of commercial purity was used; it is guaranteed 95% pure but is believed to be purer than the guaranteed value. It is supplied under pressure, and was released into the test chamber when needed. No purification of either gas was attempted, for it was believed that results obtained with gas of commercial purity would be more significant from an engineering point of view than results obtained with chemically pure gases. In the present investigation no irregularities or inconsistencies of data could be traced to the presence of impurities in the gases supplied.

The apparatus used is described and pictured in a previous publication.[2] The methods of measurement and technique employed in the study of Freon were the same as in the previous work with air, except as the use of mixed gases required special methods.

In order to obtain mixtures of gases of known composition for test purposes, it was necessary to evacuate the test chamber before admitting the gas or gases in which the test was to be performed. Pressure within the chamber was reduced by means of a vacuum pump to a value estimated at one millimeter of mercury before admitting nitrogen or Freon. By this means practically all of the residual gases were removed. This was particularly necessary for the purpose of removing all traces of Freon gas before testing in an atmosphere supposed to contain no Freon. The presence of an extremely small amount of Freon in nitrogen or air was found to be important in determining dielectric strength, sometimes increasing the sparking voltage by fifty per

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cent or more, although the amount of Freon could hardly have been more than a fraction of a per cent. The sparking voltage in such cases was highly erratic and undependable. Similar results were obtained when a trace of carbon tetrachloride was present in the test chamber.

After a series of tests with Freon, it was found best for the test chamber to be evacuated and left for several hours or days. Nitrogen was then admitted to the chamber, and it was again evacuated. This process removed all indication of the presence of Freon in subsequent tests.

In order to obtain satisfactory mixing of gases when Freon and nitrogen were used together, it was found necessary to stir the gases with an electric fan placed within the test chamber. Natural mixing by diffusion did not take place in the course of several hours. When the fan was not used, the heavier Freon went to the bottom of the test chamber and remained partially unmixed with the nitrogen. Results without use of the fan were inconsistent and meaningless. Less than five minutes of operation of the fan was adequate to give thorough mixture of the gases, and results obtained with its use were consistent and could be repeated from day to day.

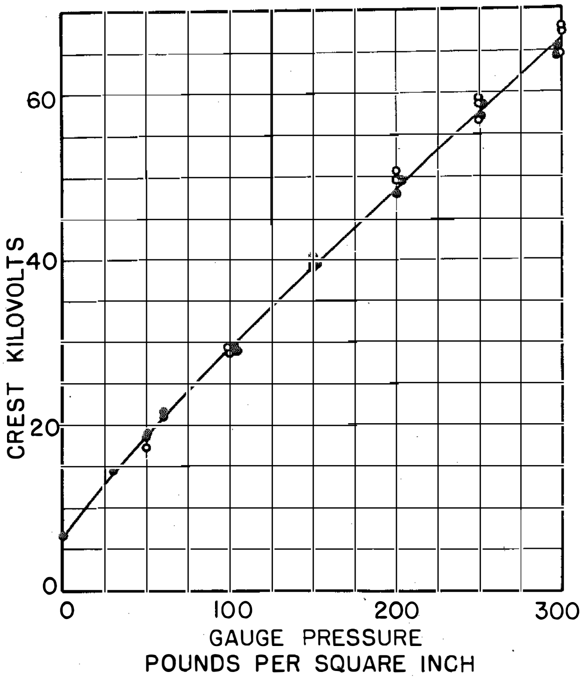

Fig. 1—Comparison of Sparking Voltages in Air and Nitrogen.

Spherical electrodes
Length of spark gap: 0.050 inch
○ *Experimental points in air*
● *Experimental points in nitrogen*

For test of sparking between spherical electrodes in gas mixtures containing Freon, aluminum electrodes were used in most cases. Aluminum was used because of its greater resistance to corrosive action under such circumstances. Brass was less resistant than aluminum, and steel was less resistant than brass. It is presumably not Freon itself that is harmful to the metal electrodes, for it is reported—in publications relating to its chemical properties—to be noncorrosive, and it is used satisfactorily for refrigeration. Electric discharge in Freon, however, is reported to produce chlorine and other corrosive products of decomposition. It is apparent from the present investigation that the products of electrical discharge in Freon are distinctly corrosive. Moreover, products of electric discharge in a mixture of Freon and air are very considerably more corrosive than those that result from Freon alone or in mixtures of Freon and nitrogen. Corrosion of electrodes in mixtures of Freon and nitrogen was about as severe as in pure Freon, and very much less than in mixtures of Freon and air.

Sparking in nitrogen was remarkably free from corrosion of any kind, and hundreds of sparks would barely tarnish the polished surface of either brass or aluminum spheres. Pointed brass electrodes lost none of their original sharpness after forty or fifty sparks in nitrogen, whereas they were noticeably rounded and measurably shortened in length by similar sparking in either air or Freon.

Results in Nitrogen

In general, sparking voltages between spheres in nitrogen are the same as between spheres in air. This conclusion was checked carefully with an 0.050-inch gap at pressures from 1 to 21 atmospheres; sparking voltages in nitrogen could not be distinguished from those in air (see Fig. 1).

A careful study of sparking between spheres at various spacings and pressures had been made in air,[2] and because of the similarity of results this was not repeated in nitrogen.

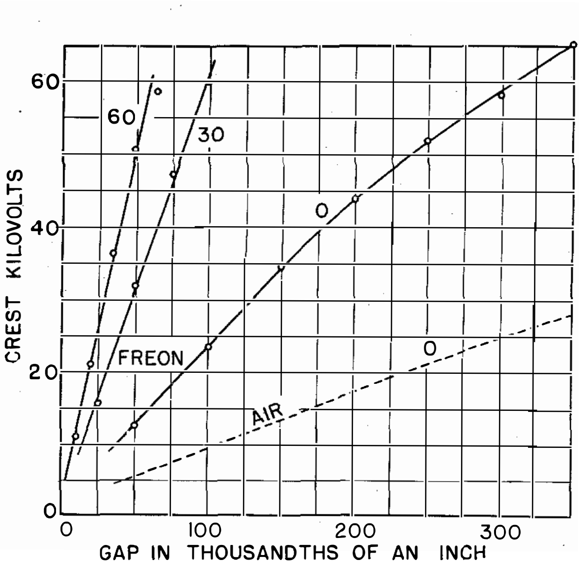

Fig. 2—Sparking Voltages in Freon.

Spherical electrodes
Gauge pressure in pounds per square inch as noted on curves

Despite the general agreement observed between sparking between spheres in air and in nitrogen, there were certain differences in detail. It has been mentioned[1,2] that in air there was a tendency for the sparking voltage to rise slightly as a number of measurements were made in rapid succession. No such result was noticed in nitrogen. It has also been mentioned that a spark would usually result in air if voltage was held for a period of several minutes at a value as much as five to seven per cent below the usual sparking value. This effect did not appear in nitrogen. The sparking values given in this report for nitrogen are average values. Most of the individual sparking values for pure nitrogen lie within one per cent of the average value, the most extreme variations being about five per cent.

It should be emphasized that a slight trace of Freon in the nitrogen would cause very erratic results, but that clean nitrogen was quite consistent.

Results in Freon

Sparking in Freon was investigated at pressures of from one atmosphere to about six atmospheres, with gaps varying from 10 mils to 250 mils (0.010 to 0.250 inch) between both brass and aluminum spheres. Sparking between points was also studied (see following). The highest pressure possible at room temperature was about six atmospheres, at which pressure the gas is in equilibrium with liquid Freon. (The vapor pressure of Freon at 70 degrees Fahrenheit is 84.82 pounds per square inch absolute, 70.12 pounds per square inch gauge.[5])

Freon was found to have a sparking voltage between spheres that was, for all pressures investigated, between 2 and $2\frac{1}{2}$ times as great as the sparking voltage in nitrogen or air at the same spacing and pressure (see Fig. 2).

The nature of the spark in Freon was not noticeably different from the sparks observed in air and nitrogen, except in color. Sparks in Freon are intensely blue, in nitrogen they are purple, and in air white or slightly yellow. The intensity of sparks in the different gases, however, appears to be much the same when due allowance is made for the amount of current flowing.

Values of sparking voltage obtained in Freon were fairly consistent, although a variation of two or three per cent from the average value was not uncommon. Variations of as much as ten percent were occasionally encountered, usually below the average sparking voltage rather than above. No "trends" of voltage values, as found in air,[2] were discovered in Freon, and there were no sparks at voltages radically different from the average value.

In general, sparking voltage between spheres in Freon was found to be proportional to the length of gap, and proportional to the pressure of the Freon gas. To be more precise, the voltage-spacing and voltage-pressure relations were found to be linear, but not exactly proportional, taking the same form as Paschen's law for sparking in air.

The breakdown voltage of Freon as determined in the present investigation can be expressed by the formula

$$V = 183PS + 4.0,$$

where V is sparking voltage in kilovolts, P is pressure in atmospheres, and S is spacing in inches. It will be seen that this equation gives voltage values for sparking in Freon between 2.4 and 2.5 times the values given by Paschen's law for air.[2]

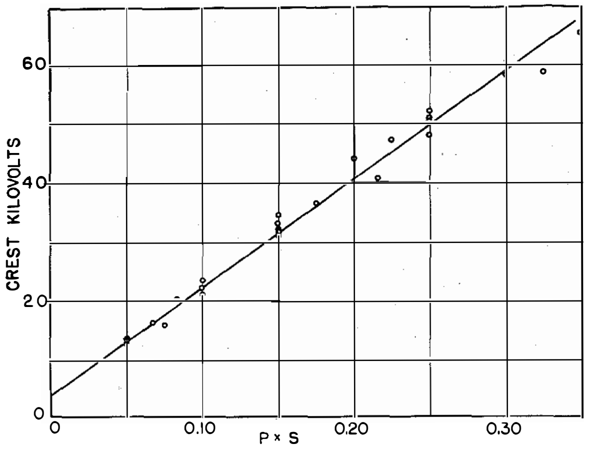

Fig. 3—Sparking Voltages in Freon.
Spherical electrodes
Points are experimental; line is computed from $V = 183PS + 4.0$ *kilovolts*
P_1 *absolute pressure in atmospheres*
S_1 *spark-gap length in inches*

The preceding formula appears to be reasonably accurate over the range of conditions of test. The values of sparking voltage obtained by experiment, each an average of five to ten individual voltage readings, are all within ten per cent of the value given by the formula. The experimental range of pressure was from one to five atmospheres, and the range of spark length was from 10 to 350 mils, giving a range of the product PS from 0.05 to 0.35 (atmosphere-inch). This is shown in Fig. 3. This formula was derived from the authors' results alone. However, it was found to give good agreement with the sparking voltages measured between flat electrodes in Freon by Trump, Safford, and Cloud (see Figs. 3 and 4 of reference 9), for pressures up to about four atmospheres (60 pounds per square inch absolute). As the vapor-pressure of Freon is approached (six atmospheres at room temperature) the experimental sparking voltages are lower than would be expected from the formula. Agreement with the work of Trump, Safford, and Cloud appears to extend the range of applicability of the formula to direct voltage as well as alternating, to gap lengths as great as 0.7-inch, and to values of the product PS as great as 2.0 (atmosphere-inches).

Results in Freon-Nitrogen Mixtures

The electric strength of mixtures of Freon and nitrogen gas was measured under a variety of conditions to determine the effect of

(*a*) Dilution of Freon by nitrogen.
(*b*) Change of pressure.
(*c*) Change of spark-gap length.

Results, which will be discussed below, were intermediate between those obtained in pure Freon and those obtained in pure nitrogen. This was the outcome that was to be anticipated. One very interesting relation, however, was discovered. It was found that a very small amount of Freon in nitrogen has a disproportionately large effect in raising the electric strength; this is discussed below.

Considerable difficulty was at first experienced in work with mixed gases, and results could not be repeated from time to time until an electric fan was used to insure thorough mixing of the gases within the test chamber. When the fan was used, however, the difficulty was entirely overcome, and sparking voltages were thereafter obtained with about the same degree of con-

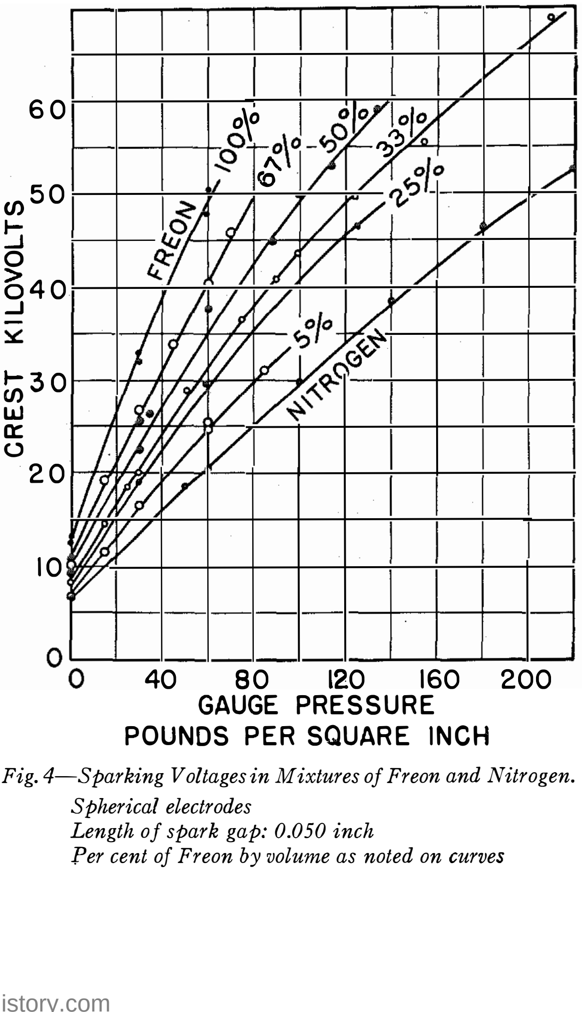

Fig. 4—Sparking Voltages in Mixtures of Freon and Nitrogen.
Spherical electrodes
Length of spark gap: 0.050 inch
Per cent of Freon by volume as noted on curves

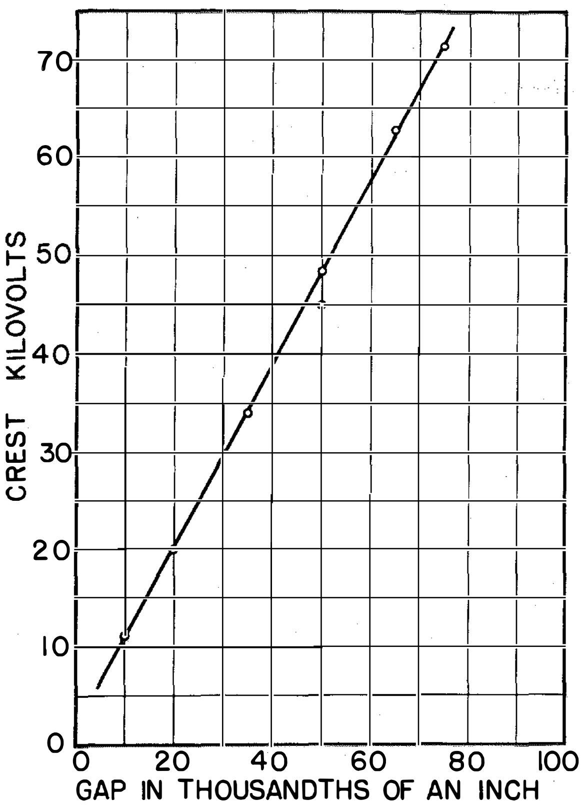

Fig. 5—Sparking Voltages in a Mixture of 50 per cent Freon and 50 per cent Nitrogen.

Spherical electrodes
Pressure seven atmospheres (90 pounds per square inch gauge)

sistency as in pure Freon; that is, individual readings of sparking voltage commonly varied two or three per cent above and below the average for a given condition, while a variation of as much as ten per cent was very unusual.

Mixtures of Freon and nitrogen that were given most attention contained 67% Freon, 50% Freon, 33% Freon, 25% Freon, and 5% Freon by volume. Most of the work was done with a spark-gap length of 50 mils (see Fig. 4). To give assurance that the normal relation between the sparking voltage and gap length exists in mixed gases, the gap length was varied from 10 to 75 mils in a mixture of 50% Freon and 50% nitrogen with the results shown in Fig. 5. As with pure gases, the voltage-distance relation is linear, and experimental data for this mixture of 50% Freon and 50% nitrogen can be represented by the formula

$$V = 132PS + 2.5 \text{ kv.}$$

(All experimental points lie within 10% of this expression.)

This suggests the possibility of finding a simple equation to represent data for all Freon-nitrogen mixtures at all pressures and spacings. For this purpose the data of Figs. 4 and 5 were replotted as Fig. 6. In this form it is evident that the relation between the amount of Freon present and the sparking voltage is linear when the concentration of Freon is greater than five per cent. When the concentration of Freon is less than five per cent a small amount of Freon produces a disproportionately large increase in the sparking voltage, as shown in detail in Fig. 6 at a pressure of three atmospheres. The linear relation shown in Fig. 6 leads to the following equation for sparking voltage in Freon-nitrogen mixtures in which the amount of Freon is greater than five per cent:

$$V = (88PS + 1.9)(1 + 1.08F),$$

where V is kilovolts, P is pressure in atmospheres, S is spacing in inches, and F is the fraction of Freon by volume, in the gas. (For pure Freon

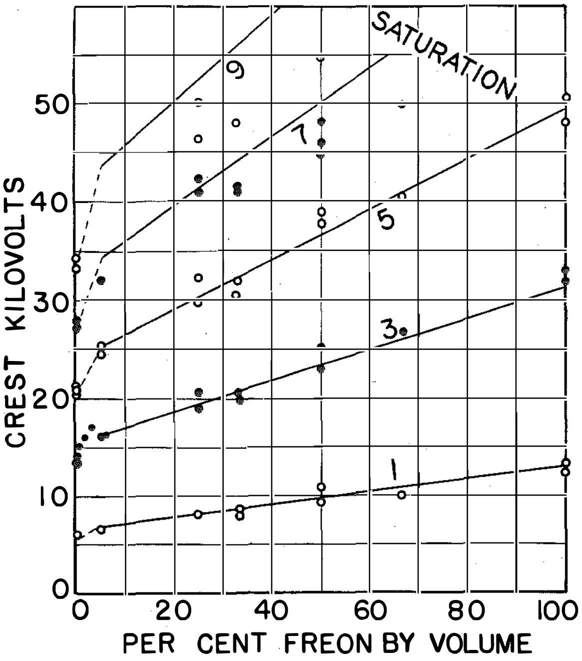

Fig. 6—Sparking Voltages in Mixtures of Freon and Nitrogen.

Spherical electrodes
Length of spark gap: 0.050 inch
Pressure in atmospheres as noted on curves
Points are experimental; lines are computed from $V = (88PS + 1.9)(1 + 1.08F)$ *kv.*

$F=1.0$; for half Freon, half nitrogen $F=0.5$; note that for pure nitrogen it is *not* correct to let $F=0$ as the formula does not apply for less than five per cent Freon.)

This equation is proposed with several reservations. As noted, it does not apply for very low concentrations of Freon. Another limitation is that the formula becomes inaccurate at high pressure. The agreement with experimental data is good for pressures up to five atmospheres. At pressures of seven atmospheres and more, the experimental sparking voltage is uniformly less than that predicted by the formula. There are two obvious explanations:

1. It is at about this same pressure that variation from a straight-line relationship becomes evident in pure air or nitrogen.
2. The discrepancies become more marked as the partial pressure of Freon in the gas under test approaches the vapor pressure of Freon.

A condition of saturation is approached when both pressure and concentration of Freon are high, corresponding to the upper right-hand corner of the chart. As the vapor pressure is approached the intermolecular forces become great and the Freon no longer approximates a perfect gas.

Finally, the formula given for mixtures of Freon and nitrogen is based on a limited amount of data. Since there are three independent variables in the equation, it would be an extremely lengthy procedure to determine the voltage for all possible combinations. The data at hand were obtained by recording slightly over a thousand individual sparking voltages, however, and appear adequate to give strong support to the above formula for pressures greater than one atmosphere, for spacings from a few mils to a few hundred mils, and for all concentrations of Freon greater than five per cent.

Some work was done with mixtures of air and Freon, but was discontinued when it was found that the products of electrical discharge were highly corrosive and tended to damage the apparatus. In particular, the spheres used as electrodes were tarnished after as few as three or four sparks and rapidly became coated with a grayish deposit. This corrosion, however, had very little effect on the electrical strength of the gap between the spheres. Indications are that the electric strength of air-Freon mixtures is similar to that of nitrogen-Freon mixtures.

Results With Pointed Electrodes

A short investigation was carried out to determine some of the salient characteristics of sparking in air, nitrogen, and Freon, between electrodes with sharp points.

Sparking in air between points was discussed at some length in a previous paper,[1] and present measurements agree, where comparable, with the results which were then obtained. Experimental procedure is difficult because the nature of the results depends to a large extent on the degree of sharpness of the points, particularly for short gaps. In general, however, as pressure is raised, the sparking voltage reaches a maximum; this maximum occurs at 8 to 12 atmospheres pressure. When pressure is further increased, the sparking voltage becomes less—sometimes very slightly less, sometimes by as much as 50%. The large decline of voltage with increasing pressure is obtained with very sharp points, while with blunt points the dip becomes less marked, and there may be no dip whatever if the points are either quite blunt or quite close together. The action is apparently dependent on whether or not corona precedes sparking; observation of corona has been made possible by the windows installed in the present test chamber.

Sparking in nitrogen between points was investigated for three lengths of gap. It was found that the sparking voltage in nitrogen is considerably lower than that in air for the lengths of gap studied. Curves of sparking voltage as a function of pressure are shown in Fig. 7. No direct comparison with the strength of air is possible because of the different shape of the curves, but it is seen from the figure that a 0.3-inch gap in air will withstand about as much voltage as a 0.5-inch gap in nitrogen. There is a decided difference in the shape of the curves; the curve for the 0.3-inch gap in nitrogen is practically flat for pressures above ten atmospheres, while the corresponding curve for air has a hump in the neighborhood of ten atmospheres pressure. When the gap is increased to 0.5 inches the curve for nitrogen is also humped, although to a lesser extent. Very short gaps (0.1-inch or less) fail to show any hump in either air or nitrogen, at least for points of ordinary sharpness. It may be mentioned that the sharpness of the points used was such that they would readily scratch the fingernail, and this sharpness was retained during sparking in nitrogen but sparking in compressed air tended to burn and blunt the points.

It is probable that difference between sparking between points in nitrogen and in air results from the high electron affinity of oxygen. Oxygen will allow the attachment of electrons to form negative ions; nitrogen will not.[6] This will greatly affect the mobility of space charge in the gas, and since sparking voltage between points is largely influenced by space charge, it is natural that nitrogen and air behave differently between points although they behave alike between spheres.

The voltage required to spark between points in Freon is considerably higher than for equal distances in air. Curves for sparking in Freon are shown in Fig. 7. Again a general comparison is practically impossible, but certain particular values may be compared in air and Freon.

The voltage required to spark 0.1 inch between points in Freon is for all pressures (from normal atmospheric pressure to the vapor pressure of Freon) greater than the voltage required to spark 0.3 inch in air or 0.5 inch in nitrogen. Over most of the pressure range the voltage required for the shorter gap in Freon is very considerably greater than for the longer gaps in air and nitrogen. It was found that a gap of 0.2 inch in Freon will support voltage comparable to published values for a gap of 30 to 50 millimeters (1.2 to 2.0 inches) in nitrogen.[7]

Since this paper was submitted, G. C. Nonken has published[10] sparking voltages for longer gaps in Freon. His curves for sparking between points (square rods) show the typical hump. A hump is just beginning to appear in the curve of Fig. 7 of this paper at the highest pressure obtainable in pure Freon, and with longer gaps it appears at lower pressure. At gap lengths of six and eight centimeters this maximum sparking voltage is at almost atmospheric pressure, and voltage declines as pressure is raised.

At atmospheric pressure comparison may be made between results obtained in Freon and the A.I.E.E. standard needle-gap sparking voltages for air, as shown in Table I.

TABLE I

Voltage Kv Crest	Length of Spark (Inches)	
	In Air (A.I.E.E. Standard)	In Freon (Experimental)
14.3	0.47	0.10
24.0	0.82	0.20

It will be seen that in general the increase of electric strength gained by the use of Freon is greater with pointed electrodes than with flat or spherical electrodes. The apparent reason is that with pointed electrodes, sparking is preceded by corona discharge, while there is no corona between spheres. The conclusion is that formation of corona is greatly impeded by Freon gas.

One of the more important and useful aspects of the behavior of Freon is the following. The maximum sparking voltage between points in Freon is greater than the sparking voltage of the same point-gap in air or nitrogen at any practical pressure of air or nitrogen. With a gap of 0.1 inch, for example, between points, Freon will withstand about 40 kilovolts at 50 to 60 pounds gauge pressure. According to data given by H. J. Ryan[8] a gap of the same length in air will not support more than 35 kilovolts even though the pressure is raised to 1,500 pounds. With longer gaps the advantage of Freon appears to be even greater.

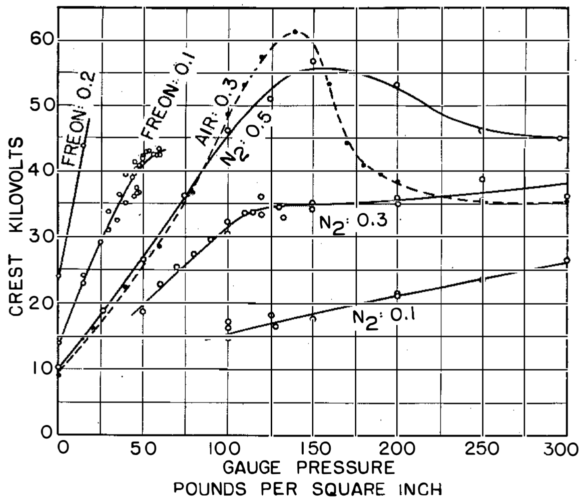

Fig. 7—Sparking Voltages in Nitrogen, Freon, and Air.
Pointed electrodes
Gas tested, and spark-gap length in inches, as noted on curves

This advantage is peculiar to pointed electrodes. In nitrogen or air the sparking voltage between points reaches a maximum at a pressure of a few atmospheres and thereafter decreases with increasing pressure, or at the most, rises very gradually. When the gap in which sparking occurs is between smooth surfaces—between spherical electrodes, for example—the maximum strength of Freon may be equaled and exceeded in either air or nitrogen by sufficiently increasing the pressure but this is not possible if the spark occurs between points.

These facts appear to make Freon potentially more useful to prevent electric discharge from points or projections than to prevent sparking or breakdown in a substantially uniform electric field. On the other hand, it must be remembered that corona or other electric discharge must not ordinarily be allowed to take place in Freon, because the decomposition products are corrosive and somewhat poisonous.

Conclusions

1. The electric strength of nitrogen between smooth electrodes is almost exactly equal to that of air.

2. Sparking voltage between sharp points is higher in air than in nitrogen (see Fig. 7).

3. Freon gas (dichlorodifluoromethane) between smooth electrodes will withstand about two and a half times as much voltage as air or nitrogen at the same pressure, but it cannot be used at pressures above about 70 pounds per square inch, gauge, as that is its approximate vapor pressure at ordinary temperatures (see Figs. 2 and 3).

4. Mixtures of Freon and nitrogen are intermediate in characteristics between the two gases used alone (see Figs. 4 to 6). The most interesting characteristic of mixtures is the large increase in electric strength produced by a very small amount of Freon in nitrogen (see Fig. 6).

5. Freon gas between pointed electrodes increases the strength of the gap very greatly, the sparking voltage being found in some cases to be of the order of magnitude of four times that in nitrogen. The maximum sparking voltage in Freon is greater than the greatest sparking voltage that can be attained in air or nitrogen at any practicable pressure.

6. The greatest advantage in the utilization of Freon between smooth surfaces is where the pressure of gas that may be used is limited by mechanical considerations. For most purposes, nitrogen at 300 pounds per square inch pressure is superior to Freon, for it has as great an electric strength, is more consistent in behavior, and does not become corrosive in the presence of electric discharge. But if the gas pressure is limited by mechanical design to 150 pounds per square inch, or less, the possible use of Freon should be carefully considered.

7. The possibility of adding a small percentage of Freon to nitrogen, and thereby increasing its electric strength by 15 to 25% appears to be a practical consideration.

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Wavelength Measurements of Decimetric, Centimetric and Millimetric Waves

By A. G. CLAVIER

***Editor's Note:**—The present article was prepared and describes work done prior to September 1939. Due to war conditions, it was not published. It has been thought that it is still of interest, both technically and to establish more clearly the status of this particular type of work prior to the war period.*

***Synopsis:**—In this article the measurement of waves shorter than one meter is considered and apparatus specially adapted to this purpose is described. Different types of available circuits are analyzed and compared, and problems of coupling to the source to be measured, as well as the necessary indicating apparatus, are outlined. A wavemeter with coaxial lines, suitable for the ready measurement of decimetric and centimetric wavelengths, is described. For the shortest wavelengths of the band under consideration, dielectric guides or interferometer methods used in the infra-red waveband may be applied.*

THE measurement of wavelengths below about one meter presents peculiar difficulties and necessitates the construction of specialized apparatus adapted to this purpose.

Up to the present it has not been possible conveniently to measure these very high frequencies by beating them with the harmonics of an oscillator stabilised, for example, by means of a piezo-electric crystal. With increasing fundamental frequencies, thinner crystals must be used and they consequently become very fragile. If, on the other hand, a much lower frequency is used, it is difficult to produce and amplify harmonics of a sufficiently high degree with vacuum tubes at present available. In this direction a limit is set by the influence of the internal connections and the time of transit of the electrons between the electrodes.[1]

Frequency meters of this kind, nevertheless, could be constructed for the lowest frequencies in the range under consideration.[2,3] The apparatus, however, would be cumbersome and would require delicate handling. In any case, wavemeters of lesser precision are needed for making measurements readily but with adequate accuracy, considering the present state of the art.

Such wavemeters can be obtained by using a high selectivity electric circuit tunable to the frequency to be measured. Association is required with (1) an element capable of being influenced by oscillation on the frequency to be determined, and (2) a detector element arranged to deflect a measuring instrument and to indicate that the tunable circuit of the wavemeter is in resonance.

In the region of decimetric waves, the longest in the field herein considered, it is still possible to construct an oscillating circuit of lumped electrical constants. The selectivity of such a circuit can easily be estimated by means of its magnification factor Q, derivable from low frequency technique. Fig. 1 shows a circuit consisting of an inductance L, a resistance R and a capacitance C in series. Between the terminals A and B an e.m.f. E of angular velocity ω is applied. For resonance, when $LC\omega^2 = 1$, the current is E/R. The voltage across the inductance

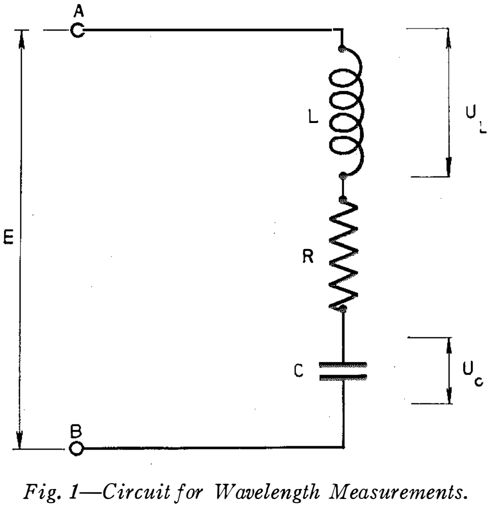

Fig. 1—Circuit for Wavelength Measurements.

and the capacitance are therefore:

$$U_L=\frac{E}{R}L\omega,\quad U_C=\frac{E}{R}\frac{1}{C\omega}.$$

These voltages are equal and their ratio to the e.m.f. applied to the terminals A, B of the circuit is the magnification factor Q:

$$Q=\frac{L\omega}{R}=\frac{1}{RC\omega}.$$

The magnification factor thus defined also characterizes the selectivity of the circuit. Actually, when not in resonance, the current in the circuit may be represented by the usual equations:

$$\frac{E}{R+j\left(\omega L-\frac{1}{\omega C}\right)}=\frac{E}{R}\cdot\frac{1}{1+j\frac{1}{R}\left(\omega L-\frac{1}{\omega C}\right)}. \quad (1)$$

Let ω_0 be the resonance angular velocity for which $LC\omega_0^2=1$. If this velocity is changed by $\delta\omega_0$, where $\delta\omega_0/\omega_0\ll 1$, the ratio of the current at angular velocity $(\omega_0+\delta\omega_0)$ to the resonance current is equal to

$$\frac{1}{1+j\frac{\omega_0 L}{R}\cdot\frac{2\delta\omega_0}{\omega_0}}=\frac{1}{1+jQ\frac{2\delta\omega_0}{\omega_0}}. \quad (2)$$

The sharpness of the resonance curve may be estimated by the difference $\delta\omega_0$ for which the current falls to a value $1/\sqrt{2}$ of the resonance current. Thus,

$$\frac{2\delta\omega_0}{\omega_0}=\frac{1}{Q}. \quad (3)$$

An oscillating circuit therefore will be the more selective, the greater the value of Q. Consequently, for a given inductance L, it is necessary to reduce as much as possible the different resistances in the circuit. The preceding analysis, where it is assumed that $\delta\omega_0/\omega_0$ remains $\ll 1$, does not apply except where the resistance is small compared to the reactance $L\omega$.

The different resistances in the oscillating circuit are:

1. High frequency resistance of the wire constituting the inductance;
2. Resistance due to losses in the part of the condenser dielectric subjected to the high frequency field;
3. Resistances due to radiation of the loop constituting the inductance and radiation of the condensers.

An examination of these different resistances shows that, for wavelengths up to 30 cm, it would be difficult for the magnification factor to exceed a few hundred. Rohde, in the wavelength range of 60–30 cm, gives as an example a factor Q of approximately 100 for a circuit consisting of a copper wire 4 mm in diameter, forming a single spiral 25 mm in diameter. This spiral is associated with a condenser, the plates of which are copper rings 8 mm in diameter; their separation is adjustable by means of micrometer screws. Such a wavemeter cannot be easily coupled to the source to be measured, or to a detector suitable for use at fairly high frequencies. From this point of view the best results are obtainable with diodes constructed so that the transit time of the electrons should not be troublesome.[1]

Obviously, circuits possessing greater magnification factors and adaptability are needed.

Butterworth[5] made an investigation of the values of Q that might be expected for inductances of predetermined geometric form. His computations, however, do not allow for losses due to radiation and apply to lower frequencies than those under consideration.

To eliminate radiation, toroidal windings may be used. For a winding of this type, with circular cross-section and with turns touching (Fig. 2), the inductance and resistance are given by

$$L=4\pi N^2\left[R-\sqrt{R^2-r^2}\right]\times 10^{-9}\text{ henries,} \quad (4)$$

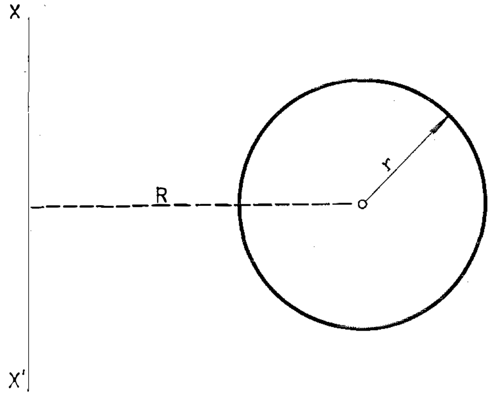

Fig. 2—Toroidal Inductance.

$$R_\Omega = 2\pi\sqrt{\rho}N^2 \cdot \frac{r}{R} \cdot \frac{1}{\sqrt{1-\left(\frac{r}{R}\right)^2}} \cdot \sqrt{f} \times 10^{-9} \text{ ohms}, \quad (5)$$

where N is the number of turns and ρ is the resistivity in electromagnetic units (about 1700 for copper).

Expressing the frequency in megacycles per second (F):

$$Q = \frac{\omega L}{R_\Omega} = 303\sqrt{F} \cdot \phi(r, R). \quad (6)$$

The function ϕ, when $(R+r) = b$ is kept constant, has a maximum for $r/R = 0.707$. For this value

$$Q_{\text{opt}} = 52b\sqrt{F} = 89R\sqrt{F}. \quad (7)$$

By adding the resonance condition,

$$L_{\mu H} C_{\mu F} = \frac{25200}{F^2}, \quad (8)$$

to this equation the curves of Fig. 3 result for the case of a single spiral, which is the most favourable condition for very high frequencies. These curves show that it is theoretically possible to obtain magnification factor values very much higher than those given by the circuits previously considered. In practice, however, it is difficult to attain the very low values of capacitance necessary for tuning, and it is even more difficult to vary this capacitance. Finally, difficulties of coupling to the source to be measured and procuring a suitable measuring detector remain very great. This type of circuit is consequently more suitable for very high frequency oscillators than for wavemeters and has been thus utilized in various ways by Kolster,[6] more recently by Hollmann,[7] and especially by Hansen[8, 9] in his researches on velocity modulation oscillators at Stanford University.

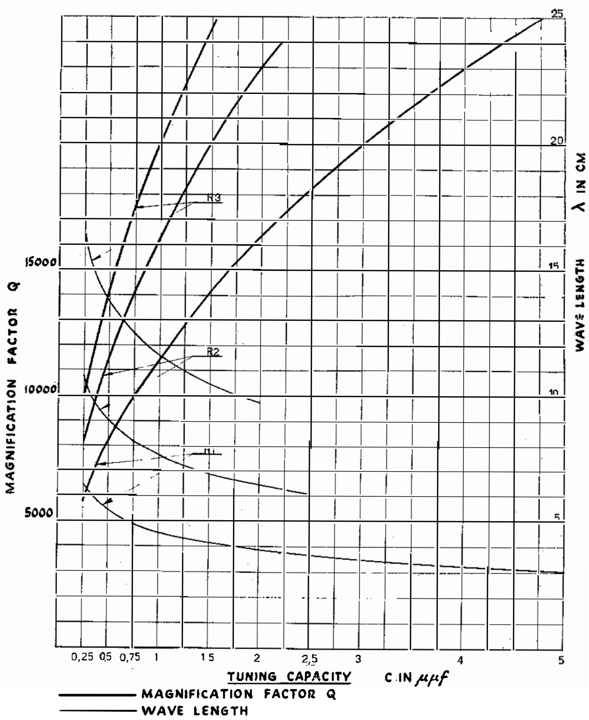

Fig. 3—Resonance Conditions of Tuned Toroidal Windings.

Circuits with Distributed Constants

The foregoing considerations and the necessity of finding an easy method of calibration in terms of wavelength have led to the use of circuits with distributed constants and, in particular,

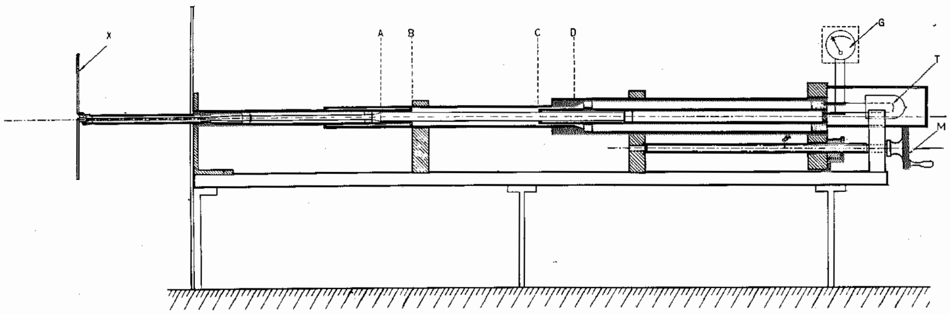

Fig. 4—Wavemeter with Coaxial Lines.

transmission lines. In the first instance, transmission lines made up of two parallel wires were considered, the systems being known technically as Lecher wires. In a system of this kind with separation between the wires small compared with the wavelength, radiation can as a first approximation be ignored and Kirchhoff's laws applied by assigning line constants R, L, C to the line. For very high frequencies, leakance between wires may be ignored.

For such a circuit it is possible to define a coefficient Q which plays the same part, so far as selectivity is concerned, as the magnification factor in circuits with lumped constants. Considering a short-circuited line of length l, calculation gives the input impedance as

$$Z=Z_0 \tanh\left(\alpha l+j\frac{2\pi l}{\lambda}\right); \tag{9}$$

Z_0 is the characteristic impedance of the line, equal to $\sqrt{L/C}$, and α is the attenuation constant equal to $R/2Z_0$.

The impedance is a maximum for the quarter-wave line; hence

$$Z_{\lambda/4}=\frac{Z_0}{\tanh \alpha l}. \tag{10}$$

If the attenuation is low, the approximation

$$Z_{\lambda/4}=\frac{Z_0}{\alpha l} \tag{11}$$

is obtained.

This expression is not valid unless αl is sufficiently small compared with 1; for an infinite attenuation $\tanh \alpha l$ tends towards 1, and $Z_{\lambda/4}$ towards Z_0.

The frequency f_0 corresponds to a wavelength λ_0 for which the length of the line is a quarter wavelength; changing by δf_0 such that $\delta f_0/f_0$ is small compared with 1, the impedance becomes

$$Z=\frac{Z_0}{\alpha l}\cdot\frac{1}{\left(1+j\frac{\pi}{\alpha\lambda_0}\cdot\frac{2\delta f_0}{f_0}\right)}. \tag{12}$$

The modulus of the impedance then drops from 1 to $1/\sqrt{2}$ for a frequency difference δf_0 such that

$$\frac{2\delta f_0}{f_0}=\frac{\alpha\lambda_0}{\pi}. \tag{13}$$

The quantity $\pi/\alpha\lambda_0$ defines the selectivity of the system and corresponds to the magnification factor.

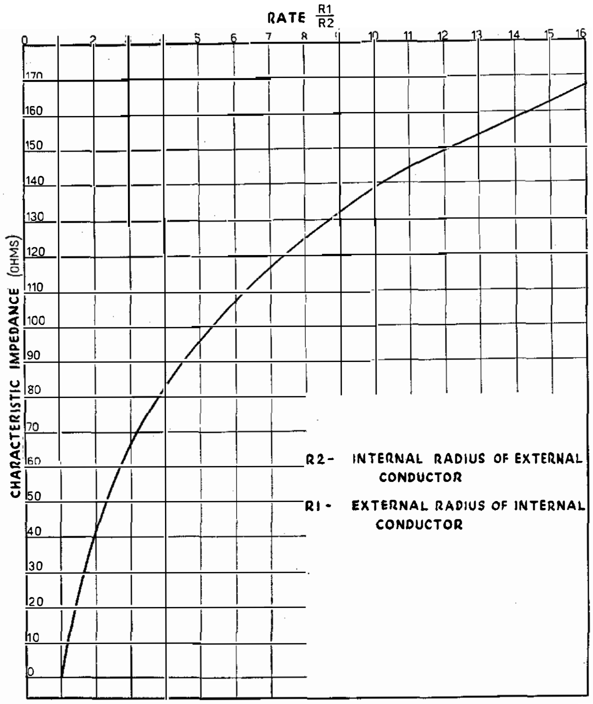

Fig. 5.

This expression becomes clearer if the expression for a circuit with lumped constants is written

$$Q=\frac{\omega_0 L}{R}=\frac{\pi}{(R/2L)T_0}=\frac{\pi}{(1/\theta)T_0}; \tag{14}$$

T_0 is the resonance period and θ the time constant of the circuit.

Conversely, replacing α by its expression as a function of the constants of the line,

$$Q=\frac{\pi}{\alpha\lambda_0}=\frac{\omega_0 L}{R}, \tag{15}$$

where L and R are constants per unit of length.

Transmission lines with parallel wires can therefore be used as circuits for the measurement of wavelengths and are especially suitable for decimetric wavelengths. The resonance positions are repeated periodically along the line and their separation gives the wavelength to be measured. Such lines, with variations have been used by numerous experimenters (see, for example, Hund[10] at the Bureau of Standards, and, in France, the theses of Mercier and Laville).

In these measurements the distance between two consecutive resonances is not exactly equal to half a wavelength in air. The phase velocity along the wires is $1/\sqrt{LC}$ and L varies with frequency. As a first approximation it is possible to take (Stéfan)

$$L = L_{\infty} + \frac{R_{\omega}}{\omega}; \tag{16}$$

L_{∞} is the inductance per unit length corresponding to a purely surface current distribution at infinite frequency. As R_{ω} is small compared with $L_{\infty}\omega$,

$$v = c\left(1 - \frac{R}{2L_{\infty}\omega}\right) = c\left(1 - \frac{1}{2Q}\right) \tag{17}$$

approximately, where c is the velocity in air. The error is very small for the frequencies considered in this article.

Lecher-wire wavemeters are in current use for the measurement of decimetric waves. They, however, have the following disadvantages: the higher the frequency the more the line radiates; moreover, it is difficult to localize the excitation at one point of the line, thus making the application of the previous theory doubtful; finally, it is not easy to eliminate effects due to surrounding objects and movements of the operator. It is consequently preferable to use *coaxial lines.* A wavemeter of this type, described below, was designed in 1931 at the Laboratories L.M.T. by the author and one of his colleagues, René Darbord.[11]

Coaxial-line Wavemeter

The wavemeter illustrated in Fig. 4 comprises essentially a test line BC of length adjustable by means of a micrometer movement M; this line is connected to the antenna X and to the thermocouple T through quarter-wave lines AB and CD. The lines in front of A towards the antenna and behind D towards the thermocouple present impedances at A and D which, in order to simplify this description, are assumed to be purely resistive lines (ρ and ρ') adjusted, for example, to a halfwave-length.

Further, let it be assumed that the characteristic impedances of the quarter-wave lines are equal (Z_1) and that Z_2 is the characteristic impedance of the measuring line. Then, in order to obtain sufficient sensitivity, it will be found that the resistances introduced by the coupling with the antenna and the thermojunction are large compared with the resistance of the measuring line, which may be neglected to a first approximation. Under these conditions, if E is the e.m.f. induced in the antenna by the source to be measured, the current in the thermocouple becomes,

$$I_{\alpha} = E\frac{Z_1^2 Z_2}{\sqrt{(A^2\cos^2\beta l + B^2\sin^2\beta l)}}, \tag{18}$$

where

$\beta = 2\pi/\lambda$,
l = length of the measurement line,
$A = Z_1^2 Z_2(\rho + \rho')$,
$B = Z_1^4 + \rho\rho' Z_2^2$.

The variation of I_{α} with l depends on $(B - A)$ which may be written

$$(Z_1^2 - \rho Z_2)(Z_1^2 - \rho' Z_2). \tag{19}$$

Several different cases may arise. In the wavemeter under consideration, Z_2 is made very much greater than Z_1^2/ρ and Z_1^2/ρ'. The current I_{α} is a maximum when the measuring line is a quarter wave long. It falls to $1/\sqrt{2}$ of its maximum value for

$$\sin\beta l = \pm\frac{A}{\sqrt{(B^2 - A^2)}}; \tag{20}$$

approximately,

$$l = \frac{\lambda}{2} \pm \frac{\lambda}{2\pi}\,\frac{A}{\sqrt{(B^2 - A^2)}}. \tag{21}$$

Predetermination of the accuracy of the measurement is thus possible. It is advisable to make Z_2 as large as possible, and Z_1 as small as possible.

The quantities Z_1 and Z_2 depend only on the ratio of the internal radius of the external conductor to the external radius of the internal conductor of the coaxial lines. The impedance obtained may be read from the curve of Fig. 5.

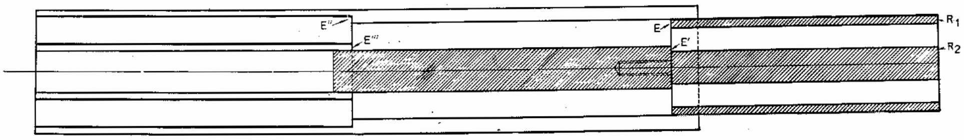

Fig. 6—Adjustable Line with Constant Characteristic Impedance.

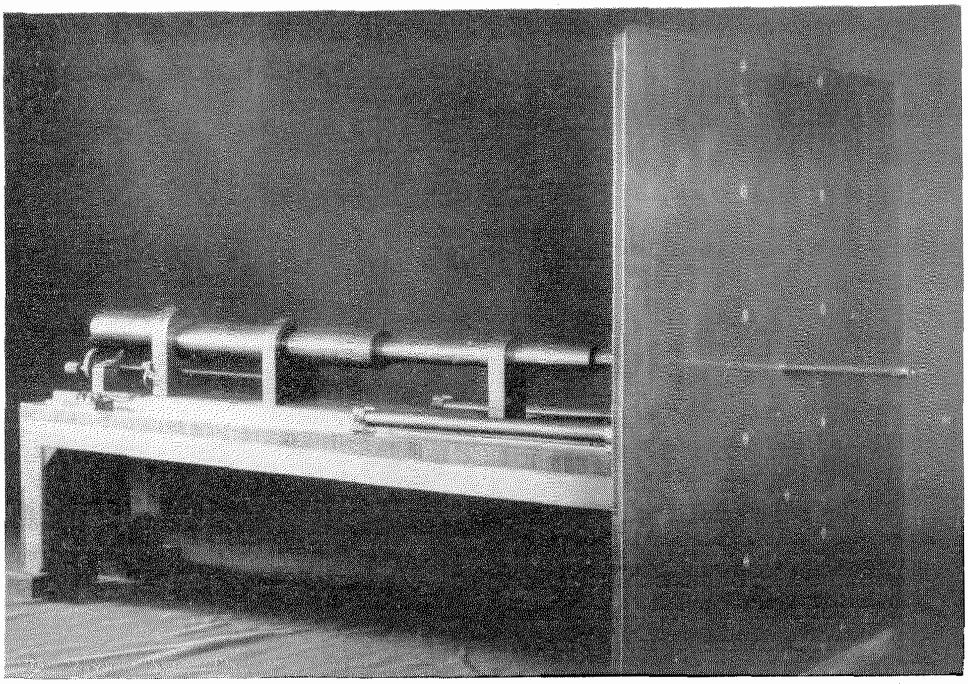

Fig. 7—Complete Wavemeter with Coaxial Lines.

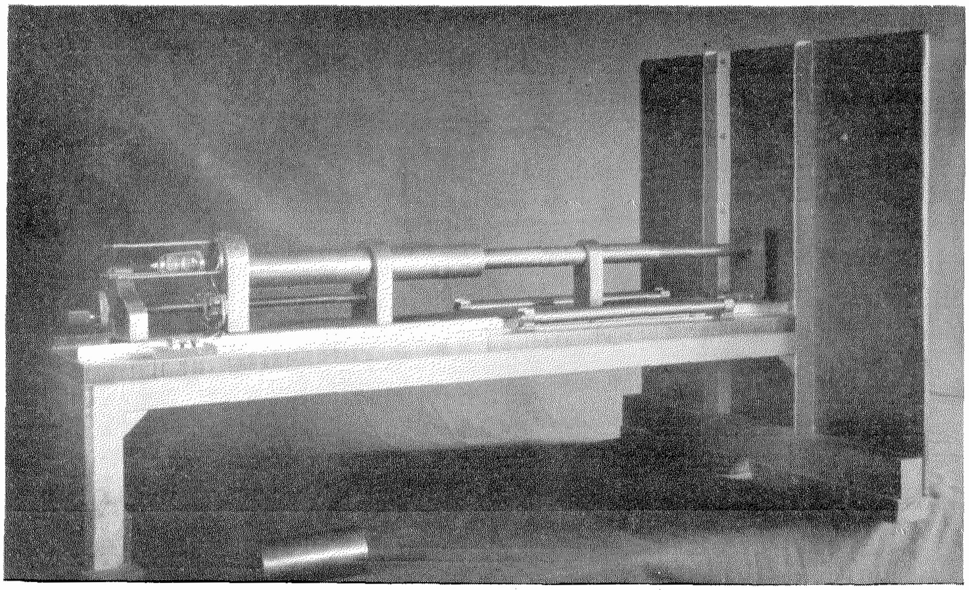

Fig. 8—Rear View of Wavemeter with Coaxial Lines.

In the models constructed it is possible to measure the wavelength to an accuracy of one part in 2000. This measurement, just as for Lecher wires, is subject to an error due to the phase velocity along the line not being equal to the propagation velocity in free space. This error is, however, very small at the high frequencies herein considered.

The above analysis strictly applies only under conditions of precise adjustment of all the lines which constitute the wavemeter. But the quarter-wave lines remain effective over a fairly wide wavelength band; the wavemeter operates correctly, for example, from 12–24 cm when the quarter-wave sections are adjusted for 17 cm.

To obtain a measuring line the characteristic impedance of which does not vary regardless of the length used, it is preferable to use the device pictured in Fig. 6. The shaded parts are movable en bloc. The characteristic impedance is constant along the line provided that the steps E, E', E'' and E''' are such that

$$\frac{R_1}{R_2}=\frac{E}{E'}=\frac{E''}{E'''}.$$

Figs. 7 and 8 are photographic reproductions of the coaxial-line wavemeter above described. They show the ease of coupling with the source to be measured and suggest the absence of interference effects due to movements of the operator when he stands behind the reflector associated with the antenna.

Coaxial-line wavemeters may be used for the measurement of wavelength up to the centimeter-waveband. For wavelengths of a few centimeters, however, the influence of the transverse dimensions of the coaxial line causes trouble and coupling problems arise. Dielectric guides therefore become necessary.

Dielectric Guides for the Measurement of Centimetric Wavelengths

The simplest dielectric guides consist merely of a metallic pipe without an inside conductor. Theory and experiment show that electromagnetic waves may be propagated through them provided that the wavelength in air is below a certain limit which is of the order of the diameter of the guide. Reference may be made to previous articles published in connection with this subject for justification of the exposition which follows (see for example, references 12, 13, 14, 15, 16 and 17).

This type of circuit does not readily lend itself to the determination of line constants, but the coefficient which plays the part of the factor Q

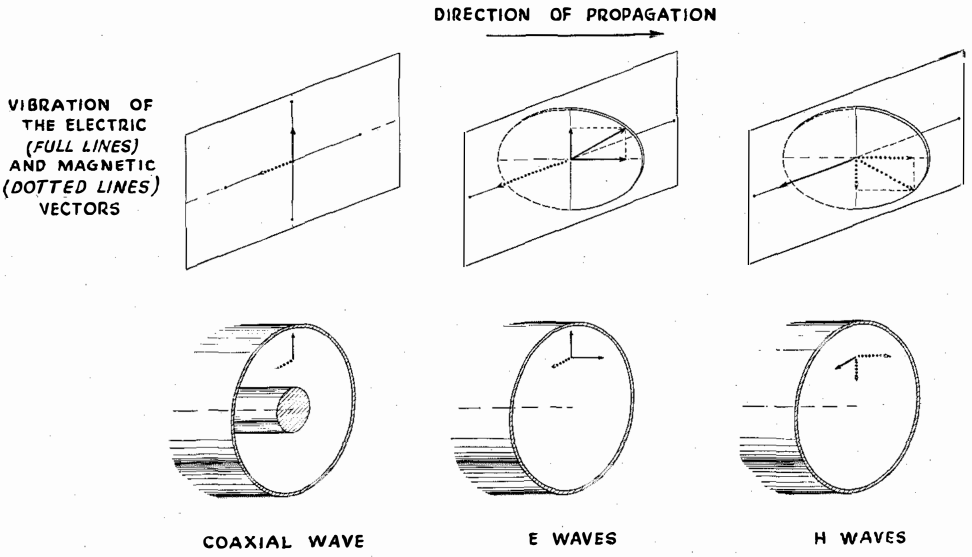

Fig. 9.

may be defined in terms of energy. For a circuit with lumped constants

$$Q=\frac{\omega L}{R}=2\pi\cdot\frac{LI^2}{RI^2}\cdot\frac{1}{T}, \tag{22}$$

where I is the rms current and T the oscillation period. Except for 2π, this is the ratio of the average stored electromagnetic energy to the amount of energy dissipated as heat during a given period.

Applying this definition to the case of a cylindrical dielectric guide, let $\overline{W}_{\text{tot}}$ be the stored electromagnetic energy per unit of length averaged over a period and $\bar{Q}_c$ the quantity of energy lost as heat per unit of length and per unit of time (losses in the dielectric, air generally, are negligible). Then

$$Q=\frac{2\pi}{T}\cdot\frac{\overline{W}_{\text{tot}}}{\bar{Q}_c}. \tag{23}$$

But the coefficient of attenuation is related to $\bar{Q}_c$ and to the mean power $\overline{W}_z$ delivered through a cross-section;[17] hence,

$$\alpha=\frac{\bar{Q}_c}{2\overline{W}_z}$$

and, consequently,

$$Q=\frac{\pi}{\alpha T}\cdot\frac{\overline{W}_{\text{tot}}}{\overline{W}_z}. \tag{24}$$

$T\overline{W}_z$ is the energy which passes through a cross-section per period. This energy occupies a guide length λ_g such that

$$T\overline{W}_z=\lambda_g\overline{W}_{\text{tot}};$$

hence

$$Q=\frac{\pi}{\alpha\lambda_g}. \tag{25}$$

Calculation shows, as might be expected, that λ_g is the wavelength corresponding to the group velocity, V_g, determining the speed of transmission of energy. In dielectric guides V_g and the phase velocity V_p are such that

$$V_gV_p=v^2, \tag{26}$$

where v is the velocity of propagation in free space. In coaxial lines, to the same approximation, $V_g=V_p=v$, which again gives the expression used above.

The constant $Q=\pi/\alpha\lambda_g$ may easily be computed for dielectric guides. It is, however, necessary to recognize *the different wave structures* which may be propagated and which each give different values of α and λ_g.

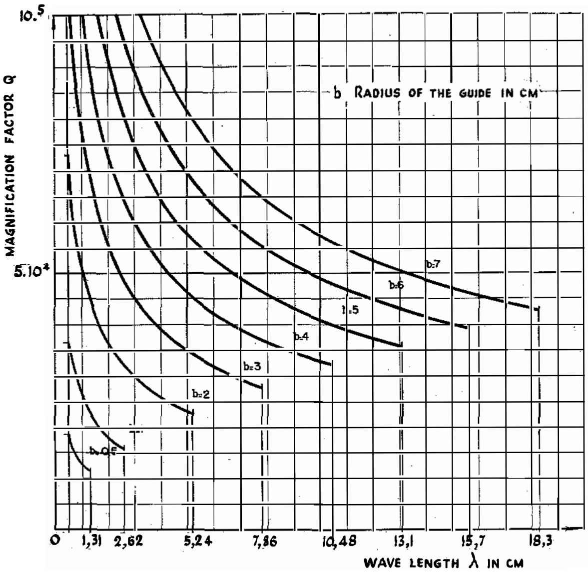

Fig. 10.

The principal structures are classified as E waves and H waves, characterized by the directions of the electric and magnetic vectors. This classification is shown diagrammatically in Fig. 9 where, for purposes of comparison, the directions of the vectors in the lossless coaxial line are given.

For fundamental wave structures[16, 17] calculation gives:

$$E_0 \text{ Wave} \quad Q_{E0}=\frac{\pi}{2}\cdot\frac{b\sqrt{f}}{\alpha_0 v} \tag{27}$$

$$H_0 \text{ Wave} \quad Q_{H0}=\frac{\pi}{2}\cdot\frac{b\sqrt{f}}{\alpha_0 v}\cdot\frac{f^2}{f_c^2} \tag{28}$$

$$H_1 \text{ Wave} \quad Q_{H1}=\frac{\pi}{2}\cdot\frac{b\sqrt{f}}{\alpha_0 v}\cdot\frac{1}{0.44+(f_c^2/f^2)}. \tag{29}$$

In these expressions b is the radius of the guide, f_c the cut-off frequency, v the velocity of propagation in free space and α_0 a coefficient which depends on the materials employed. If μ_1 and μ_2 are the permeabilities of the dielectric and of the conductor, ϵ_1 the dielectric constant of the dielectric, and σ_2 the conductivity of the conductor,

$$\alpha_0=\frac{1}{4}\cdot\sqrt{\frac{\mu_2\epsilon_1}{\sigma_2\mu_1}}. \tag{30}$$

Put in the same form, the coefficient of the coaxial cable becomes

$$Q_c=\frac{\pi}{2}\cdot\frac{b\sqrt{f}}{\alpha_0 v}\cdot\frac{2}{\left(1+\frac{b}{a}\right)\Big/\left(\text{logh}\ \frac{b}{a}\right)},\qquad(31)$$

a maximum occurring when the ratio b/a of the radii is equal to 3.6 (minimum attenuation). This coefficient takes account only of the copper losses; in the E_0 case, it is lower in the ratio of 1 to 1.8.

The expression $\pi/2\cdot b\sqrt{f}/\alpha_0 v$ may also be put in the form $\mu_1/\mu_2\cdot b/\delta$, where δ is the skin thickness at the frequency used;[8]

$$\delta=\frac{1}{\sqrt{(2\pi\sigma_2\mu_2\omega)}}.\qquad(32)$$

It can be shown that the above expressions are applicable at the cut-off frequency. This is the case with which Hansen deals. The tuning of the circuit then no longer depends on the length of the guide sections but only on the radius. Propagation in the strict sense along the axis does not really take place; the circuit may be likened to one with lumped constants. The coefficient Q may therefore be given the form

$$Q_{E_0}=\frac{\pi}{\left(\frac{Rl}{2\mu_1 l}\right)T},\qquad(33)$$

where l is the axial length, and the circuit may be considered as having an inductance per unit length equal to μ_1.

Hansen[8] allows for losses in the terminal walls, which multiply the above factor Q by $1/(1+b/l)$.*

The order of magnitude of the factor Q_{E_0} to which theory points is shown by the curves of Fig. 10.

To measure wavelengths with dielectric guides, it is necessary to transform the wavelength measured along the guide into the wavelength in air. Experiment indicates that it is possible, in the present state of the art and with transmitter frequency stability available, to rely on the theoretical relationships established between these wavelengths. This relationship is given by the curves of Fig. 11 for the principal wave structures which require consideration.[18] It will be appreciated that it is advisable to work fairly closely to the cut-off wavelength since in this region a relatively small variation in the frequency causes a considerable variation in the wavelength along the axis of the guide.

Measurements of wavelength have been made below a centimeter with the equipment illus-

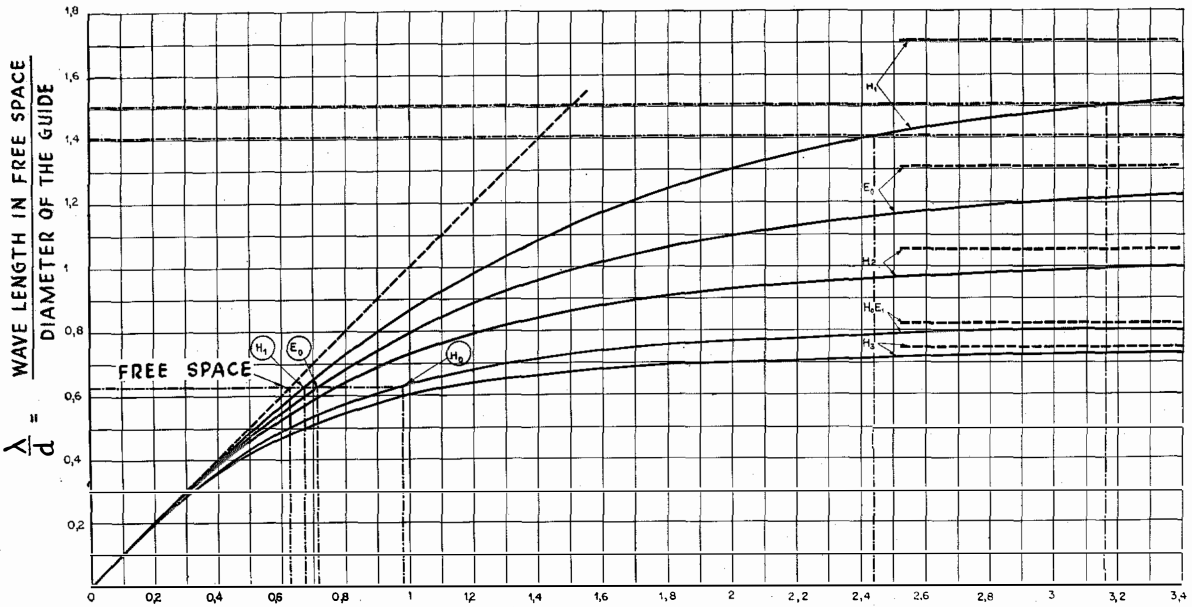

Fig. 11.

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* It will be noted on reading Hansen's article [8] that the thickness of the skin which he deals with is equal to $1/\sqrt{2}$ of the quantity δ used in the present treatise.

trated in Fig. 12. The wavelength of a magnetron especially constructed for wavelengths of this order required determination. The magnetron sent an H_1 wave into a guide of 0.5 cm radius. A crystal detector was coupled to the guide and connected to the milliammeter visible in the figure. At the end of the guide a movable piston, which had very good high frequency contacts with the wall of the guide, was displaced by a micrometer lead. Accuracy was increased by taking measurements at a certain number of half wavelengths.

Other methods of measurement have been utilized. In particular, the quasioptical properties of these oscillations suggest the adaptation of interferometers and gratings. Thus, as might be expected, there is a tendency towards the technique of measurement used at the long end of the infra-red spectrum.

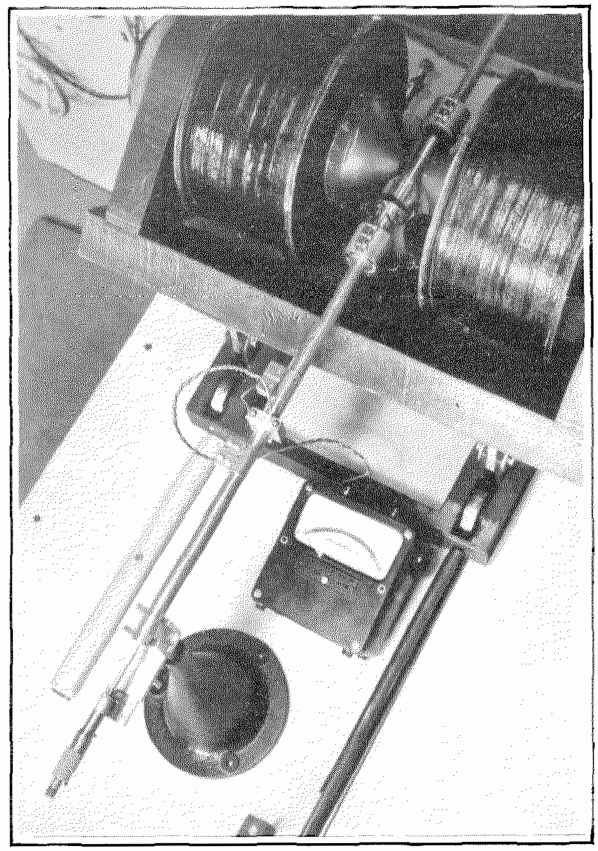

Fig. 12—Measuring Device Using a Dielectric Guide.

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Some Simplified Methods of Determining the Optical Characteristics of Electron Lenses*

By KARL SPANGENBERG, *Associate, I.R.E.*, and LESTER M. FIELD, *Student, I.R.E.*

Editor's Note. *Novel methods of obtaining optical characteristics of electron lenses were developed by the authors in the course of a general research on electron optics. The work has been carried on by the Electrical Engineering Department of Stanford University under the sponsorship of the International Telephone and Telegraph Corporation.*

Summary

Some new methods of calculating lens characteristics are proposed which are relatively simpler and more accurate than those previously suggested. The first is an extension of Salinger's method of joined circular segments applied to paraxial rays in fields with a rotational symmetry. This requires as information only the axial potential and derivatives thereof. This method is the computational equivalent of the original graphical method. A second method makes use of the action function which is approximated from the potential function. Electron paths are taken as normal to the lines of constant action. A third method replaces the convergent and divergent parts of the usual lens with equivalent thin lenses and then calculates the focal lengths by means of combination formulas applied to the two thin lenses. All calculating methods are, however, sufficiently long in application and indeterminate in accuracy that experimental methods of finding lens characteristics are preferred.

A new experimental method makes use of a demountable vacuum tube. Lens characteristics are determined from angular magnifications measured from the shadows cast by object screens illuminated by a point source of electrons. No moving screens are required nor is it necessary to generate rays parallel to the axis. By observing magnifications for all voltage ratios for two positions of the object screen enough data are available to determine the four cardinal focal distances for all voltage ratios. The results are considered more accurate and cover a greater range of voltage ratios than those reported by previous investigators. A graphical method has been developed for determining the spherical-aberration characteristics of the lens from the curvature of the object-screen images observed on the fluorescent screen.

Results are presented in a new and simplified form in addition to the standard form showing the variation of focal distances with voltage ratio. The new form gives associated object and image distances and corresponding magnification for any voltage ratio. The relation between the four useful variables is thus given on one chart for each lens. In effect this new form is a graphical presentation of the complete solution of the lens equation which shows clearly the relation between the four associated variables and gives quantitative results which can be applied directly. The new form reveals a number of properties of lens strength and magnification which have not been previously recognized.

I. Methods of Calculating Electron Paths

A. Previous Methods

A NUMBER of methods for calculating the characteristics of electron lenses from the potential field have been proposed. All of these calculate the principal rays of the lens, that is, the rays entering the lens parallel to the axis from the right and from the left, and then determine the location of the focal points and principal planes from these rays. When the four cardinal values of the lens, that is, the location of the two focal points and the two principal planes are known as a function of the voltage ratio, then the operation of the lens is completely determined.

The method of Klemperer and Wright[1] is the trigonometric ray-tracing method of physical optics applied to electrostatic lenses. The electrostatic field is broken up into a succession of thin

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* Paper presented before the Summer Convention of the I.R.E., Detroit, Michigan, June 24, 1941. Reprinted from *Proceedings of the I.R.E.*, March, 1942.

[1] O. Klemperer and W. D. Wright, "Investigations of Electron Lenses," *Proc. Phys. Soc.*, March, 1939, **51**, part II, pp. 296–317.

lenses having a constant ratio of equivalent index of refraction for adjacent lenses. Formulas are given for calculating the effect of every refraction at a lens surface upon the angle of a ray and the point at which it crosses the axis. Lens surfaces are assumed to be spherical and their radius of curvature must be determined either graphically or from the axial potential. The method requires a large number of equivalent thin lenses, at least twenty for an accurate determination, and the results converge slowly as the number of segments taken is increased.

From purely mechanical considerations Maloff and Epstein[2] have proposed several methods based upon a step-by-step solution of the differential equation of the paraxial electron. The methods give the electron path as an exponential function of the axial distance in any increment and join the paths in successive increments both in magnitude and slope. The methods are capable of good accuracy but the computations are lengthy. Information necessary for calculation is the axial potential and its derivatives.

Another approximate method based upon the differential equation of the paraxial electron has been proposed by Gans.[3] The axial potential is replaced by a number of straight-line segments which approximate it closely and the differential equation is then solved for the successive regions in which the potential is linear and the gradient is constant. At each boundary between segments there is a jump in the slope of the electron path because of the infinite value of the second derivative of potential at the junction of the straight-line segments. The final path as determined by this method consists of a number of curved segments of path connected together, giving a path which is continuous but which has discontinuities in slope at the corners of the segmented approximation to the axial distribution of potential. Such a path cannot represent accurately the true nature of the path within the lens but it can be used to obtain relations between initial and final values with considerable accuracy. The method is relatively easy to apply and gives fair accuracy for as few as six segments in the approximate axial potential curve.

B. METHOD OF JOINED CIRCULAR SEGMENTS

A new method which is the equivalent in simplicity and accuracy of any of the methods described above is based upon an extension of the general method of Salinger.[4] By considering the electron path to be a section of a circle at any point, it follows from equating the centrifugal force of the motion to the centripetal force of the field that the instantaneous radius of curvature is given by $R=2E/\overline{\nabla_n E})$ where E is the potential at the point in question and $\overline{\nabla_n E}$ is the component of the gradient of the potential normal to the instantaneous direction of motion. This is a relation which holds for all fields and permits a graphical construction of an electron path to be made by joining segments of circles tangentially.

For application to the case of paraxial electrons in an electron gun a graphical method is not feasible because the radii of curvature are so long that they cannot readily be drawn. However, it is possible to make use of the well-known series expansion for potential along the axis to obtain some simple relations which will give a step-by-step location of the electron as it moves through the field. For electrons close to the axis and making a small angle with it the normal component of the gradient is

$$\overline{\nabla_n E}=\sqrt{(r^2E_0'')^2+(E_0'\theta)^2}, \qquad (1)$$

in which the subscript zero indicates axial potential, the primes indicate derivatives in the axial direction, θ is the angle which the ray makes with the axis, and r is the radial distance from the axis to the electron path. If the radius of curvature R is determined from the potential E and the normal gradient as given in (1), and the electron be assumed to be swung through a circular arc of angle x such that the displacement Δs is about 1/40 of the distance through the lens, then the axial displacement Δz equals the displacement Δs to within 0.1%. Thus

$$\Delta z=Rx \qquad (2)$$

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[2] I. G. Maloff and D. W. Epstein, "Electron Optics in Television," McGraw-Hill Book Company, New York, N. Y., 1938, pp. 81–89.

[3] R. Gans, "Electron Paths in Electron Optics," *Zeit. für Tech. Phys.*, February, 1937, **18**, pp. 41–48.

[4] H. Salinger, "Tracing Electron Paths in Electric Fields," *Electronics*, October, 1937, **10**, pp. 50–54.

and the radial displacement is given by

$$\Delta r = Rx\left(\theta + \frac{x}{2}\right). \tag{3}$$

Initial and final values of r and θ for any increment are obviously given by

$$r_f = r_i - \Delta r, \tag{4}$$

$$\theta_f = \theta_i - x, \tag{5}$$

in which the subscripts f and i represent final and initial values.

By means of the above formulas the path through a lens may readily be calculated. The method is quite accurate because the path is made up of short segments of arcs of circles which join tangentially.

C. ACTION FUNCTION METHOD OF CALCULATING ELECTRON PATHS

This method is based upon the principle that electrons will move in paths which are normal to surfaces of constant action where the action a is defined as the integral of the product of the square root of potential and distance

$$a = \int \sqrt{E\,ds} \tag{6}$$

and is given in general by

$$(\nabla a)^2 = E, \tag{7}$$

which may be written as

$$\left(\frac{\partial a}{\partial r}\right)^2 + \left(\frac{\partial a}{\partial z}\right)^2 = E \tag{8}$$

in cylindrical co-ordinates.

The method given here approximates the action function from the known potential and then determines the electron paths through the action field. This is done by writing action as an even-powered series in r

$$a = a_0 + a_2 r^2 + a_4 r^4 + \cdots, \tag{9}$$

where the a's are functions of axial distance. Taking the gradient of this, squaring, and then equating term for term to the expression for potential gives

$$a_0'^2 = E_0 \tag{10}$$

and

$$4a_2^2 + 2a_0' a_2' = -E_0''/4 \tag{11}$$

as relations determining the first two coefficients.

The last differential equation cannot readily be solved exactly, but a solution over a small interval in which the coefficients may be considered to remain constant gives

$$a_{2R} = \frac{a_{2L} - \dfrac{E_0''z}{8\sqrt{E_0}}}{1 + \dfrac{2a_{2L}z}{\sqrt{E_0}}}, \tag{12}$$

where a_{2R} is the value of a_2 at the right of the interval and a_{2L} is the value at the left. By means of the above expression it is possible to calculate the value of a_2 as a function of z. When this is known, enough information is available to determine the path of an electron entering the lens parallel to the axis.

At any point in the lens the slope of the electron path M is given by the ratio of the r to the z component of the gradient of the action function. For electrons close to the axis this is

$$M = \frac{2a_2 r}{\sqrt{E_0}}, \tag{13}$$

from which

$$\Delta r = (2a_2 r/\sqrt{E_0})\Delta z, \tag{14}$$

so that

$$\ln_\epsilon \frac{r_2}{r_1} = 2\int_{z_1}^{z_2} \frac{a_2}{\sqrt{E_0}} dz, \tag{15}$$

in which r_2 and r_1 are final and initial radial distances, respectively, and z_2 and z_1 are the final and initial axial distances between which the calculations are made. The distances z_1 and z_2 are the points at the ends of the gun field at which the derivatives of potential are inconsiderable. This integral tells at what distance r_2 from the axis an electron will emerge from the lens if it enters at a distance r_1 from the axis.

The above integral is readily evaluated numerically. When the initial and final radial distances as given by the above integral are known and the initial and final slopes are also known the focal distance and location of the principal plane are easily determined. The principal plane is located by the intersection of the straight-line-path portions through the initial and final points drawn with the initial and final slopes, respectively. The focal distance is the reciprocal of the final slope multiplied by the final radial distance.

The method outlined above requires, as data from which to work, only the axial distribution of potential. The advantages of the method are that the numerical processes involved are relatively simple to apply and that the actual numerical work involved is less than that involved in any of the other methods tested. Essentially there is only one step-by-step formula to apply and the results of this operation are integrated through the lens structure. The only disadvantage of the method is that it is not valid in cases in which the electron crosses the axis within the lens structure. This is not a serious limitation because most of the practical lenses focus well beyond the last electrode.

D. METHOD OF EQUIVALENT THIN LENSES

The usual electron lens has a convergent behavior on the low-potential side and a divergent behavior on the high-potential side, the net lens behavior being convergent. The behavior is convergent when the second derivative of the axial potential is positive and divergent when the second derivative is negative. It is reasonable, therefore, to consider that the lens is made up of two thin lenses, a convergent lens followed by a divergent lens.[5] If the strength and location of these lenses are known the cardinal points of the equivalent thick lens may be determined.

The focal lengths of the convergent lens as shown in Fig. 1 are given by

$$\frac{1}{F}=\int_{z_1}^{z_m}\frac{E''}{2\sqrt{2E}}dz \tag{16}$$

and

$$f_1=F\sqrt{2E_1}, \tag{17}$$

$$f_2=-f_1\sqrt{E_m/E_1}, \tag{18}$$

where F is a focal term from which the focal lengths are derived, E_1 is the lowest potential on the lens axis, E_m is the potential at the point at which the second derivative assumes a value of zero, changing sign. The integration of (16) is carried over the region in which the second derivative is positive.

Similarly the focal distances for the divergent component of the lens are given by

$$\frac{1}{F'}=\int_{z_m}^{z_2}\frac{E''dz}{2\sqrt{2E}} \tag{19}$$

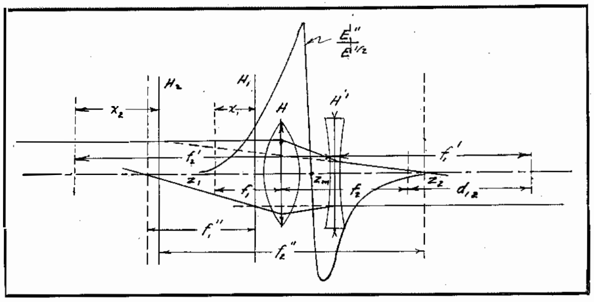

Fig. 1—Thin-lens Equivalent of a Thick Lens: Nomenclature.

and

$$f_1'=F'\sqrt{2E_m}, \tag{20}$$

$$f_2'=-f_1'\sqrt{E_2/E_m}, \tag{21}$$

where E_2 is the highest value of potential reached on the axis on passing through the lens.

When the focal lengths of the convergent and divergent components of the lens are known the focal characteristics of the entire lens are readily determined, this being a simple problem in the combination of lenses. When the distance between the second focal point of the convergent component and the first focal point of the divergent component is d_{12} then the focal lengths of the entire lens are[6]

$$f_1''=-f_1f_2/d_{12}, \tag{22}$$

$$f_2''=f_1'f_2'/d_{12}. \tag{23}$$

The location of the first principal plane measured from the first focal point of the convergent component is

$$x_1=f_1f_2/d_{12}+f_1'' \tag{24}$$

and the location of the second principal plane as measured from the second focal point of the divergent component of the lens is

$$x_2=f_1'f_2'/d_{12}+f_2''. \tag{25}$$

The method is extremely rapid in application. Some uncertainty exists as to the exact location of the thin lens components. The location of the lens components is best taken as being at the center of the area represented by the integrals of (16) and (19), as shown in Fig. 1.

All of the methods referred to above are subject to some error which is difficult to determine except by more detailed and extensive

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[5] L. M. Myers, "Electron Optics," D. Van Nostrand Company, New York, N. Y., 1939, p. 131.

[6] S. Rosin and O. H. Clark, "Combinations of Optical Systems," *Jour. Opt. Soc. Amer.*, March, 1941, **31**, pp. 198–201.

calculations. In general it may be said that although the methods are satisfactory, experimental methods are preferable, and usually more dependable.

II. Experimental Method

A. METHOD OF DETERMINING FOCUSING CHARACTERISTICS

The experimental method used in determining the lens characteristics is based upon observed magnifications of measuring grids placed before and after the lens structure.

A grid of closely spaced parallel wires (for measurement purposes only and not for control of the beams) is placed in the fore part of the lens. This grid casts a shadow upon a fluorescent screen following the lens. In order to avoid the need of a tube having parts which can be moved relative to one another while in a vacuum, another measuring grid is used between the end of the gun and the fluorescent screen. This arrangement is shown schematically in Fig. 2 in which the measuring grid in the fore part of the lens is indicated by a horizontal row of dots. With this arrangement of measuring grids, it is necessary to make observations on the magnifications of two grids, as the voltage ratio of the main lens electrodes is varied, for each of two distances of the lens from a point source of electrons. Hence two complete runs must be made to obtain the data from which the complete lens characteristics can be measured.

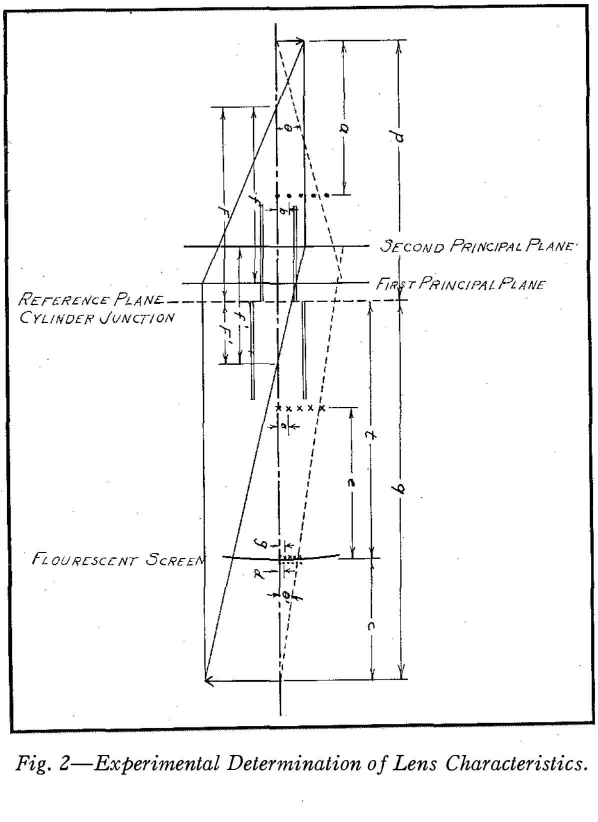

Fig. 2—Experimental Determination of Lens Characteristics.

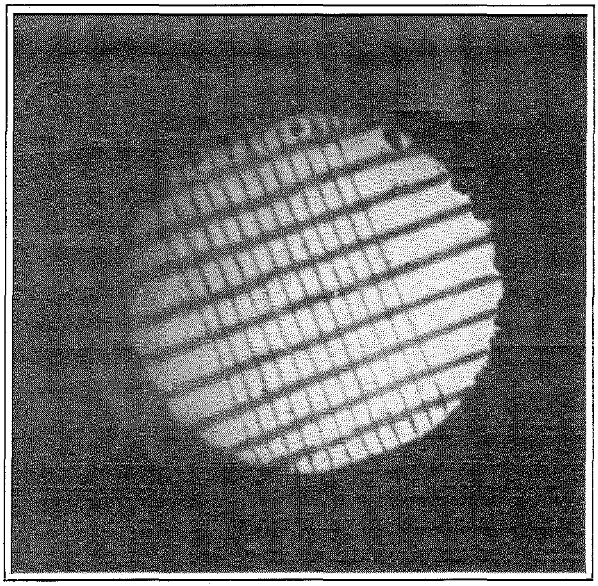

Fig. 3—Shadows of Measuring Grids on Fluorescent Screen.

The details of the mathematical relations involved can be seen from Fig. 2. The cathode-lens structure gave the effect of a point source of electrons at a known point near the cathode. The location of this point and the constancy of its position under varying conditions of lens voltage ratio were determined by placing two measuring grids in the fore part of the lens and observing the ratio of their magnifications. The constancy of the ratio of magnifications indicated that the location of the point source changed very little with lens voltage ratio and also over the normal range of control-grid voltages used. The location of the point source was very nearly at the control-grid aperture. When these facts were once determined from a test run it was no longer necessary to use two measuring grids in the fore part of the lens.

With the point source of electrons available the following general method is applied: The angular magnification of the bundle of rays is determined from screen patterns obtained on the fluorescent screen, such as that shown in Fig. 3.

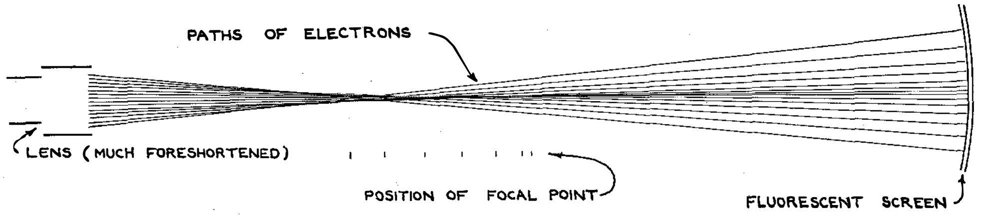

Fig. 4—Graphical Method of Determining Spherical Aberration: 1.5 to 1 Cylinder Lens, $E_2/E_1=4.5$.

Here the lines in one direction are the shadows of one measuring grid and the lines in the other direction are the shadow of the other measuring grid. When the angular magnification is known then for any given voltage ratio the lateral magnification can be determined from Lagrange's law, which states that the product of the internal magnification and the angular magnification is equal to the square root of the ratio of the final and initial potentials.[7] Image distances at each of the two object distances used are given for various voltage ratios from magnifications of the second grid alone. The object distances are known from physical measurements on the gun assembly. When lateral magnification, object distance, and image distance are known as a function of voltage ratio for two different values of the object distance then the cardinal quantities f, f', F, and F' of the lens may be calculated readily.

The method by which this calculation is made will be briefly indicated. Object and image distances can be expressed in terms of the lateral magnification and focal distances as

$$p=-f/m+F, \tag{26}$$

$$q=-mf'+F'. \tag{27}$$

These two equations involve the four quantities f, f', F, and F' as unknowns. In order to determine them it is necessary to know two sets of associated values of p, q, and m for the same voltage ratio. When subscripts 1 and 2 are used to indicate values of p, q, and m for two different values of p at a given voltage ratio, then there may be obtained from the above relations the following expressions for the cardinal focal distances

$$f=\frac{p_1-p_2}{\dfrac{1}{m_1}-\dfrac{1}{m_2}}, \tag{28}$$

$$f'=\frac{q_1-q_2}{m_1-m_2}, \tag{29}$$

$$F=\frac{p_1m_1-p_2m_2}{m_1-m_2}, \tag{30}$$

$$F'=\left(\frac{q_1}{m_1}-\frac{q_2}{m_2}\right)\Big/\left(\frac{1}{m_1}-\frac{1}{m_2}\right). \tag{31}$$

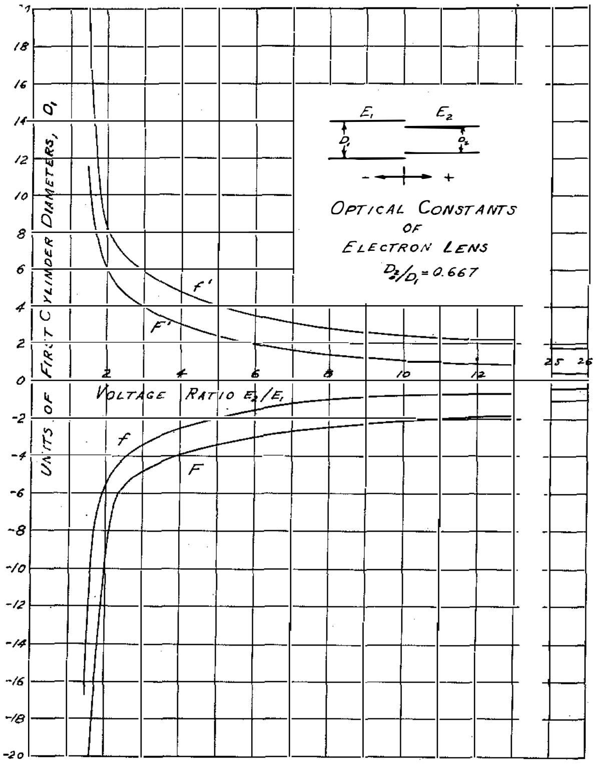

Fig. 5—Optical Constants at a Two-diameter Cylinder Lens, $D_2/D_1=0.667$.

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[7] O. Klemperer, "Electron Optics," Cambridge University Press, New York, N. Y., 1939, p. 12.

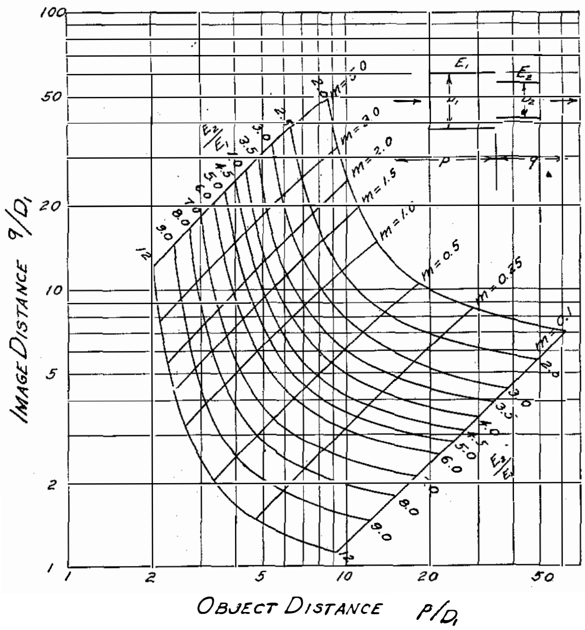

Fig. 6—Object-image—Distance Curves of a Two-diameter Cylinder Lens, $D_2/D_1=0.667$.

Up to this point the relations are the same as those used by Maloff and Epstein.[2] It is now only necessary to show how the lateral magnification may be deduced from the screen patterns to complete the collection of necessary relations. Referring to Fig. 2 it is seen that the angular magnification is given by

$$m_a=\theta'/\theta. \qquad (32)$$

For small angles such as are encountered in the gun the angular magnification in terms of the dimensions is given very closely by

$$\theta'/\theta=ad/bc, \qquad (33)$$

in which c is the distance beyond the fluorescent screen to the point at which the ray would focus. This distance is determined from the spacings of the grid images as follows:

For focus beyond fluorescent screen

$$c=\frac{e}{1-\frac{s}{g}}. \qquad (34)$$

For focus between second measuring grid (crosses) and fluorescent screen

$$-c=\frac{e}{1+\frac{s}{g}}. \qquad (35)$$

When the angular magnification is known, then the lateral magnification may be calculated from Lagrange's law as previously indicated.

With the above relations the cardinal quantities are readily calculated. In practice this is most easily done by plotting curves of the various quantities involved against voltage ratio because the same voltage-ratio observations may not have been taken on one run as on the other. There is a small hole in each curve at the point where the beam focus is at the fluorescent screen because the image becomes so small here that it is not possible to measure the spacings of the wires on the images. However, there is no trouble in drawing smooth and continuous curves through these holes if the data are taken with care. It is convenient to plot curves of reciprocal magnification rather than of magnification because the latter becomes infinite when the focus is on the fluorescent screen, whereas the reciprocal magnification is continuous through zero at this point.

B. DETERMINATION OF ABERRATION CHARACTERISTICS

Of all the types of aberrations encountered in electrostatic lenses, the most serious is spherical

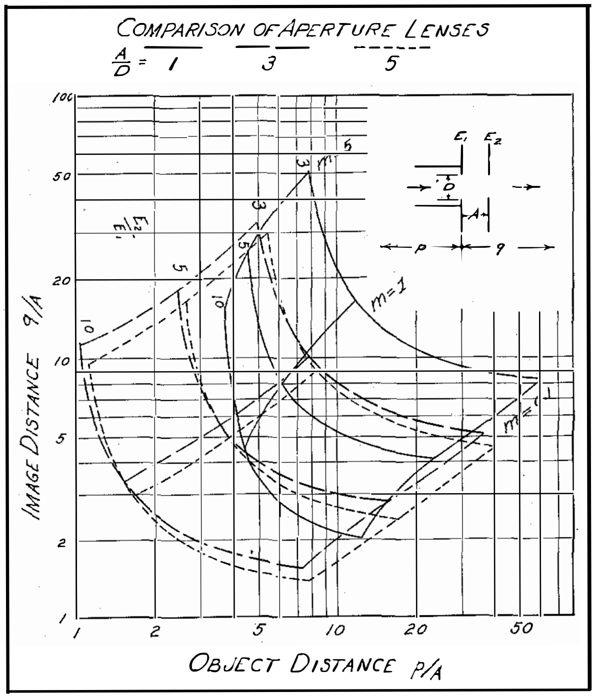

Fig. 7—Comparison of Aperture Lenses.

aberration. This is always present to some degree and is very difficult to reduce and nearly impossible to eliminate completely.

The screen patterns from which the focusing characteristics were obtained can also be used to determine the spherical aberration. The intersections of the grid-wire images tell how far from the axis any ray, starting off of the axis, will fall in the image. With this information it is possible to determine the spherical aberration by a graphical method. A ray diagram such as that shown in Fig. 4 can be drawn connecting points on the image with corresponding points of emergence at the lens. From this diagram it is possible to determine the variation in the focal point with the original radial distance of the rays. It is also possible to determine the minimum spot for any lens aperture.

III. Results

This paper is concerned primarily with methods and there will be given here only samples of the results as obtained by the methods described.

A. Optical Constants

The focusing characteristics of the lenses tested may be presented in what has become a conventional form. In this form the focal distances and the distances from a reference point in the lens to the focal points are plotted as a function of the voltage ratio. Such a representation is given in Fig. 5 in which the reference point is the cylinder junction. It is seen that the characteristics are readily obtained for an extremely wide range of voltage ratios, roughly 25 to 1.5, or about three times any previously reported.

B. Object-Image Distance Curves

The focal characteristics were also presented in a new form which is believed to have many advantages over the conventional representation. From (26) and (27) it is seen that at any given voltage ratio the object and image distances are parametric with magnification in terms of the focal distances. Since the focal distances themselves are quantities which are used in determining the answer to any lens problem but

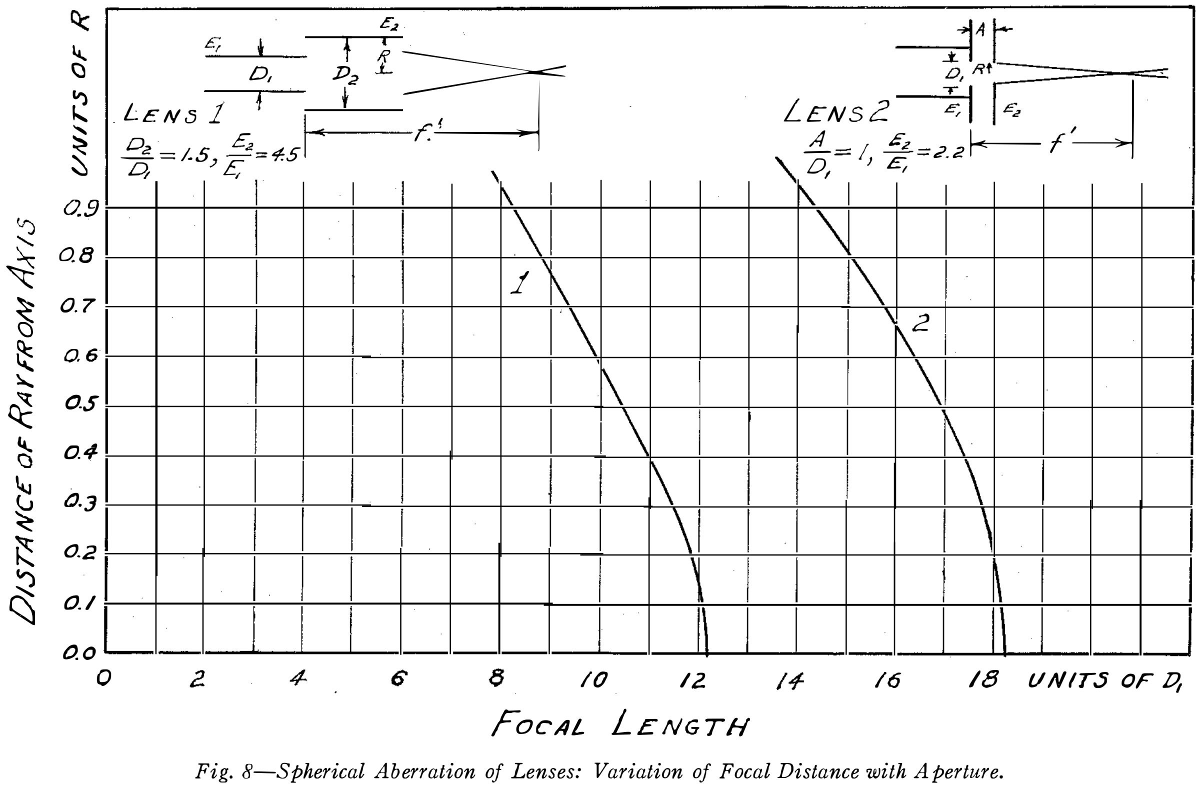

Fig. 8—Spherical Aberration of Lenses: Variation of Focal Distance with Aperture.

which do not appear in the answer it seems logical to seek a representation in which these quantities do not appear. Such a representation is shown in Fig. 6. This representation will be referred to as the object-image—distance curves of the lens. The curves give immediately the image distance corresponding to any object distance at a given voltage ratio and show also the corresponding magnification. Essentially this is a graphical representation of the solution of all possible problems associated with the lens.

The object-image—distance curves have several important merits. They give immediately quantitative relations between the controllable variables. They make possible a design procedure which is direct and does not depend upon any trial-and-error calculations. They show very clearly the effect of changes in voltage and physical structure. They reveal some universal lens properties which may not have been noted previously. They make possible a quick and comprehensive comparison of the characteristics of different lenses or of lenses of the same type with different dimensions. Such a comparison is shown in Fig. 7 which shows the effect of changing the ratio of aperture diameter to aperture spacing in an aperture lens. In this figure, object distance and image distance are measured from the first aperture, D is the aperture diameter, and A is the axial distance between apertures.

C. ABERRATION CHARACTERISTICS

Some typical aberration curves as determined graphically from the screen patterns are shown in Fig. 8. These show the decrease in focal distance as the ray separation from the axis is increased. Such curves are about the same for all lenses. These curves are nearly universal in that the reduction in focal distance is approximately a percentage function of the focal distance itself. A sample curve showing the spread of spot

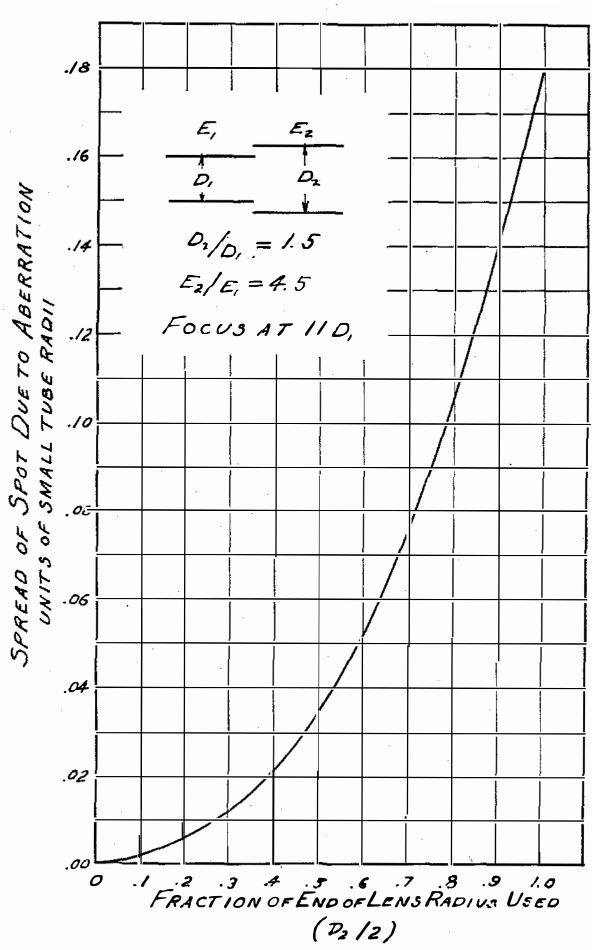

Fig. 9—Aberration Curve: Variation of Minimum Spot Size with Aperture.

produced by aberration is shown in Fig. 9. This is also nearly a universal curve.

IV. Conclusions

The methods proposed here are improvements on previously proposed methods from the standpoint of simplicity, ease of execution, and accuracy of results. The new representation of lens characteristics tells the whole story of the lens at a glance. The experimental method permits simultaneous determination of focal characteristics and aberration properties.

Telephone Statistics of the World[1]

COUNTRIES	Date of Statistics	NUMBER OF TELEPHONES			Telephones per 100 Population
		Government Systems	Private Companies	Total	
NORTH AMERICA:					
United States#	Jan. 1, 1941	—	21,928,182	21,928,182	16.56
Canada	"	222,580	1,238,458	1,461,038	12.78
Central America	"	15,249	20,360	35,609	0.41
Mexico	"	3,000*	175,726	178,726	0.89
West Indies—					
Cuba	"	891	67,592	68,483	1.57
Puerto Rico	"	531	17,456	17,987	0.95
Other Places in the West Indies	"	11,464	21,168	32,632	0.39
Other Places in North America	"	100	20,452	20,552	5.19
Total	"	253,815	23,489,394	23,743,209	12.66
SOUTH AMERICA:					
Argentina	Jan. 1, 1941	—	460,857	460,857	3.46
Bolivia	"	—	2,621	2,621	0.08
Brazil	"	1,291	289,619	290,910	0.65
Chile	"	—	90.943	90,943	1.81
Colombia	"	9,000*	33,233	42,233	0.46
Ecuador*	"	4,200	3,400	7,600	0.26
Paraguay	"	—	3,800	3,800	0.39
Perú	"	—	35,151	35,151	0.52
Uruguay	Jan. 1, 1939	34,810	11,846	46,656	2.20
Venezuela	Jan. 1, 1941	760	31,096	31,856	0.88
Other Places in South America	"	3,398	—	3,398	0.60
Total (Estimated as of Jan. 1, 1941)		60,000	965,000	1,025,000	1.11
EUROPE:					
Belgium	Jan. 1, 1940	428,752	—	428,752	5.11
Bulgaria	"	31,225	—	31,225	0.48
Denmark	"	17,813	441,944	459,757	11.95
Eire	Mar. 31, 1941	46,726	—	46,726	1.56
Finland	Jan. 1, 1940	8,837	177,736†	186,573	4.81
France	"	1,622,680	—	1,622,680	3.86
Germany (incl. Austria and Sudetenland)	June 30, 1939	4,226,504	—	4,226.504	5.28
Great Britain and No. Ireland	Mar. 31, 1941	3,348,000	—	3,348,000	7.00
Greece	Jan. 1, 1940	5,967	48,437	54,404	0.76
Hungary	"	178,325	790	179,115	1.76
Italy	Jan. 1, 1941	—	685,815	685,815	1.58
Netherlands	Jan. 1, 1940	461,424	—	461,424	5.23
Norway	June 30, 1939	153,000*	97,000*	250,000	8.52
Portugal	Jan. 1, 1941	21,000*	54,803	75,803	0.98
Roumania	"	92,107	—	92,107	0.51
Russia¶	Jan. 1, 1939	1,272,500	—	1,272,500	0.75
Spain	Jan. 1, 1941	—	336,448	336,448	1.31
Sweden	"	906,917	1,736	908,653	14.26
Switzerland	"	474,038	—	474,038	11.23
Yugoslavia	Jan. 1, 1940	72,000*	—	72,000	0.45
Other Places in Europe*	Jan. 1, 1941	550,000	130,000	680,000	1.20
Total (Estimated as of Jan. 1, 1941)		13,920,000	1,980,000	15,900,000	2.75
ASIA:					
British India	Mar. 31, 1939	31,878	51,500	83,378	0.02
China*	Jan. 1, 1941	40,000	120,000	160,000	0.04
Japan	Mar. 31, 1939	1,367,958	—	1,367,958	1.89
Other Places in Asia*	Jan. 1, 1941	220,000	108,000	328,000	0.16
Total (Estimated as of Jan. 1, 1941)		1,710,000	290,000	2,000,000	0.19
AFRICA:					
Egypt	Jan. 1, 1940	67,983	—	67,983	0.30
Union of South Africa	Mar. 31, 1941	232,885	—	232,885	2.21
Other Places in Africa*	Jan. 1, 1941	146,000	1,460	147,460	0.11
Total (Estimated as of Jan. 1, 1941)		450,000	1,460	451,460	0.27
OCEANIA:					
Australia	Jan. 1, 1941	704,868	—	704,868	9.97
Hawaii	"	—	41,568	41,568	9.64
Netherland Indies	Jan. 1, 1940	48,321	4,492	52,813	0.08
New Zealand	Mar. 31, 1941	228,346	—	228,346	13.96
Philippine Islands	Jan. 1, 1941	2,504	31,419	33,923	0.20
Other Places in Oceania*	"	5,300	380	5,680	0.25
Total (Estimated as of Jan. 1, 1941)		992,000	78,000	1,070,000	1.06
TOTAL WORLD (Estimated as of Jan. 1, 1941)		17,385,815	26,803,854	44,189,669§	2.02

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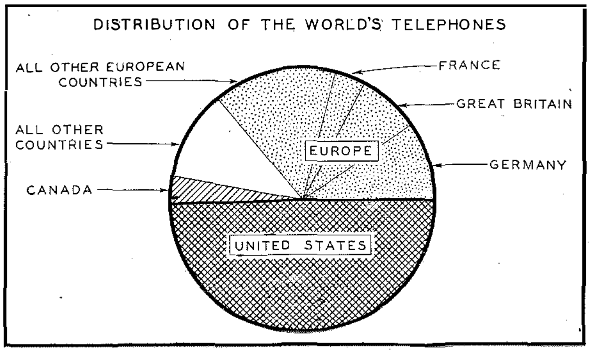
[1] Compiled by Chief Statistician's Division, American Telephone and Telegraph Company, and issued under the date April 1, 1942. "Owing to war conditions, official data for recent dates are not available for many countries. The statistics herein are the latest available from authentic sources."

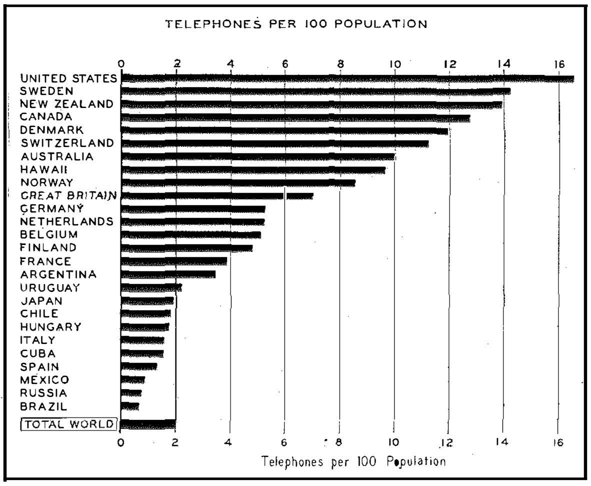
* Partly estimated. # As of January 1, 1942, there were 23,521,000 telephones in the United States.

† January 1, 1939. ¶ U.S.S.R., including Siberia and Associated Republics.

§ Approximately 58% of the total number of telephones in the world are estimated to be automatic or "dial" telephones, including, on January 1, 1941, some 11,700,000 "dial" telephones in the United States.

Telephone Statistics of the World—*continued*





Recent Telecommunications Developments

INTELIN HIGH TENSION APPLICATIONS.—Developments in the application of Styrene to high tension cables, such as described in previous issues of this journal,[1] are proving particularly important at the present time in view of the resulting saving in materials heretofore necessary for jointing and terminating cables. Such applications, offered in the U. S. A. under the trademark Intelin by the International Telephone and Radio Manufacturing Corporation, have permitted elimination of tin wiped joints for many services. Simultaneously, safeguards definitely prolonging the service life of cable installations have been provided.

In equipment potheads, the I.T. and R.M. is utilizing characteristics of the various styrenes to produce potheads about ⅓ the size and with about ⅓ the number of parts compared with previous types. Furthermore, the need for scarce non-ferrous metals and oil resistant gaskets is eliminated entirely; the amount of copper conductors required is reduced appreciably; and the pothead characteristics are improved. The importance of these applications will be evident when it is considered that electric power companies have over 20,000 miles of high tension cable serving the larger metropolitan centers in U. S. A. Industries, railroads and shipyards have about an equal amount.

Due to their initial lower cost and relative ease of effecting emergency repairs, overhead lines have been largely retained notwithstanding their considerably greater hazard and more numerous service interruptions. Underground installations, on the other hand, have not been entirely free from failures resulting in loss of power supply, sometimes for considerable periods. The greater safeguards provided by styrene applications will result in appreciable reductions in such outages and should accelerate the replacement of overhead lines by the less hazardous underground installations.

INTELIN HIGH FREQUENCY APPLICATIONS.—Intelin high frequency cables, recently developed, are capable of withstanding a temperature range from −30°C to + 85° C for prolonged periods without adversely affecting the cable, which remains flexible under these conditions. The Intelin insulation has a dielectric constant of 2.38 and a power factor at 100 megacycles of 0.0007. A minimum quantity of critical materials is required.

The cables are sheathed with a special plastic extruded covering resistant to oil, gasoline and water. Cables meeting a variety of service conditions can be produced.

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HIGH FREQUENCY MARINE TRANSMITTER, TYPE 167-A.—Following requirements specified by the Marine Division of the Mackay Radio and Telegraph Company, the Federal Telegraph Company has developed and is producing a new marine H.F. transmitter unique in the marine field. The frequency range is 2 to 24 mc with continuous coverage and micrometer adjustment in the oscillator control. While the transmitter is equipped for CW operation, it can be made available for both CW and MCW transmissions.

All controls are mounted on the front panel, thus enabling the operator to adjust the transmitter on any specified frequency within its range without recourse to any adjustments inside the cabinet. The circuit design is such that improper adjustment of the transmitter on any unwanted frequency harmonic is most unlikely. Hence choice of the proper frequency is positive and transmission on an erroneous frequency harmonic is practically impossible.

The transmitter is designed to operate on a voltage of 115 or 230 d-c and has an antenna power output of 200 watts on frequencies from 2 mc to 16 mc. The power output over the 16 mc to 24 mc range is in excess of 150 watts.

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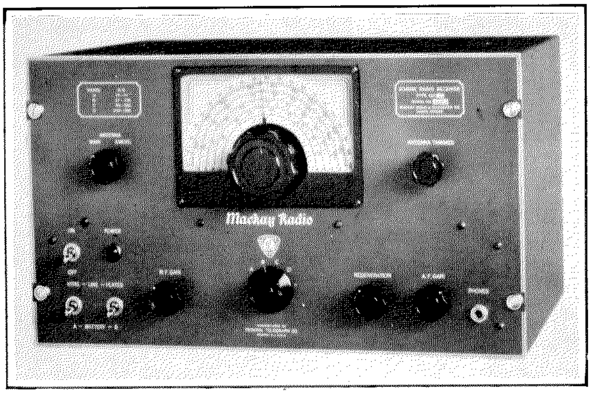
[1] "The Application of Styrene to H. T. Cable Systems," by T. R. Scott and J. K. Webb, *El. Com.*, Part I: Vol. 16, No. 2, 1937; Part II: Vol. 16, No. 3, 1937; Part III: Vol. 17, No. 1, 1938; Part IV: Vol. 19, No. 2, 1940; Vol. 19, No. 4, p. 141, 1941.

Combination Marine Receiver, Type 128-A.—The Federal Telegraph Company has developed and is manufacturing, in accordance with requirements specified by the Marine Division of the Mackay Radio and Telegraph Company, an IF–LF combination TRF marine receiver embodying some novel outstanding features. It employs the latest type of metal tubes and a circuit which is highly efficient and non-radiating. The frequency range is 15 kc to 650 kc and the dial is accurately calibrated in four separate bands with vernier adjustment.



A built-in power supply provides for plate voltage from either a-c or d-c 115 volt ship supply line. "B" batteries may be used instead, if desired. The standard receiver employs a 6 volt storage battery for the heaters of the tubes but operation of the heaters from an a-c line source can be provided on special order. On the front panel toggle switches provide for instantaneous changeover from the ship's supply line to auxiliary batteries. Consequently two requirements of the marine regulations are met in a single unit, i.e., a combined main and an emergency receiver.

A control knob mounted on the front of the panel provides for switching the receiver from the main to the emergency or auxiliary antenna.

Puerto Rico.—The Porto Rico Telephone Company, associate of the International Telephone and Telegraph Corporation, is meeting the greatly increased demand for service through the installation of additional telephone equipment in central offices and elsewhere and through the use of carrier systems designed to increase the capacity of long distance circuits with substantial savings in copper and other strategic materials. The San Juan-Santurce metropolitan area is being converted from manual to automatic operation to meet increased service demands and provide more adequate facilities.

The Radio Corporation of Porto Rico, another I.T. & T. associate, has converted its broadcasting station, WKAQ, from 1 kw operating on 1240 kc to 5 kw operating on 620 kc. The higher power and change of frequency have resulted in complete coverage of the island.

As a result of increased traffic on the radio link between San Juan and Miami, twin channel, single sideband, short wave radio equipment will be installed in San Juan, Puerto Rico, in 1942. This will give Puerto Rico two high grade commercial circuits working directly with New York, capable of handling greatly improved point-to-point transmissions of broadcast programs.

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New Mackay Radio Circuits.—The Honolulu-Chungking and SanFrancisco-Wellington radiotelegraph circuits, mentioned in the previous issue of this journal as under test, are now in operation. Other circuits recently inaugurated by the Mackay Radio and Telegraph Company are: New York-Honolulu; New York-Cairo; New York-Asuncion (Paraguay); San Francisco-Chungking; and San Francisco-Sydney/Melbourne.

INTERNATIONAL TELEPHONE AND TELEGRAPH CORPORATION

Associate Companies in the Western Hemisphere

UNITED STATES OF AMERICA

International Standard Electric Corporation: *Manufacturer and Supplier of Communication and Other Electrical Equipment Through Licensee Companies Throughout the World; Exporter of Communication and Other Electrical Equipment*.....New York, N. Y.

International Telephone & Radio Manufacturing Corporation: *Manufacturer of Communication and Other Electrical Equipment*........East Newark, N. J.

Federal Telegraph Company: *Manufacturer of Radio Equipment*..........................Newark, N. J.

Commercial Cable Company: *Trans-Atlantic Telegraph Service*.....................New York, N. Y.

Commercial Pacific Cable Company: *Trans-Pacific Telegraph Service*.................New York, N. Y.

Mackay Radio and Telegraph Company: *International and Ship-Shore Radio Telegraph Services; Supplies, Operates and Maintains Marine Communication and Navigational Equipment*........ New York, N. Y.

All America Cables and Radio, Inc.
All America Cables and Radio, Inc. maintains 67 Company-owned telegraph offices in 23 countries and islands throughout Central and South America and the West Indies..........................New York, N. Y.

The Cuban All America Cables, Inc.: *United States-Cuba Telegraph Service*............New York, N. Y.

ARGENTINA

*Compañía Standard Electric Argentina: *Manufacturer of Communication and Other Electrical Equipment* ....Buenos Aires

Compañía Internacional de Radio (Argentina): *Radio Telephone Service*..............Buenos Aires

Sociedad Anónima Radio Argentina: *Radio Telegraph Service* ....Buenos Aires

Compañía Telefónica Argentina: *Telephone Operating System*.........................Buenos Aires

Compañía Telegrafico-Telefónica Comercial: *Telephone Operating System*...............Buenos Aires

United River Plate Telephone Company, Limited: *Telephone Operating System*...........Buenos Aires

BOLIVIA

Compañía Internacional de Radio Boliviana: *Radio Telephone Service* ....La Paz

BRAZIL

*Standard Electrica, S. A.: *Manufacturer of Communication and Other Electrical Equipment*
Rio de Janeiro

Companhia Radio Internacional do Brasil: *Radio Telephone and Telegraph Services*.....Rio de Janeiro

Companhia Telefonica Paranaense, S. A.: *Telephone Operating System* ....Curityba

Companhia Telephonica Rio Grandense: *Telephone Operating System* ....Porto Alegre

CHILE

Compañía de Teléfonos de Chile: *Telephone Operating System* ....Santiago

Compañía Internacional de Radio, S. A. (Chile): *Radio Telephone and Telegraph Services*.....Santiago

CUBA

Cuban Telephone Company: *Telephone Operating System* ....Havana

Radio Corporation of Cuba: *Radio Telegraph Service*
Havana

MEXICO

Mexican Telephone and Telegraph Company: *Telephone Operating System*................Mexico City

PERU

Compañía Peruana de Teléfonos Limitada: *Telephone Operating System*.....................Lima

PUERTO RICO

Porto Rico Telephone Company: *Telephone Operating System*..............................San Juan

Radio Corporation of Porto Rico: *Radio Telephone Service and Radio Broadcasting*............San Juan

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Associate Companies in the British Empire

*Standard Telephones and Cables, Limited: *Manufacturer of Communication and Other Electrical Equipment* ....London, England
Branch Offices: Birmingham, Leeds, England; Glasgow, Scotland; Cairo, Egypt; Calcutta, India; Pretoria, South Africa.

*Creed and Company, Limited: *Manufacturer of Teleprinters and Other Communication Equipment*
Croydon, England

International Marine Radio Company, Limited: *Supplies, Operates and Maintains Marine Communication and Navigational Equipment*..Liverpool, England

*Kolster-Brandes Limited: *Manufacturer of Radio Equipment* ....Sidcup, England

*Standard Telephones and Cables Pty. Limited: *Manufacturer of Communication and Other Electrical Equipment* ....Sydney, Australia
Branch Offices: Melbourne, Australia; Wellington, N. Z.

*Licensee Manufacturing and Sales Company of the International Standard Electric Corporation, New York, N. Y.