No. 164

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The London-Birmingham Coaxial Cable System

A. H. MUMFORD, B.Sc. (Eng.), A.M.I.E.E.

Reprinted from articles published in Volumes 30 and 31 of The Post Office Electrical Engineers' Journal

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Part. I.—Description of the System

Introduction.

THE recent advent of high definition television has presented communication engineering organisations with the problem of providing land lines capable of transmitting television programmes to different parts of the country. The problem consists essentially in developing a transmission system capable of handling a band of frequencies ranging up to 2 megacycles per second or more, with negligible attenuation and distortion. Once the necessity for such a system arises it becomes immediately apparent that, in view of recent achievements of communication engineering research, the system might well be applied to multi-channel carrier telephone working; whether or not such an application is desirable becomes a matter which must be settled finally by various economic considerations.

The practicability of constructing such a system had been studied by the Bell Telephone Laboratories of the American Telephone and Telegraph Company for some years when, in 1934, Espenschied and Strieby[1] described their wideband system, in which the "go" and "return" lines each comprised a single concentric or coaxial pair. Stated briefly, the system utilised the range of frequencies from 60 kc.p.s. to 1,020 kc.p.s. for the transmission of 240 circuits, channels being evenly spaced throughout this range at intervals of 4 kc.p.s. The coaxial lines had an internal diameter of approximately ½ inch, amplification by means of repeaters of the negative feed-back type being provided at intervals of 10 miles. The influence of radio technique on the design is seen particularly in the channel filters in which the piezo-electric coupling between the electrical and mechanical oscillations of quartz crystal plates was used to provide the equivalent of inductive reactances with much lower losses than could be obtained by the use of inductance coils. The equivalent circuit of a vibrating crystal plate involves capacitors as well as inductors and the manner in which these are associated made it necessary to develop a special technique of filter design. More recently a description of the experimental system installed between New York and Philadelphia has appeared.[2]

The mathematics of the transmission of alternating currents over a concentric system of conductors was fully worked out by Russell in 1909 but it is only in the last few years that this arrangement of conductors has come into prominence as a high frequency transmission line, although concentric lines have been in use for a number of years as feeders for short wave radio aerial systems. For reasonable cost in transport and installation as underground lines, it is necessary that such cables shall be flexible enough to permit of being wound on to drums like present type telephone cables. Flexibility has been attained in certain designs by forming the outer conductor of specially shaped overlapping ribbons of copper laid up together in a spiral to form a tube, the inner wire being positioned with respect to the outer conductor by means of a cotton rope.

A similar construction can be used for a shielded pair line which can be regarded as having two conductors instead of a single central wire, the outer tubular conductor of the coaxial line now performing only the functions of an electrostatic and electromagnetic screen. The advantage of the shielded pair line at low frequencies is unquestionable but larger overall dimensions for an equal attenuation, as compared with a co-axial line, are necessary.

The freedom of a coaxial line from crosstalk and the effects of external disturbances at high frequencies is due to the screening effect of the outer conductor but at the lower frequencies, say below 100 kc.p.s., its efficiency as a screen falls off rapidly and at voice frequencies the unbalanced nature of the circuit renders it unsuitable for the transmission of telephone currents. This is not of importance where a wideband system is required for the transmission of a large number of telephone conversations, but it renders this type of line unsuitable for the transmission of television signal currents unless these are first modulated to bring them into an appropriate range of frequencies.

At the present time the maximum gain for which it is practicable to design a negative feedback repeater is dependent upon the highest frequency to be transmitted and upon the ratio of the highest to the lowest frequency to be transmitted. Broadly an increase in either of these factors involves a decrease in the other, if the maximum gain for which it is practicable to design is not to be reduced. Since this necessitates the incoming signals being modulated to bring them into an appropriate range of high frequencies, the lower attenuation of the coaxial line becomes an attractive proposition and hence this type of cable has been adopted in this country for transmission over relatively long distances.

It was realised about 1934 that the transmission of television programmes over land lines for simultaneous transmissions from television broadcasting stations would be required in this country before many years had elapsed. This alone might have been deemed sufficient justification for proceeding but the inherent possibilities of cheapening the cost of long distance

[1] L. Espenchied and M. E. Strieby: "Systems for Wide-band Transmission over Coaxial Lines." *Electrical Engineering*, 1934. Vol. 53, p. 1371.

[2] M. E. Strieby: "A Million-Cycle Telephone System." *Electrical Engineering*, 1937. Vol. 56. p. 1.

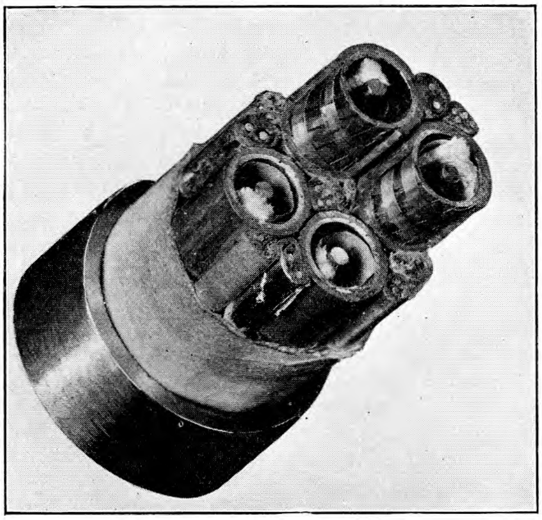
circuits with such a system was an important consideration. It was decided, therefore, to conduct an experiment with a view to determining the technical and economic advantages associated with the use of multi-channel carrier telephony over an extended frequency range collaterally with the provision of television circuits between London and Birmingham. The greater urgency for short distance television circuits and the urgent necessity for the provision of telephone circuits between London and Birmingham and beyond has led to the concentration of effort chiefly on the telephone aspect of the project.

Previous articles in the Journal have dealt with the principles of wide-band carrier telephony[3] and the factors determining the design of the cable itself[4]. The present article describes the London-Birmingham experiment in greater detail and will be followed by other articles detailing the equipment supplied and giving test results.

The System.

The London-Birmingham cable includes four coaxial pairs, two of which were included for television transmission and the other two for telephony. For telephony one pair is used for each direction of transmission, the same frequency band being employed in each cable. Each pair is designed to have an attenuation not exceeding 6·4 db. per mile at a frequency of 2·1 Mc.p.s. The centre conductor consists of a solid copper wire, 0·125 in. diameter, and the outer conductor of twelve specially shaped interlocking copper tapes, giving a radial thickness of 30 mils to the self-supporting tube so formed; the inner diameter of the outer conductor is 0·45 in. The inner conductor is positioned in the centre of the tube by means of cotopa cords. The outer conductor is bound by thin brass tapes and a thin lead sheath extruded directly on to the brass binding. The inclusion of a lead sheath over each of the coaxial cores increases the ease of handling the cores in the subsequent manufacturing operations and during installation. It also has advantages in the event of penetration of the outer sheath by moisture. Experience has shown that this type of coaxial pair with its self supporting outer conductor of many segments can be wound on drums of normal size and then laid without any distortion reacting upon its transmission qualities. The centre space and the interstices between the four coaxial cores are occupied by six 25-lb. conductor star quads and four 40-lb. conductor screened pairs. The make-up of the cable is illustrated in Fig. **1**.

The installation of the cable between London and Birmingham—a total route length of 125 miles—has been completed. The attenuation-frequency and crosstalk-frequency characteristics of a typical repeater section are given in Figs. **2** and **3**. It will be seen that the maximum gain required is of the order of 50 db. and that the component of attenuation due to dielectric loss amounts to about 20 per cent. of the total loss. In later designs even this low figure has been considerably reduced. The extension of the cable towards Manchester is now in progress.



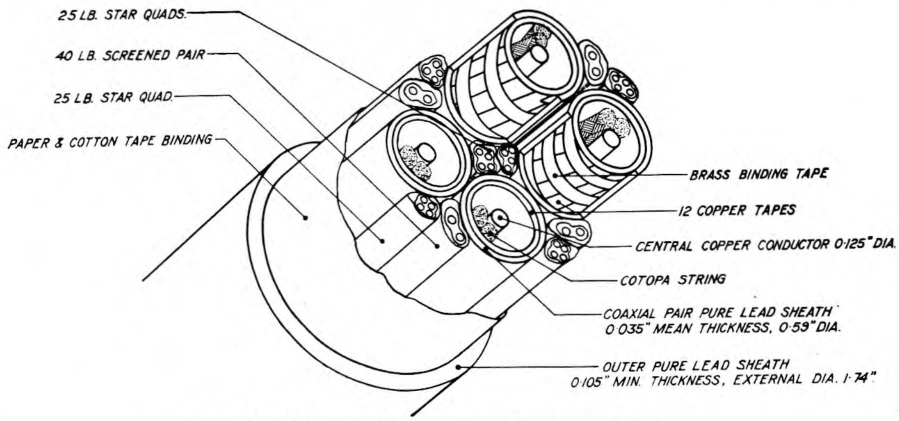


Fig. **1**.—London-Birmingham Coaxial Cable.

[3] *P.O.E.E.J.*, Vol. 29, p. 329.
[4] *P.O.E.E.J.*, Vol. 30, p. 138.

Selection of Frequency Band.

When this experiment was begun early in 1935, 1·4 Mc.p.s. was the highest frequency that had been used successfully in the modulation of a television transmitter. The width of the frequency band to be provided for the transmission of television signals was, therefore, fixed tentatively at a value slightly above 1·4 Mc.p.s., namely 1·6 Mc.p.s.; the possibility that it might be desirable to extend this band at some future date has not been overlooked.

The width of the frequency band having been fixed it remained to locate the band in the frequency

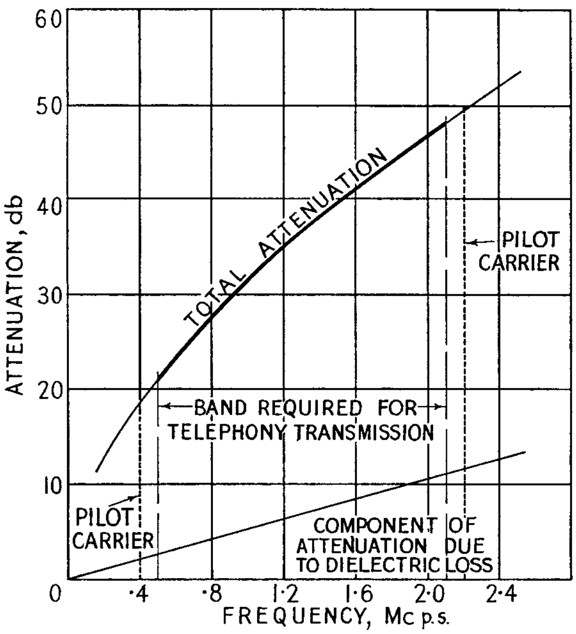


FIG. 2.—ATTENUATION/FREQUENCY CHARACTERISTIC FOR TYPICAL REPEATER SECTION, 7·5 MILES.

spectrum. Consideration of cable attenuation obviously made it desirable to utilise the lowest possible frequencies; on the other hand the difficulty of designing suitable equipment increases rapidly as the ratio of the upper frequency limit of the band to the lower limit increases. Preliminary experiments indicated that, initially, it would be inadvisable to use a frequency ratio much in excess of 4. The 1·6 Mc.p.s. band was therefore located between the limits of 0·5 and 2·1 Mc.p.s.

Frequency Separation between Channels.

It was decided to proceed with the design of telephone terminal equipment on the basis of providing circuits spaced at 5 kc.p.s. intervals and to reduce the the spacing to 4 kc.p.s. if this were found to be expedient when the performance of the first part of the installation had been ascertained. The scheme chosen enables the reduced spacing to be adopted with only minor changes in detail. Since the effective

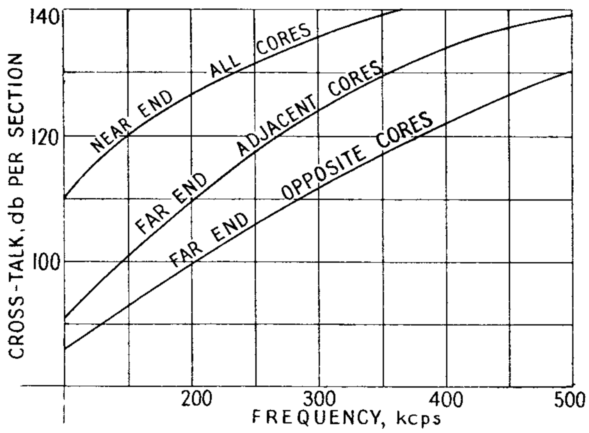


FIG. 3—CROSSTALK/FREQUENCY CURVES FOR TYPICAL REPEATER SECTION (6·1 MILES).

transmission band extends from 0.5 to 2.1 Mc.p.s. it is hoped that some 320 to 400 channels will be provided on each coaxial pair.

The frequency band for each audio frequency circuit over which transmission was to be substantially uniform was fixed tentatively at 2,700 c.p.s., although it was felt that at least 3,000 c.p.s. was desirable in view of future developments. It is anticipated that even with the closer spacing of 4 kc.p.s. uniform transmission up to some 3,200 c.p.s. will be effected. See Fig. 4.

The Modulation Process.

Since it is impracticable to modulate directly up to the frequencies actually to be transmitted over the cable, the modulation process must be carried out in several stages. In the present system three stages of modulation have been adopted. Fig. 5 and Table I illustrate the frequency spectra appropriate to the modulation process when 5 kc.p.s. spacing is employed together with the changes involved in an alteration of the spacing to 4 kc.p.s. The adoption of the

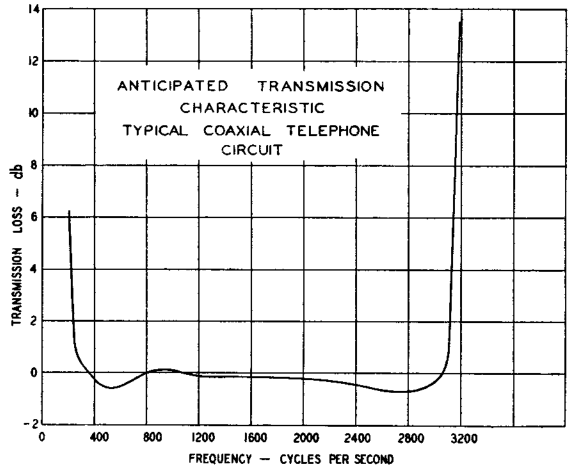


FIG. 4.—ANTICIPATED CHARACTERISTIC OF TYPICAL TELEPHONE CIRCUIT.

reduced frequency spacing of 4 kc.p.s. would increase the number of channels in each group from 8 to 10, the band occupied by a group and the arrangement of groups and super-groups remaining unchanged.

The first stage of modulation, using 5 kc.p.s. spacing locates the speech bands between 60 and 100 kc.p.s., eight channels completely filling the band. The groups of eight channels so formed are used to modulate carrier frequencies in group modulators which locate these groups between 300 and 500 kc.p.s. Five groups completely fill the band and form a "super-group" comprising 40 channels. These super-groups are translated to the appropriate portions of the frequency band which the amplifiers have been designed to handle, by means of a final stage of modulation, eight super-groups occupying the whole of the band.

An inverse process is followed in demodulation. Fig. 6, which is self-explanatory, shows diagrammatically the method by which any desired channel is selected from a multitude of incoming channels.

TABLE I

FREQUENCY ALLOCATIONS

Frequency spacing of channels	5 kc.p.s.			4 kc.p.s.		
Channel No.	Channel Frequency Band kc.p.s.	Channel Carrier Frequency kc.p.s.	Channels occupying frequency band kc.p.s.	Channel Frequency Band kc.p.s.	Channel Carrier Frequency kc.p.s.	Channels occupying frequency band kc.p.s.
1	60-65	65	60-100	60-64	64	60-100
2	65-70	70		64-68	68	
3	70-75	75		68-72	72	
4	75-80	80		72-76	76	
5	80-85	85		76-80	80	
6	85-90	90		80-84	84	
7	90-95	95		84-88	88	
8	95-100	100		88-92	92	
9	—	—	—	92-96	96	
10	—	—	—	96-100	100	
Channel carrier frequency multiple of	5 kc.p.s.			4 kc.p.s.		

Group No.	Group Frequency Band kc.p.s.	Group Carrier Frequency kc.p.s.	Groups occupying frequency band kc.p.s.
1	300-340	400	300-500
2	340-380	440	
3	380-420	480	
4	420-460	520	
5	460-500	560	
Group carrier frequency multiple of	40 kc.p.s.		

Super-Group No.	Super-Group Frequency Band kc.p.s.	Super-Group Carrier frequency kc.p.s.	Super-Group occupying frequency band kc.p.s.
1	500-700	1,000	500-2,100
2	700-900	1,200	
3	900-1,100	1,400	
4	1,100-1,300	1,600	
5	1,300-1,500	1,800	
6	1,500-1,700	2,000	
7	1,700-1,900	2,200	
8	1,900-2,100	2,400	
Super Group carrier frequency multiple of	200 kc.p.s.		

No. of telephone channels available	320	400
Brief description of system	8/5/8 (5 kc.p.s.)	10/5/8 (4 kc.p.s.)

The discrimination required for the selection of a single sideband from the products resulting from any modulation step is far higher in the lower frequency than higher frequency stages. Thus crystal filters have been adopted in the initial modulation and final demodulation stage in order that the high selectivity and uniformity of response in the pass band characteristic of this type of filter, may be utilised. Subsequent stages use filters of the more normal type employing inductors and capacitors only.

Fig. 7 is a block schematic to illustrate the assembly of channels, groups and supergroups at a terminal station. For simplicity, only one super-group is shown in complete detail, the additional equipment for further super-groups being indicated to a limited extent.

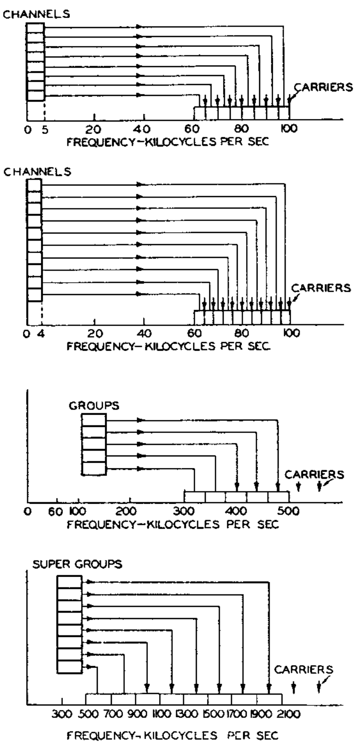


FIG. 5—FREQUENCY ALLOCATION OF SYSTEM.

Stability of Carrier Supply.

The application of carrier telephony to such high frequencies as those involved in the system being described, demands an extremely high degree of frequency stability and accuracy of synchronisation of the carrier suppliers at each end of the system. The frequency of the carrier reintroduced in the receiving demodulator may be permitted to differ from that suppressed at the transmitting end of the circuit by as much as 20 c.p.s. without reducing the intelligibility of the demodulated speech materially although not without some loss of naturalness. On the other hand, the requirements for voice frequency telegraphs and for music, which might well be transmitted by merging two or more adjacent channels to provide a sufficiently wide frequency band, are very much more stringent, and make it necessary to reduce the frequency difference to the order of one c.p.s. This implies a difference of less than one part in two million between the corresponding carrier frequencies generated at each end of the system.

In view of these stringent requirements the carrier generating equipment has been designed in such a way that all frequencies required at the two ends of the system are derived from a common source by processes of frequency division and multiplication. The master control consists of a crystal controlled oscillator of high frequency stability which is located at one of the terminal stations, the necessary link to the other terminal being provided by means of a pilot frequency transmitted over the line. The frequency of the master oscillator and the pilot have a common value of 400 kc.p.s., a multiple of both 4 and 5 kc.p.s. so that the carrier supplies for 4 or 5 kc.p.s.

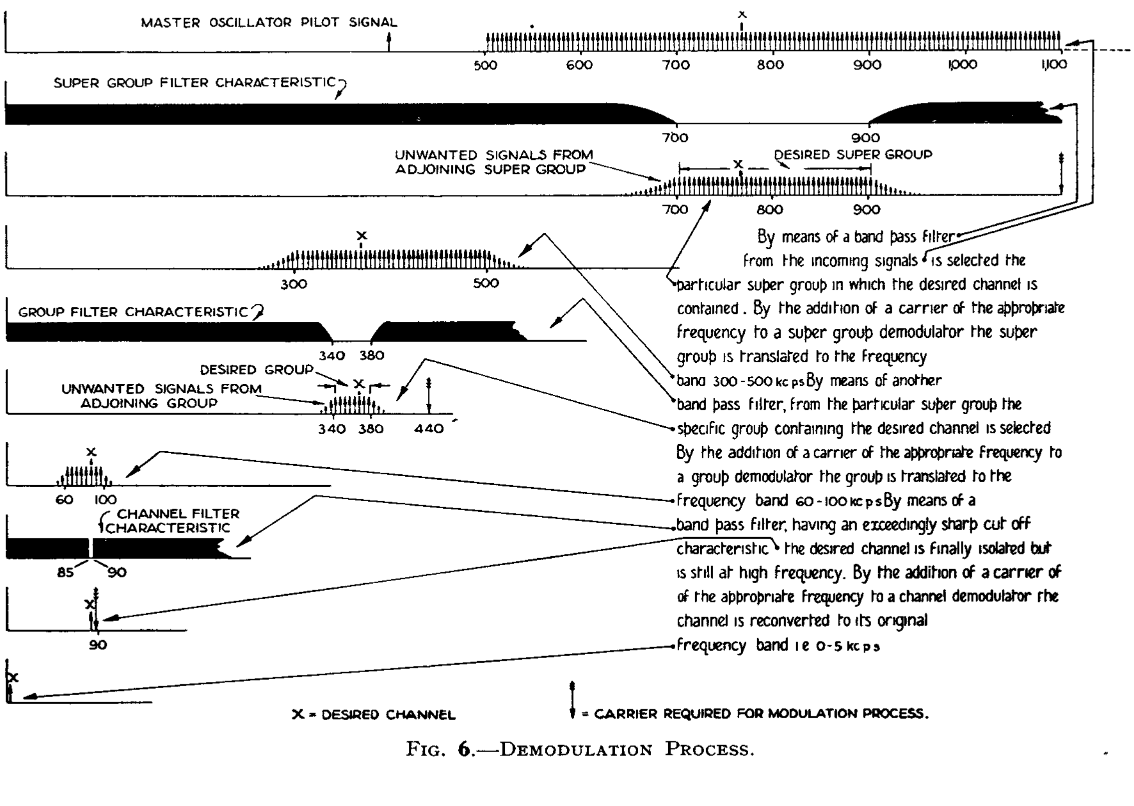


FIG. 6.—DEMODULATION PROCESS.

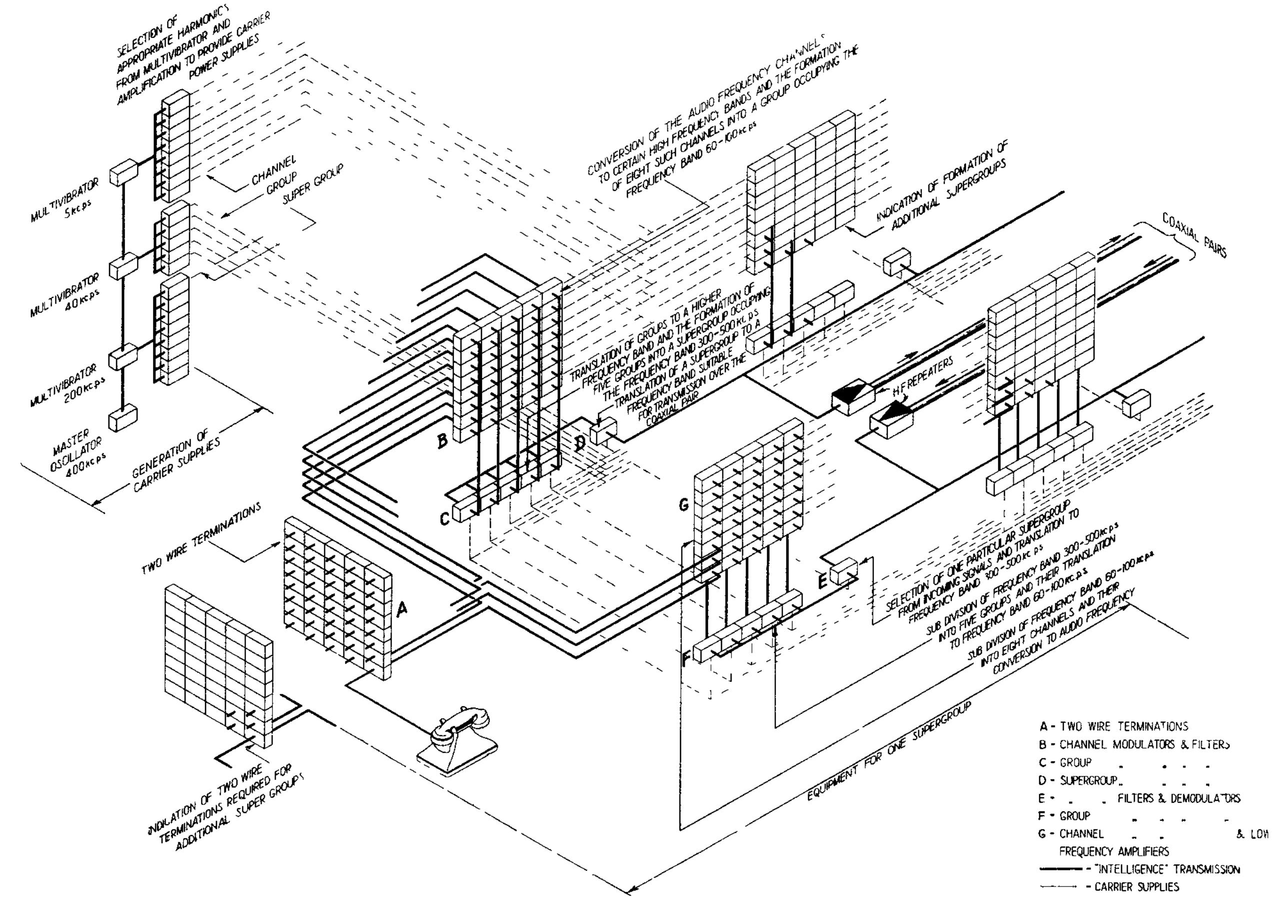


FIG. 7.—SCHEMATIC DIAGRAM OF TERMINAL EQUIPMENT REQUIRED FOR COAXIAL SYSTEM, NEGLECTING POWER EQUIPMENT.

spacing may be derived from the master oscillator without alteration in frequency.

The production equipment at each terminal employs three synchronised multi-vibrators, operating on the fundamental frequencies of 200, 40 and 5 kc.p.s. respectively, from which the three harmonic series corresponding to the super-group, group and channel carriers may be formed. See Table I.

Spacing of Repeater Stations.

The shielding afforded by the outer conductor of the coaxial pair at frequencies above 500 kc.p.s., the lowest frequency used for telephone transmission, is of such a high order that crosstalk and interference from outside sources or between coaxial pairs is negligible. Thus, in this system crosstalk and external disturbance do not limit the level to which the speech currents may be allowed to drop as they do in the normal trunk cable system. Since crosstalk and interference are negligible in the present system thermal agitation noise developed in the cable and valve noise become the factors limiting the drop in speech level that can be tolerated. The thermal agitation noise is strictly amenable to calculation and is a fundamental limitation constituting a constant irreducible noise level at the input of each repeater. In considering the overall noise level for a complete system it must be remembered that the noise introduced in the various repeater sections is additive; the signal-to-noise ratio at the end of a long circuit will therefore be less than it is at the end of the first repeater section.

It is obviously desirable to ensure in the design of the repeater that the intermodulation interference caused by the output signal level—the minimum value of which is fixed by the fundamental limitation detailed above—is appreciably lower than the total resistance and valve noise. It was estimated that the minimum level to which the signals could be permitted to fall, while giving the normal grade of service on circuits up to 400 miles in length, was 60 db. below the corresponding level at entry to the circuit. Making due allowance for future developments of television technique which might require the transmission of a wider band than 1.6 Mc.p.s., and such increased requirements are already being actively discussed, it was decided to limit the attenuation of repeater sections at 2.1 Mc.p.s. to 50 db.

The design of cable adopted has resulted in a permissible maximum repeater spacing of 7.9 miles, the actual lengths varying from 6 to 7.9 miles. The route layout is shown in Fig. 8.

Power Supply to Repeater Stations.

The coaxial tube forms a useful means of transmitting a 50 c.p.s. power supply, and in the present scheme power is fed over the coaxial conductors from selected repeater stations. In general, these

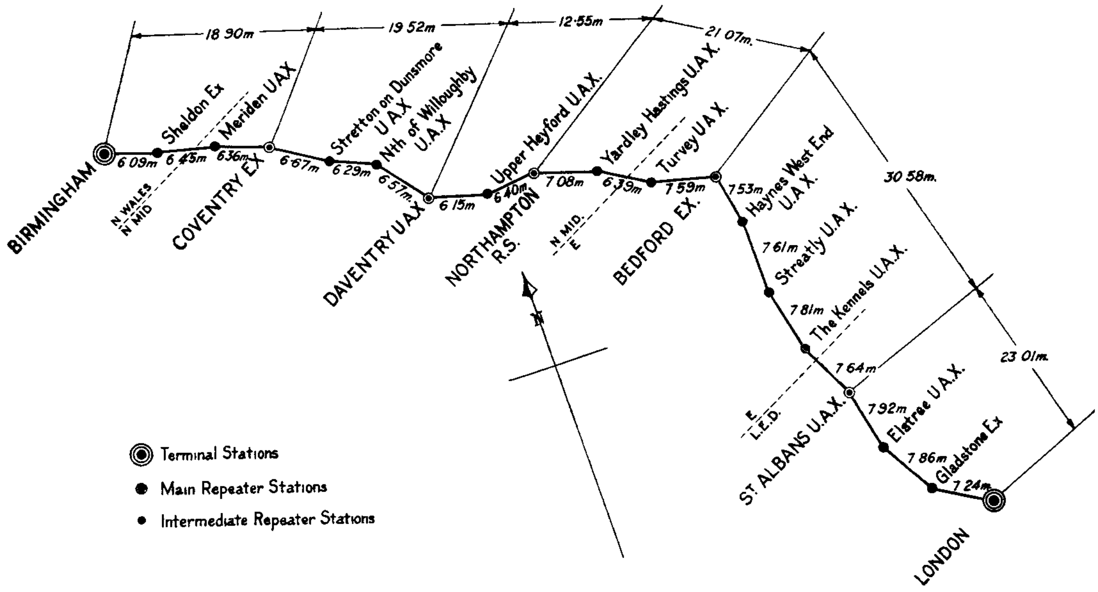


FIG. 8.—LONDON-BIRMINGHAM COAXIAL CABLE ROUTE.

main stations feed one repeater station on either side, the main power feeding points and the intermediate stations which receive power along the coaxial tubes being shown in Fig. 8. It has been possible by this means to reduce the number of supply sources to seven with a consequent reduction in the possible number of power supply failures due to external causes, the reliability of the power supply to the repeater stations being of fundamental importance. Automatic standby power equipment available for immediate operation is being tried at the main repeater station at Northampton. If found necessary similar standby equipment will be provided at the other main stations. The transmitting voltage on this scheme has been reduced to as low a value as is consistent with maintaining the regulation within reasonable limits. A voltage of 350 has been adopted, and with this the factor of safety against breakdown of the cable, which was tested to 2,000 volts in the factory, should be adequate. The power

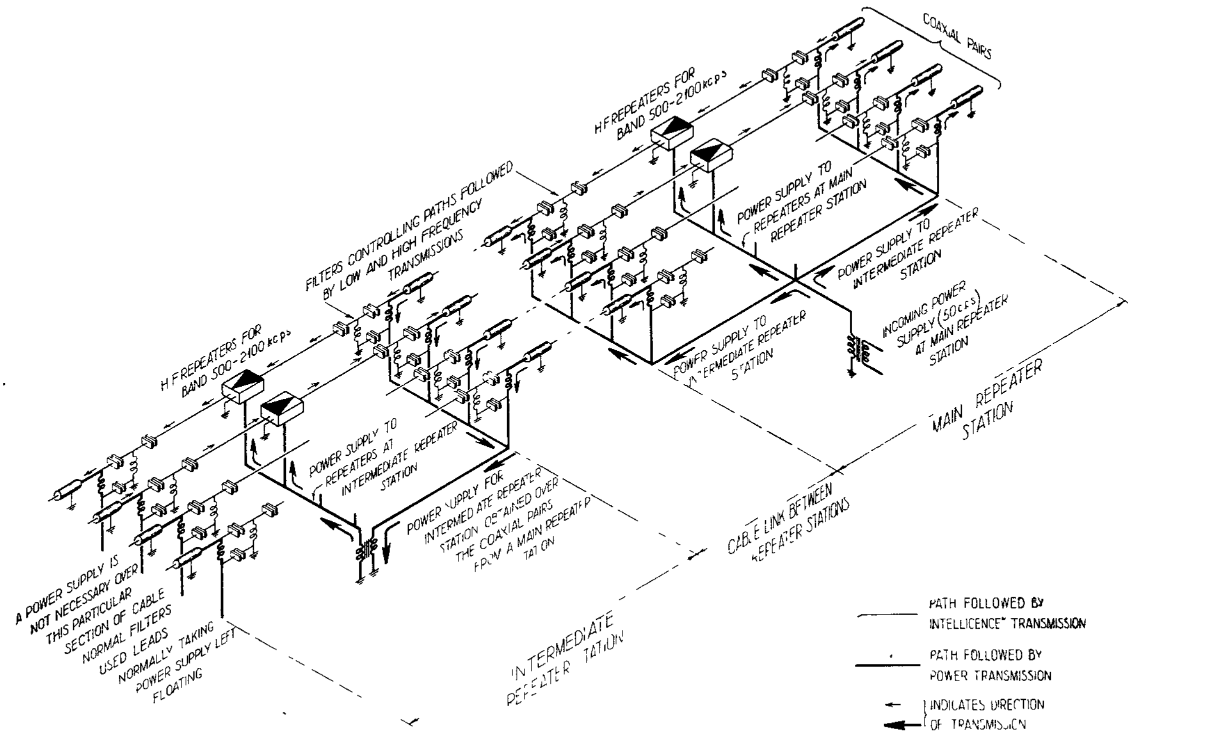


FIG. 9.—SCHEMATIC DIAGRAM ILLUSTRATING SIMULTANEOUS POWER AND INTELLIGENCE TRANSMISSION OVER THE COAXIAL PAIRS.

supply at every main repeater station is stepped up to 350 volts, and all power equipment is designed to operate from 280-350 volts.

For the purpose of power transmission the four coaxial tubes are connected, electrically in parallel, at power supply frequencies by means of low-pass filters teed together. The high frequency signals are bypassed by means of high-pass filters. The arrangements necessary at a typical main and intermediate repeater station are shown in the block schematic Fig. 9. The high-pass filter has to attenuate the 350 volt 50 cycle voltage so that the power frequency voltage on the grid of the first valve in the repeater produces negligible intermodulation with the H.F. signal channels. The half section, low-pass filter is necessary to prevent crosstalk at high frequencies via any impedance in the power supply and the connections between two coaxial tubes carrying signals at a level difference of up to 60 db., i.e., a crosstalk attenuation of at least 130 db. is required. In addition the low-pass filter has to carry a power current of 2 amperes without undue heating.

Unnecessary transmission of power for lighting, inspection, etc., over the coaxial cables is avoided by having a local power supply brought in to all the intermediate stations.

The High Frequency Repeater.

The possibility of transmitting hundreds of channels through a single output valve operated at a comparatively low anode voltage is perhaps one of the most surprising developments connected with the advent of wide-band systems of telephony. The effective amplitude of speech currents of a single conversation varies widely from moment to moment, and if a few conversations only are handled together in an amplifier it is necessary to provide for instantaneous peak values in an appreciable proportion of conversations coinciding at frequent intervals. When, however, the number of conversations is greatly increased the proportion of these in which simultaneous peak values will occur sufficiently frequently to have a practical bearing on design will be very greatly reduced. In an amplifier handling hundreds of conversations the power will not be greatly in excess of the average power handled by the repeater when all circuits are busy.

The use of negative feed-back repeaters theoretically permits harmonic production to be reduced to any desired value, provided there is sufficient inherent gain to allow of the consequent reduction in gain by feed-back. The realisation of a constant high stage gain over the frequency band concerned requires a valve having a very high value of the parameter (mutual conductance)/(input + output capacitance). It might be stated here that the application of negative feed-back to a high gain amplifier working at these frequencies presents a very definite problem as in order to obtain even a relatively low stage gain the phase shift through the couplings is considerable. Small interwiring capacitances and lead inductance, which can be neglected at lower frequencies, are of paramount importance. The gain of the repeater at 2.2 Mc.p.s. must be 53 db. to provide for the longest repeater section. This does not allow for any additional losses such as that due to internal cabling, or basic loss of the equaliser.

Provision of Spare Repeater Equipment.

For each direction of transmission between London and Birmingham nineteen 4-stage repeaters have to be traversed. For the complete system, therefore, a total of 152 valves are employed on the cable, the failure of any one of which would affect all the circuits. As most of the repeaters are installed in unattended repeater stations, steps have been taken to secure immediate continuity of service in the event of the failure of a valve or other component in the repeater. A spare repeater is provided for each main repeater, the spare being automatically switched in if the main repeater fails.

Equalisation of Attenuation-frequency Characteristic of the Cable.

As mentioned in an earlier section, the level to which the high frequency signals can be allowed to fall is set by resistance and valve noise. If the frequencies corresponding to all the channels are transmitted to line at the same level, only the channel highest in frequency could fall to the prescribed limit since the attenuation of the line would be progressively less for other channels. If the output level of each channel is such that after traversing a repeater section the levels of all channels have fallen to the same point, that is by pre-equalisation, the average power handled by the repeater can be materially reduced without passing the restriction set by noise. For this reason, pre-equalisation has been adopted in the present system.

Compensation of Variation of Cable Attenuation due to Temperature Changes.

Although the cable is laid in buried ducts throughout the route, an appreciable annual temperature cycle is present. Measurements made on cables along the same route indicated that this cycle would be somewhat as shown in Fig. 10; recorded temperature

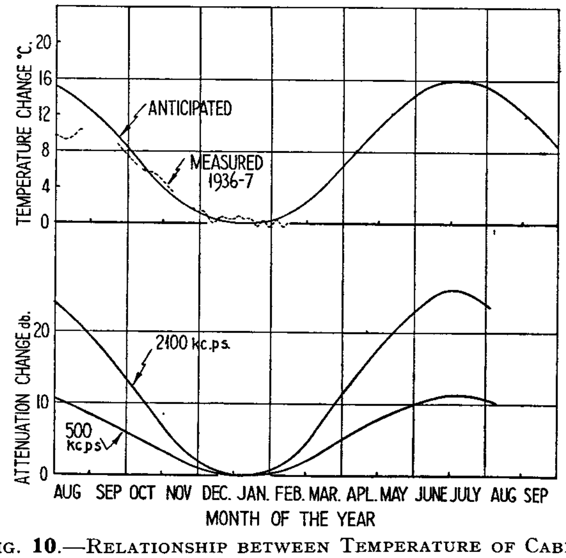


FIG. 10.—RELATIONSHIP BETWEEN TEMPERATURE OF CABLE AND THE TIME OF YEAR, SHOWING ALSO THE CORRESPONDING CHANGE IN ATTENUATION.

measurements made on a typical repeater section during the past few months are superimposed on the diagram. The possible maximum temperature variation limits assumed for design purposes are:—Daily 1°C, Weekly 4°C, Monthly 8°C and Yearly 20°C. The total attenuation of the cable between London and Birmingham at 2.1 Mc.p.s. is approximately 800 db., a value which will be subject to an annual variation of about 30 db. due to these temperature changes. At 0.4 Mc.p.s. the corresponding loss is approximately 340 db, subject to a variation of about 12 db. The difference between the values of loss at the two edges of the band amounts therefore to some 460 db., and in this figure also the annual variations are considerable.

The extremely high cable losses necessitate correspondingly high values of repeater gain and equalisation. The latter quantities have to be balanced against the cable loss with the utmost precision since, for satisfactory operation, it is desirable that the overall transmission loss of cable, repeaters and equalisers, shall be maintained within +2 db. of zero.

Maintenance Control.

Certain of the stations have been termed main repeater stations, and at such stations it is anticipated that staff will always be available to give attention to the cable and equipment under fault conditions. The remaining stations have been termed intermediate repeater stations and their control and maintenance is effected from the main stations. The main control of the system is vested in London and Birmingham and by giving appropriate signals these stations can get in touch, over separate L.F. speaker circuits, with the staff at the main stations and give maintenance instructions for that station and its particular satellites.

The occurrence and location of various failures at both main and intermediate repeater stations is immediately made known at the terminal stations by means of a fault indicating system.

Part II.—Description of the Repeaters and Terminal Equipment

TERMINAL STATION MODULATING EQUIPMENT

THE modulating equipment includes all the apparatus connected directly in the paths between the 2-wire audio frequency circuits and the repeaters terminating the coaxial pairs, together with certain other apparatus it has been found convenient to associate therewith. The functions of the modulating equipment having been outlined already in the general discussion of the system, it is possible to proceed directly to a technical description of the equipment itself.

R.T.P.,[1] the scatter being such that less than 1 per cent. exceeds zero level. The modulating equipment has, therefore, been designed to handle input levels on the 2-wire side up to R.T.P. without introducing appreciable distortion and crosstalk and, unless the contrary is stated, levels at various points in the system will be given in terms of the level due to a single circuit experiencing an input on the 2-wire side of R.T.P. The level at various points in the circuit, and the transmission equivalent of the various units are given in the block schematic shown in

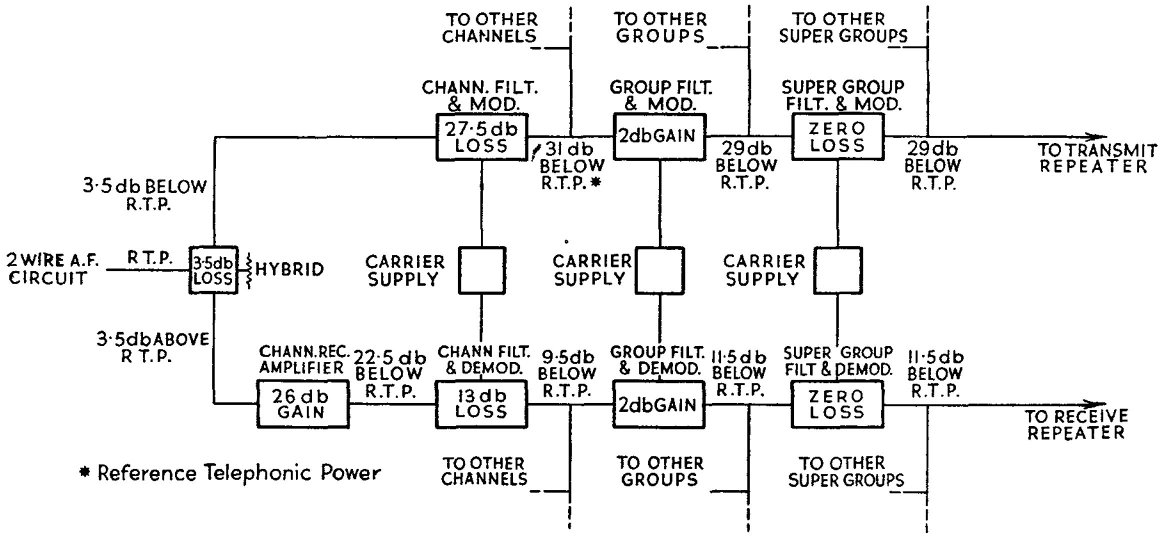


FIG. 11.—BLOCK DIAGRAM OF TERMINAL EQUIPMENT.

The transmission equivalents of the various parts of the circuit are governed by the following factors :—

The coaxial pairs, their repeaters and equalisers together provide transmission paths having 5 db. loss at all frequencies from 500 to 2,100 kc.p.s. The combined gain of the modulating equipment at the two ends must therefore be 5 db. for every circuit in order that the 2-wire to 2-wire loss of the overall circuits provided by the system shall be substantially zero. In practice this is realised by designing the various units in the modulating equipment so that the transmission equivalent for each circuit shall be approximately the same initially, and providing for an individual adjustment of gain in the receive leg of each circuit so that the zero loss condition may be satisfied as closely as possible.

The incoming levels of speech from various subscribers at the terminals of a trunk circuit are distributed about a mean value of 14 db. below

Fig. 11, which indicates the apparatus used at one terminal station in setting up a single circuit.

It will be appreciated that the majority of the equipment involved in the provision of the coaxial carrier telephone system is common to groups of 8, 40 or 320 circuits depending upon the part of the system in which it is located. There is, however, a considerable portion of the modulating equipment which has to be multipled directly in proportion to the number of circuits provided. The 2-wire terminations, channel receive amplifiers, channel modulators and demodulators and channel filters comprise the latter class. Economic factors, therefore, weigh much more heavily in the design of these particular units than they do for the rest of the equipment.

The various parts of the modulating equipment will now be described in greater detail.

[1]Reference Telephonic Power

Two-Wire Terminations.

The 2-wire terminations employed for converting the 2-wire audio frequency circuits into 4-wire circuits are of some interest in that they are considerably smaller than those hitherto employed in trunk working. Two complete terminations are assembled on a $3\frac{1}{2}$-in. deep mounting plate of the normal width of 19 ins. The terminations employ transformers (type 49) originally developed by the Post Office for use on toll circuits. These have been found to be sufficiently good to warrant their substitution for the more expensive and more bulky type normally used in termination units. A typical insertion loss characteristic when operating between 600 ohm circuits is given in Fig. **12**. Under the same conditions, the balance between 4-wire circuits measured at 800 c.p.s. is of the order of 55 db.

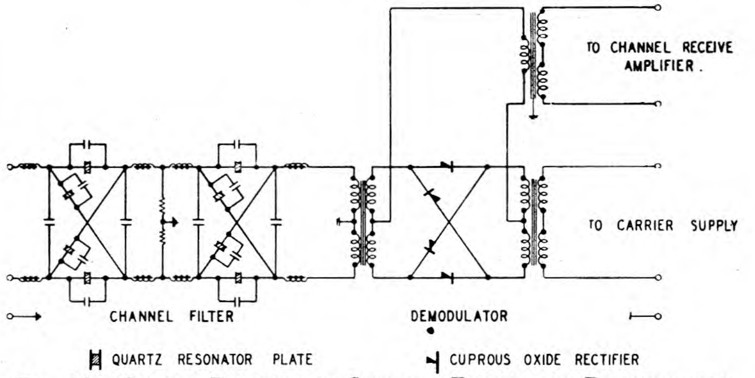


FIG. **14**.—CIRCUIT DIAGRAM OF CHANNEL FILTER AND DEMODULATOR.

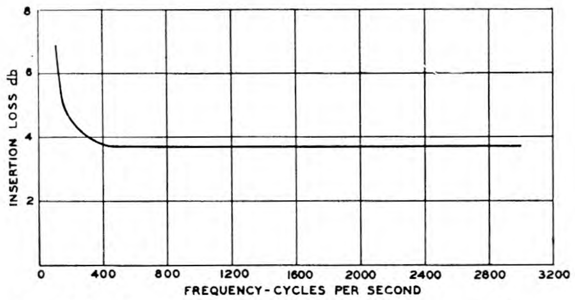


FIG. **12**.—INSERTION LOSS CHARACTERISTIC OF 2-WIRE TERMINATION. 2-WIRE TO 4-WIRE.

Channel Receive Amplifiers.

The level at the output terminals of each channel demodulator is increased some 25 db. or so by a channel receive amplifier (Fig. **13**) connected between the demodulator and the 2-wire termination. The amplifier serves two other purposes, viz. to compensate for a certain amount of premature attenuation introduced by the channel filters near the edges of the pass band, and to adjust the overall loss between 2-wire circuits to zero. Each amplifier employs a single stage of amplification using triode valves, P.O. type V.T.82, two amplifiers being accommodated on the same mounting plate. The maximum gain of an amplifier measured at 800 c.p.s. is approximately 30 db., and output levels up to 11 db. relative to one milliwatt can be provided without introducing more than 2 per cent. spurious harmonic content. The cross-talk between two amplifiers mounted on the same unit is not worse than 80 db.

Channel Modulators and Demodulators.

Balanced modulators incorporating cuprous oxide rectifiers are used for the initial stage of modulation. In the type of modulator indicated in Fig. 14 the terminals into which the modulating oscillation is injected and from which the side-band output is obtained, may be interchanged without altering the properties of the modulator ; moreover the effective input impedance in one case appears to have the same value as the effective output impedance in the other. These properties enable the same type of circuit to used for demodulation as well as modulation. Further, the filter which serves to separate one side-band from the other in the output circuit of the modulator has its counterpart in the filter which is required to restrict and select the band of frequencies applied to a demodulator. In view of the resemblance between the modulator and demodulator circuit arrangements, similar units incorporating the modulator and its associated filter have been used for modulation and demodulation with the sole exception that an

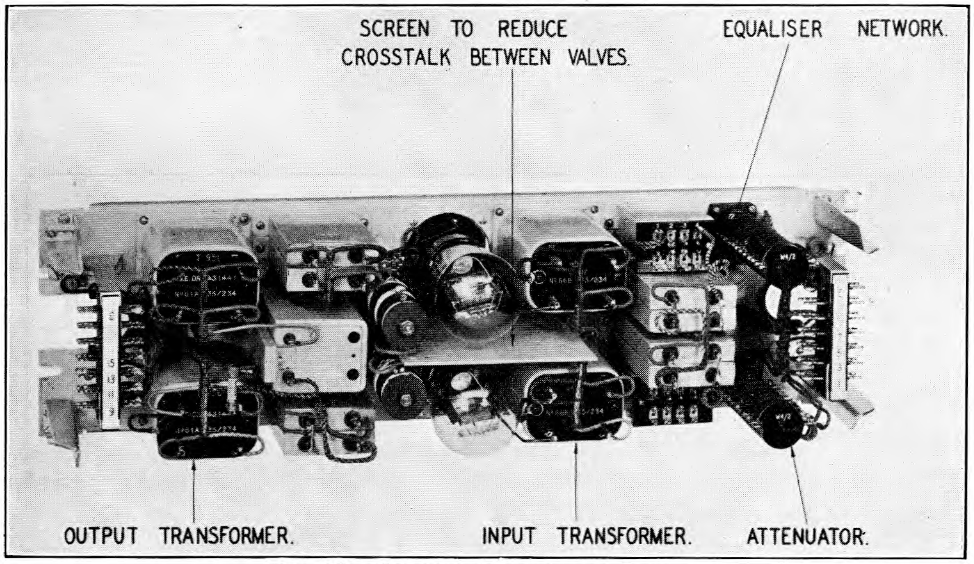


FIG. **13**.—CHANNEL RECEIVE AMPLIFIERS.

attenuator, used in the modulator to reduce the level of the modulating oscillations, is omitted in the demodulator.

In general, modulators give rise to unwanted modulation products of various orders as well as those it is desired to utilise, particularly when the current-voltage characteristics of the non-linear elements in the circuit depart largely from the parabolic form, as with copper oxide rectifiers. The particular form of modulator shown possesses the advantage that all unwanted products up to and including most of the fourth order products tend to balance out in the output circuit, this cancellation including both the oscillations originally applied to the modulator, i.e. the carrier and modulating oscillations. The absence of these components is of particular interest not only because it is highly desirable to eliminate the carrier at the transmitting end of the circuit, but because the absence of the modulating component as well makes it unnecessary for the circuit connected to the output terminals of the modulator to provide a low impedance path either to the carrier or modulating oscillations. Although no special arrangements have been made to balance out the carrier precisely, apart from matching the rectifier elements, the carrier leak present in the output circuit is normally some **40** db. below the input level. Since the carrier re-introduced in the corresponding channel demodulator at the distant end of the circuit has exactly the same frequency as that originally suppressed, there is no possibility of beats occurring between the re-introduced carrier and the residue. It is only necessary for the magnitude of the carrier residue to be small compared with that re-introduced so that the phase relationship of the two does not affect the magnitude of the resultant appreciably.

With a carrier power of **7** db. relative to **1** milliwatt injected into a modulator the conversion loss of the modulator and its associated filter is of the order of **13** db., of which **7·5** db. is introduced by the filter itself. Input levels of tone up to **9** db. relative to **1** milliwatt may be modulated without introducing appreciable distortion in the overall transmission.

Channel Filters.

The channel filters are called upon to provide high discrimination against frequencies transmitted by adjacent channels combined with uniform response in a relatively narrow pass band. These requirements make it uneconomic, if not impossible, to build satisfactory filters using inductors and capacitors exclusively. The solution is provided by the use of filter sections of such a type that some of the reactive elements may be realised in the normal way, using inductors and capacitors, without impairing the performance of the filter, whereas the remainder may be substituted by quartz crystal resonators which function as substantially ideal reactive elements. The equivalent circuit of a typical crystal is shown in Fig. **15**.

The capacitors connected across the resonators (Fig. **14**) are adjustable so that due allowance can be made for stray capacitances, and small deviations from the nominal values of the various elements. The crystal resonators are of the normal " X " cut variety utilising the resonance of the " Y " wave; a typical crystal in its associated holder is shown in Fig. **16**. Gold electrodes are deposited on the two main surfaces of the plate, which is then held between contacts fixed at an angle to coincide with the nodal plane. The inductors are of toroidal form employing iron dust cores. The fixed and adjustable capacitors, which like the inductors require to be of high stability, employ a ceramic dielectric and electrodes which are deposited directly on the surface of the dielectric by a combination of chemical and electrolytic processes. The resistors between the two sections of the filter are used to improve the response of the filter in the pass band. The overall insertion loss characteristic of a complete channel filter operating between **300** ohm circuits is given in Fig. **17**.

In practice, each channel filter and its associated modulator or demodulator is assembled on a common mounting plate. The complete circuit diagram and assembly of such a unit are shown in Figs. **14** and **18** respectively.

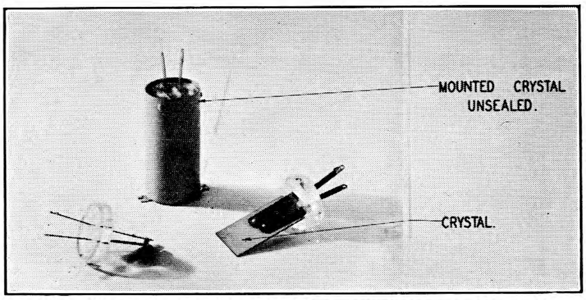


FIG. **16**.—HOLDER FOR CHANNEL FILTER CRYSTAL RESONATOR.

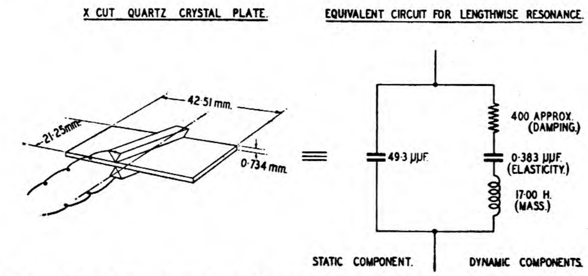


FIG. **15**.—EQUIVALENT CIRCUIT OF QUARTZ RESONATOR, **62.39** KC.P.S

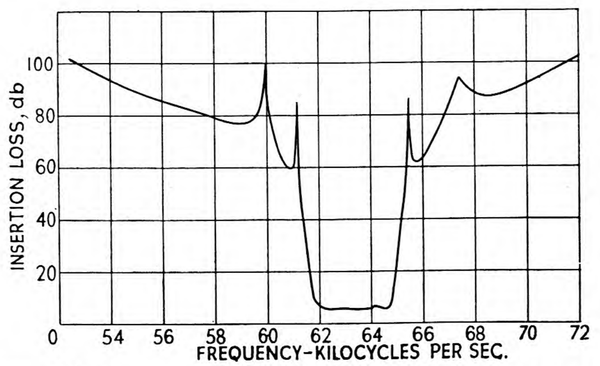


FIG. **17**.—INSERTION LOSS CHARACTERISTIC OF CHANNEL FILTER.

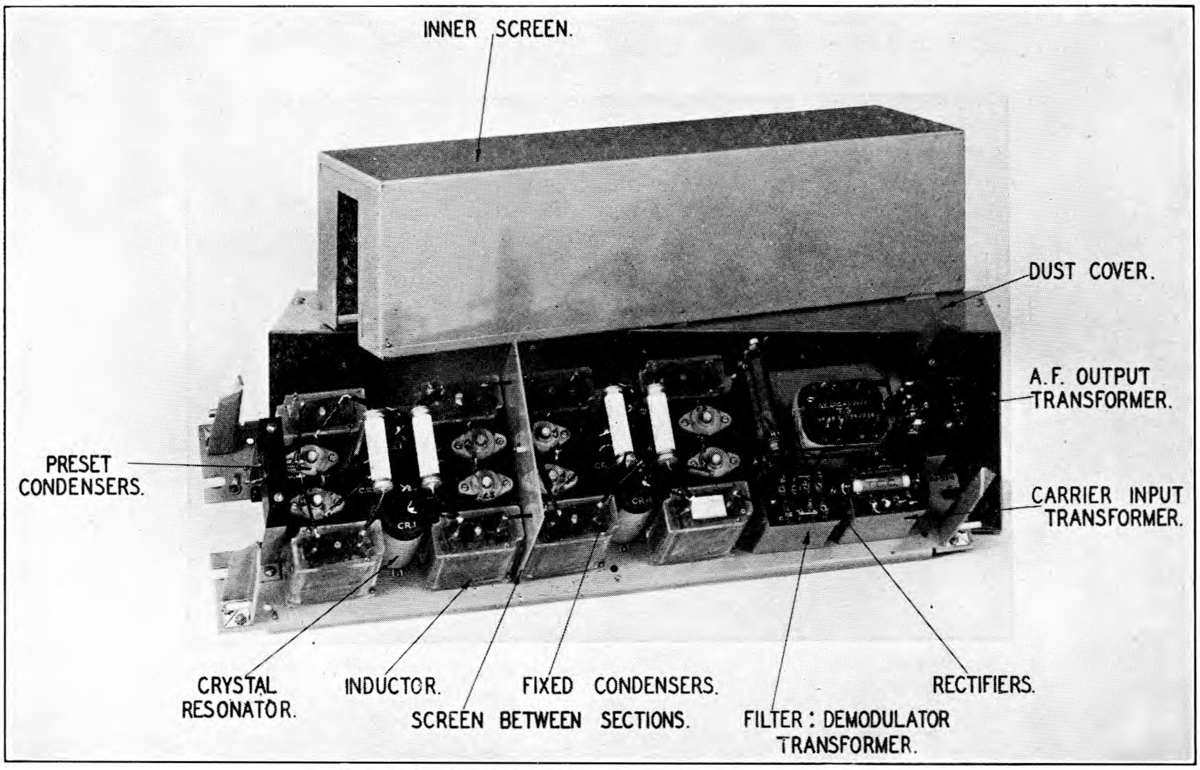


FIG. **18**.—CHANNEL FILTER AND DEMODULATOR.

Group Modulators and Demodulators.

The intermediate stage of modulation is carried out by means of Carson type modulators employing P.O. valves type V.T.82. Here again it is unnecessary to take special steps to balance the carrier out exactly apart from using matched valves, because the filter following the modulator introduces considerable attenuation at the carrier frequency. The overall gain of the modulator is adjusted to have the correct value after installation by means of a constant impedance attenuator in the input circuit. The maximum conversion gain of the modulator and filter combined is approximately 10 db., the filter itself introducing a loss of 1·5 db., and side band output levels up to about 1 milliwatt for each of two tones may be handled by the modulator without introducing appreciable distortion or crosstalk in the overall transmission of the system. The group demodulators are similar in type to the group modulators but some circuit details are necessarily different owing to the output frequency bands for the modulators having become the input frequency band for the demodulators and vice versa.

Group Filters.

As the performance requirements of the filters associated with the group modulators and demodulators are not particularly stringent, ladder type filters of the normal type employing inductors and capacitors only, are employed. The high frequencies and relatively narrow band widths involved make it necessary to take special account of stray capacitances, and it has been found advantageous to localise these capacitances by using double screening so that allowance can be made for them in the adjustment of the filter elements.

The circuit diagram of a complete filter showing the way in which the screens are connected is given in Fig. **19**. The series arm of the filter is completely surrounded by a screen joined to one of its terminals; its impedance is, therefore, independent of local conditions and may be adjusted as an independent unit. A second screen completely encloses the screened series arm and the elements of the shunt arm, the latter being adjusted allowing for the

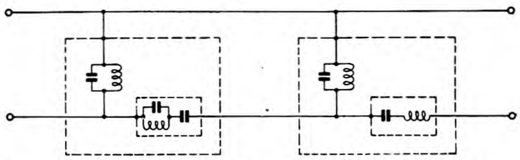


FIG. **19**.—SCHEMATIC DIAGRAM OF GROUP FILTER.

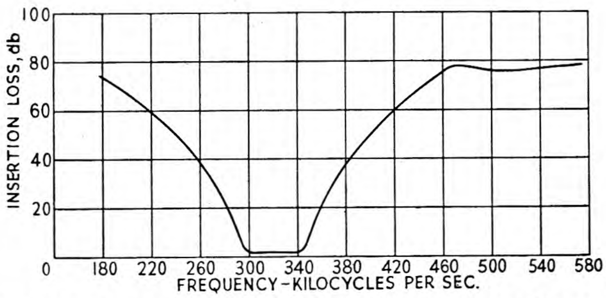


FIG **20**.—INSERTION LOSS CHARACTERISTIC OF GROUP FILTER.

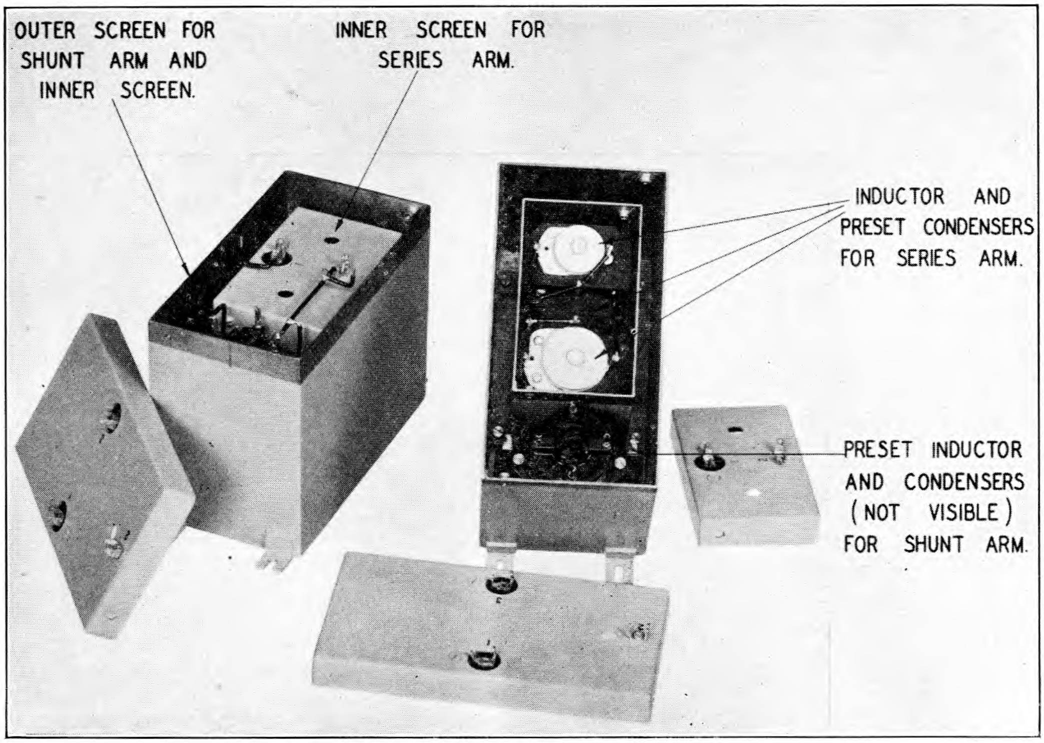


FIG. 21.—DOUBLE SCREENED FILTER SECTIONS.

capacitance between the screens. Adjustable inductors and capacitors are used in the shunt and series arms respectively in order that the various frequencies of resonance and anti-resonance may finally be adjusted to their correct values when the filter elements have been mounted in their screens. The insertion loss characteristic of a typical group filter is given in Fig. **20** and a filter section shown in Fig. **21**. The modulators and filters are assembled on the same mounting plate.

Super-Group Modulators, Demodulators and Filters.

The super-group modulators, demodulators and filters are very similar in general design to the corresponding units used for the groups; there is, however, the outstanding difference that the equipment used for the higher frequency super-groups operates at about four times the frequency. This imposes most rigid limitations on the design of transformers and demands greatly increased precision in the construction and adjustment of filters; nevertheless satisfactory equipment has been evolved. The following performance figures for the units designed to operate on the highest super-group frequency band will be of some interest :—

The maximum conversion gain of the modulator and filter is **8** db., the filter itself having a loss of **2** db. Side band output levels up to about **1** milliwatt for each of two tones may be handled without introducing appreciable distortion in the overall transmission. The insertion loss characteristic of one of the filters is given in Fig. **22**. The curve is almost identical in shape with that of a group filter given in Fig. **20** but is included as representing an interesting application of filter technique to high frequencies. The complete

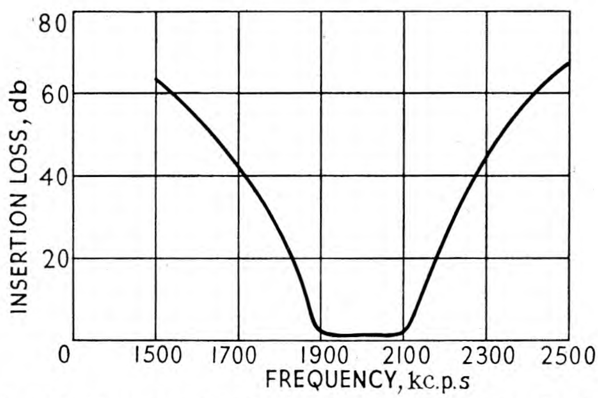


FIG. 22.—INSERTION LOSS CHARACTERISTIC OF SUPER GROUP FILTER.

assembly of a modulator and its associated filter is shown in Fig. **23**.

TERMINAL STATION CARRIER GENERATION EQUIPMENT

The order of frequency constancy necessary for the **21** carrier frequencies required at each terminal, in order that corresponding carrier frequencies may not vary mutually by more than a few cycles, is achieved most easily by relating each one harmonically to the frequency generated by a single master oscillator designed to give the required frequency stability. The percentage constancy of the master

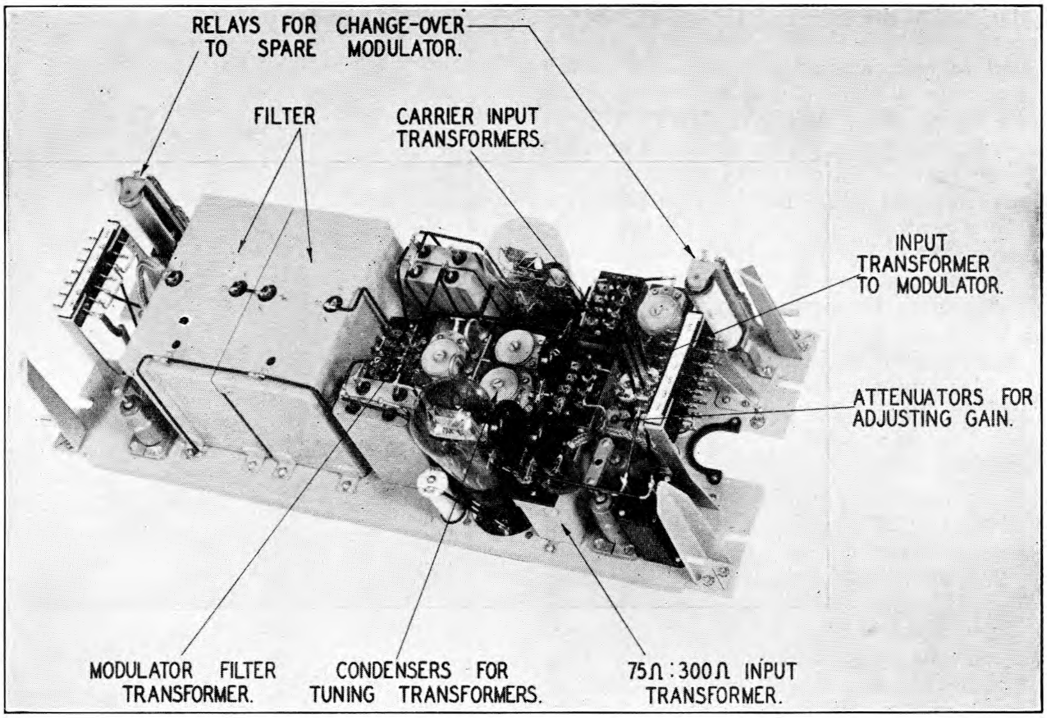


FIG. 23.—SUPER-GROUP MODULATOR AND FILTER.

is translated to each carrier and the relative merits of the system, as compared with one which employs separate oscillators at both terminals for each carrier, are readily appreciated. Thus, the number of precision oscillators is reduced from **42** to **1** and the operation of the speech circuits is unaffected by normal frequency variations of the master. A further advantage which will obtain when the scheme is applied to a cable network extending throughout the country is the supply of standard frequencies available at each terminal for other purposes.

The carriers are generated in synchronised frequency-multiplying equipment at London and Birmingham. The drive for both sets of equipment is a master oscillator located at the London terminal and the carrier frequencies at the two terminals are precise integral multiples or sub-multiples of the master frequency. The values of the **21** carrier frequencies, chosen to facilitate the system of generation, are **1,000** to **2,400** kc.p.s. in **200** kc.p.s. steps for the **8** super-groups, **400** to **560** kc.p.s. in steps of **40** kc.p.s. for the **5** groups and **65** to **100** kc.p.s. in steps of **5** kc.p.s. for the **8** channels. Provision has also been made for extension of the system to provide the **10** channel frequencies, **64** to **100** kc.p.s., in steps of **4** kc.p.s., required for a channel spacing of **4** kc.p.s.

The equipment is divided into four main parts, the master oscillator, production, selection, and power amplification. The carriers are generated in a series of synchronised multi-vibrators which make up the production equipment. The individual carriers are filtered in the selectors and the requisite signal level is obtained in the power amplifiers prior to distribution of the carriers to the modulator and demodulator units. Sufficient power is developed in the selectors on each carrier frequency to energise four sets of power amplifiers and it will be necessary to repeat only the power amplifiers for each additional pair of cable terminations up to a maximum of four pairs. Failure of any part of the system is so vital that two sets of equipment are installed at each terminal and, on the occurrence of a fault, the faulty apparatus is automatically replaced, without causing interference with the service, and both aural and visual warnings of the fault are given.

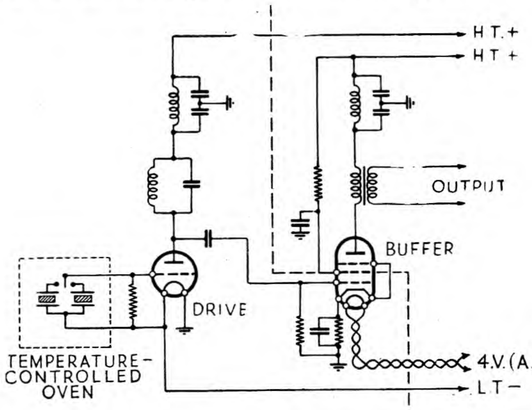


FIG. 24.—CIRCUIT DIAGRAM OF CRYSTAL DRIVE UNIT.

The Master Oscillator.

The drive circuit, Fig. **24**, employs a **400** kc.p.s. $Y_{\theta T}$ quartz plate of sensibly zero frequency-temperature coefficient. Minimum damping of the crystal is ensured by the use of a nodal plane suspension and by a reduction of air pressure in the holder to less than 1 mm. of mercury. The effective frequency-temperature coefficient of the mounted crystal is within ± 0·5 parts in 10^6 per 1° C temperature change. It is mounted in a thermostatically controlled oven designed to reduce ambient variations at the crystal to less than ± 0·05° C and aural and visual warnings of a temperature change of ± 0·25° C from the control value are given. Two mounted crystals are included in each oven, either of which may be switched into circuit at will. The load on the drive is stabilised by a pentode buffer stage, from the anode of which the required **400** kc.p.s. outputs are obtained. No special precautions have been taken to stabilise the supply voltages as the normal variations will not appreciably affect the generated frequency. Photographs of the master oscillator crystal with its associated holder and the completed oscillator unit are shown in Figs. **25** and **26** respectively.

Frequency Production.

As pointed out earlier the production equipment at each terminal (see Fig. **27**), employs three synchronised multi-vibrators operating on the fundamental frequencies, **200**, **40** and **5** kc.p.s. respectively, from which the three harmonic series corresponding to the super-group, group and channel carriers are obtained. The application of the multi-vibrator to the production of a series of frequencies which are harmonically related to a standard frequency is well known. Briefly, the oscillation generated in a multi-vibrator is rich in harmonics and, although the fundamental frequency primarily determined by the circuit constants is unstable, it may be controlled by a signal whose frequency is equal to or is a low order multiple of the fundamental. Thus, if f is the fundamental frequency of the multi-vibrator, it may be controlled by a signal of frequency nf, where n is an integer, and a harmonic series of f is avaliable. The upper practical limit of n is about **10**.

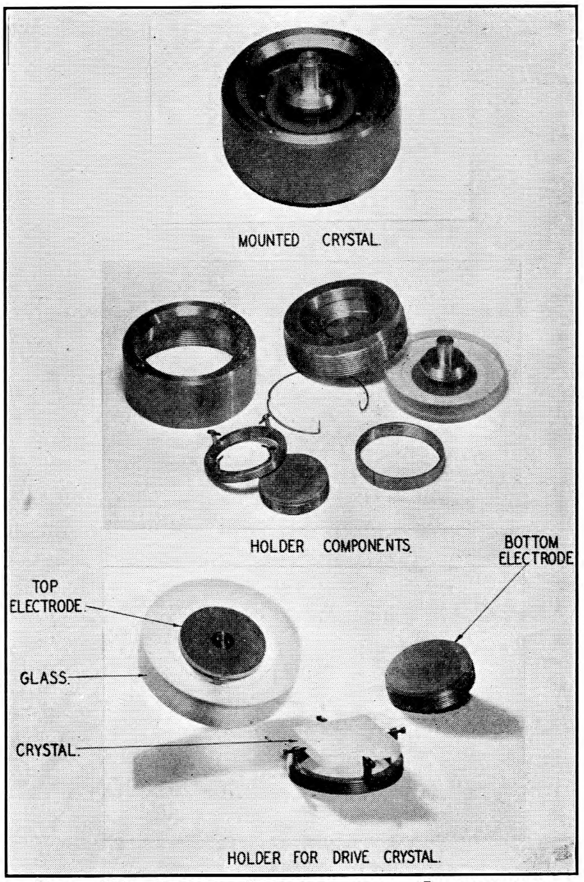


Fig. **25**.—Drive Crystal and Components.

An amplified output from the drive controls the frequency of the **200** kc.p.s. multi-vibrators at London and Birmingham, the control signal for the

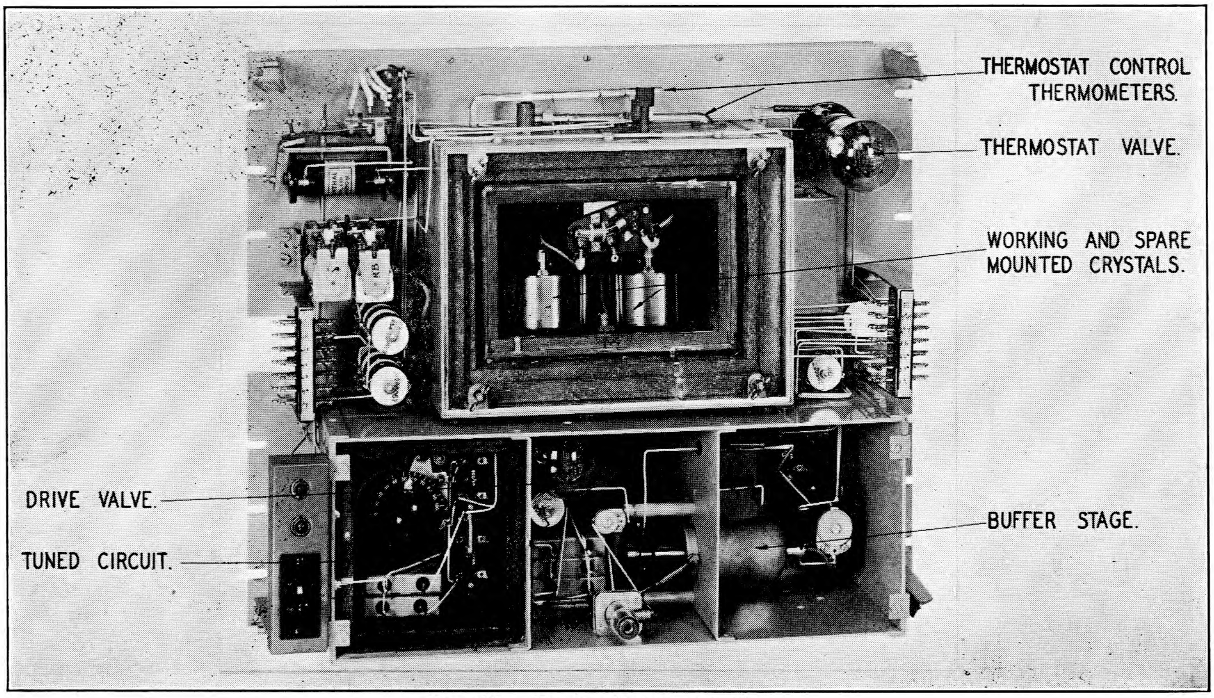


Fig. **26**.—Drive Oscillator Unit.

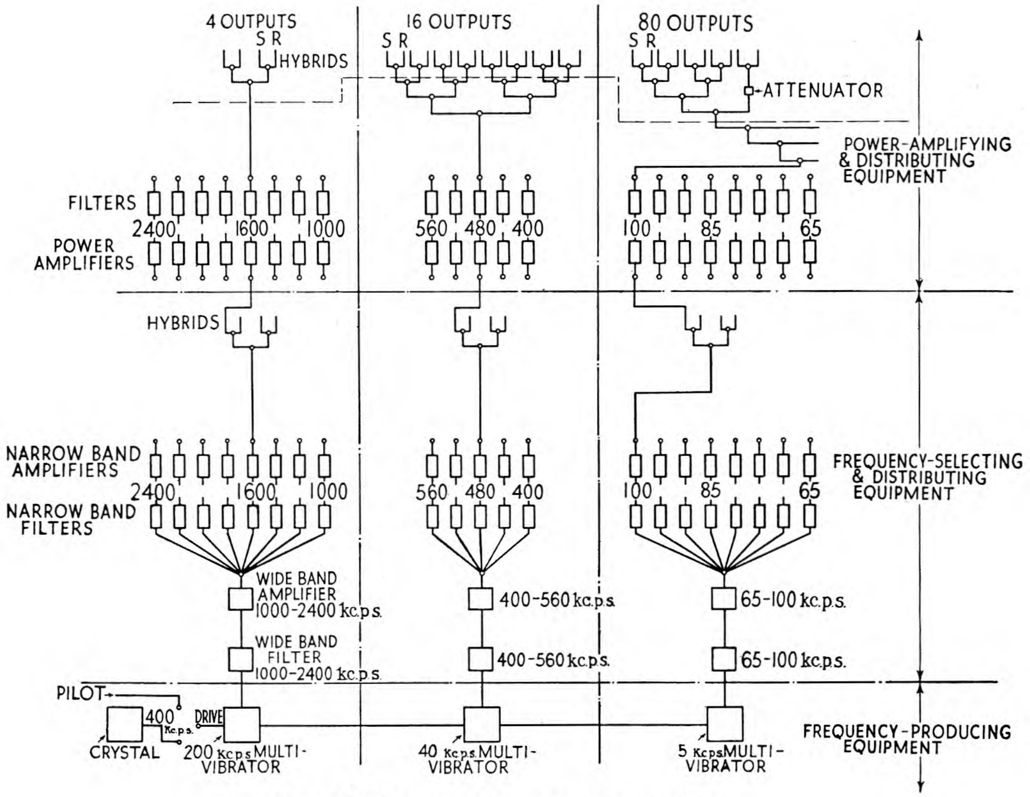


Fig. **27**.—Carrier Production Equipment.

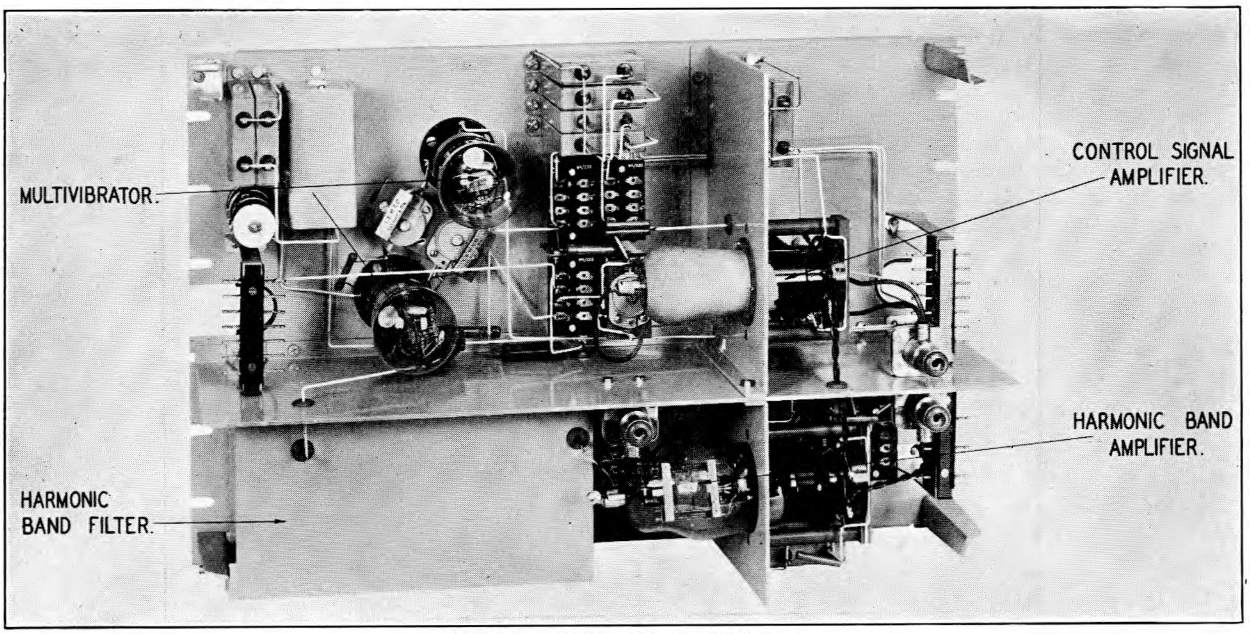


Fig. **28**.—Multi-Vibrator Unit.

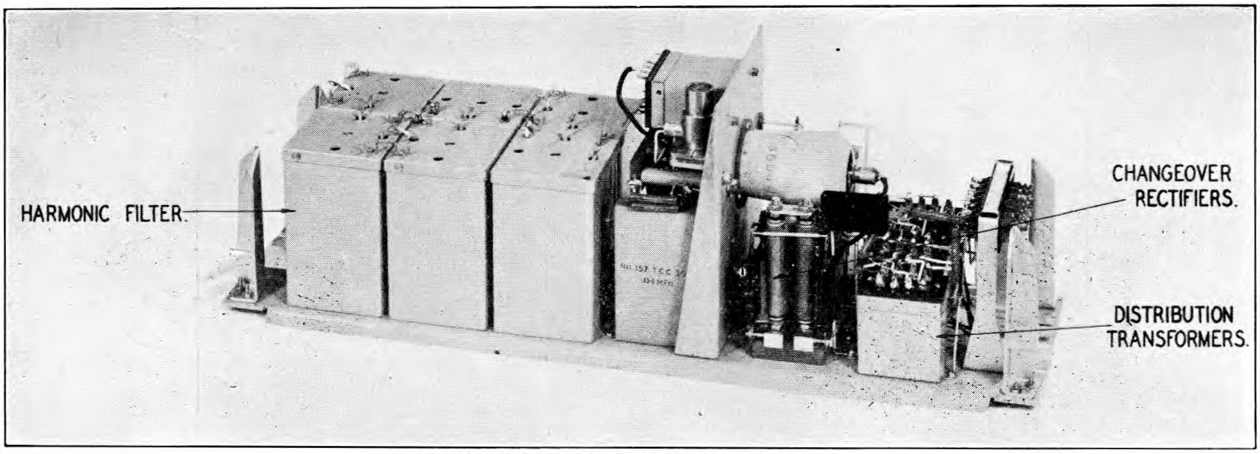


FIG. 29.—FREQUENCY SELECTOR UNIT.

latter terminal being transmitted through the cable. In effect, the control of the 200 kc.p.s. multi-vibrator is accomplished on its 2nd harmonic and the harmonic series of 200 kc.p.s., which includes the super-group frequencies, is produced. In a similar manner each 40 kc.p.s. multi-vibrator is synchronised on its 5th harmonic by a fundamental output from its 200 kc.p.s. multi-vibrator and a further harmonic series of 40 kc.p.s., which includes the group frequencies, is obtained. The process is then repeated for the channel frequencies by locking the 5 kc.p.s. multi-vibrator with an output from the 40 kc.p.s. multi-vibrator. It is not desirable to control the 5 kc.p.s. multi-vibrator direct from the 40 kc.p.s. multi-vibrator and the control is effected indirectly through a 20 kc.p.s. multi-vibrator. The production of the 10 channel frequencies of 64 to 100 kc.p.s. in steps of 4 kc.p.s. will be accomplished with the aid of a 4 kc.p.s. multi-vibrator locked by a second 20 kc.p.s. multi-vibrator. The three harmonic series corresponding to the super-group, group and channel carriers are selected by the respective harmonic band filters and each series is amplified in its harmonic band amplifier. In view of the similarity of the various multi-vibrators, selectors and power amplifiers only one of each type will be discussed.

Each multi-vibrator and associated harmonic band filter and amplifier are mounted as a single unit. The frequency of the uncontrolled multi-vibrator has been approximately adjusted by trimmer condensers to that of the control, which is fed to one anode circuit through a pentode amplifier. The harmonic series is selected from the second anode in a three section band-pass filter designed to pass the required band of carrier frequencies and amplified in a pentode amplifier. A photograph of a typical unit is shown in Fig. 28.

Frequency Selection.

The individual carriers are filtered from their respective harmonic band amplifiers by narrow band filters and each carrier is amplified to a level sufficient to energise four power amplifiers, the four outputs being obtained with a hybrid distribution system. The selector, Fig. 29, comprises a 6-section band-pass filter and a pentode amplifier. The filter is designed to select one carrier frequency, the pass band loss being less than 10 db. and the loss on adjacent carrier frequencies greater than 60 db. The outputs of corresponding working and standby selectors are connected to the contacts of a relay mounted on the standby unit and the relay tongue is connected to a hybrid system giving four independent outputs. The changeover from working to standby is made by a master relay operated by rectified outputs from both selectors.

Additional outputs are taken from the 100 kc.p.s. and 2,200 kc.p.s. selectors to provide signals for the loss of synchronism unit, and a 2,200 kc.p.s. pilot for the repeater changeover equipment.

Power Amplification.

One of the four carrier outputs from each selector is fed to a power amplifier in which the carrier is amplified to provide the level required at the associated modulator and demodulator units. When the anticipated 320 circuits are in service each super-group, group and channel amplifier respectively

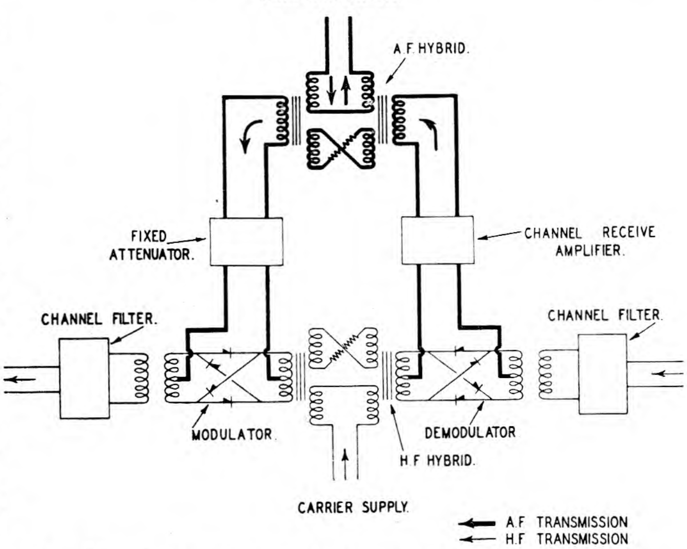


FIG. 30.—SCHEMATIC ILLUSTRATING THE USE OF HYBRIDS IN THE TERMINAL EQUIPMENT.

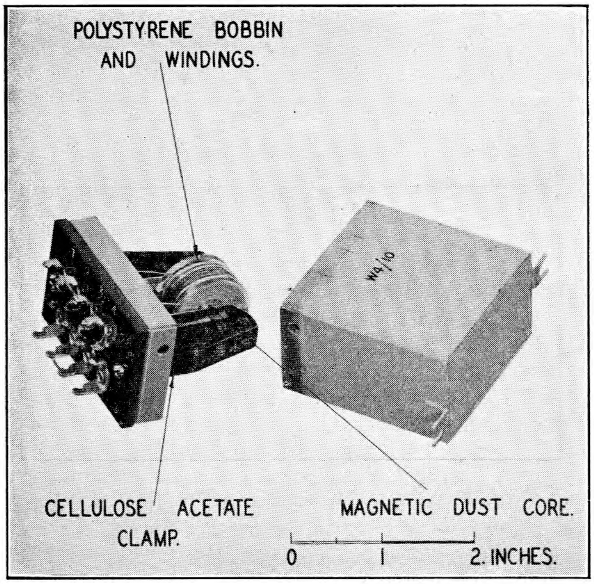


Fig. 31.—Typical Carrier Frequency Transformer.

will feed 2, 8 and 40 modulators and a similar number of demodulators. The distribution of the carriers is accomplished in a hybrid distribution system and this is illustrated in Fig. **30**. A typical carrier frequency transformer is shown in Fig. **31**.

The signal levels of the respective carrier series are obtained with one stage of amplification using a single pentode valve for the super-group and group series, and with two paralleled pentodes for the channel series. The amplifier output is filtered in a 3-section band pass filter designed to introduce a loss of 40 db. on the 2nd harmonic frequency. The output switching system is similar to that for the selectors, the working and standby outputs being connected to relay contacts and the relay tongue to the hybrid distribution system. The relay is switched through a master relay operated by rectified outputs from both amplifiers. Fig. **32** shows a photograph of a typical channel power amplifier unit.

Changeover Equipment.

The operation of the cable is so dependent on the uninterrupted operation of the carrier equipment that it has been thought advisable to duplicate the apparatus at each terminal. The two sets known as the "working" and "standby" equipments are mounted on opposite sides of a rack assembly, the one being almost a mirror image of the other. On the occasion of a fault on the working set the faulty apparatus is automatically replaced by its standby equivalent without interfering with the service, and visual and aural warning of the fault are given. The "working" apparatus cannot be brought into operation again until the switching system has been reset manually. It has not been found practicable to arrange for a single faulty working unit to be replaced by its standby unit owing to the switching complexity introduced and to the maintenance difficulties which would be experienced on a bay in which part of the apparatus was in service. Consequently, both the working and standby sets are divided into two parts, the first the production and selection equipment, and the second the power amplifiers ; each part is switched independently.

Apparatus faults may be considered under four main headings, respectively, failure of drive, loss of synchronism of multi-vibrators, failure of carrier output at selectors and carrier failure at the power amplifier output. These failures are not independent inasmuch as a drive failure will cause the multi-vibrators to lose synchronism and failure of the carrier output at the selectors will be reflected in a corresponding power amplifier failure. A detailed description of the changeover system is not possible here but the design is such as to prevent unnecessary changeovers. For instance should the carrier output of the channel selector on 95 kc.p.s. fail, then the selector unit changeover will take place but the power amplifiers will not be affected.

The London master oscillator unit normally controls the multi-vibrators at both terminals ; at the remote terminal by means of a pilot signal transmitted over one of the coaxial pairs. A second drive unit is kept in continuous operation at Birmingham, however, and a pilot signal transmitted to London. In the event of failure of the London drive at either terminal, control of the system is switched automatically to the Birmingham drive. In the remote possibility of a failure of the two pilot signals due to faults outside

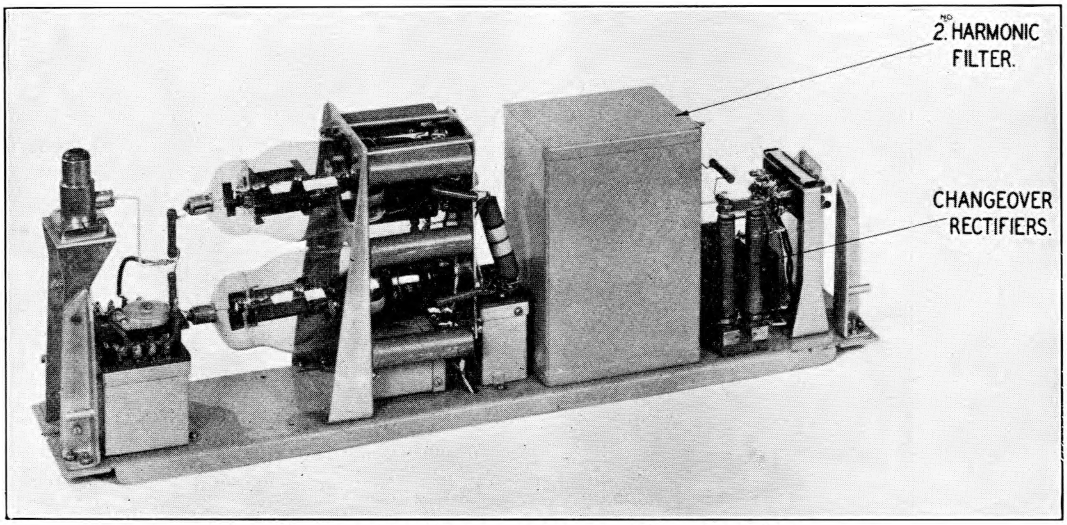


Fig. 32.—Channel Power Amplifier (Working) Unit.

the respective drives then the drive at each terminal takes control of its own multi-vibrators. In this connection the frequency stabilities and agreements of the two drives are such that the speech circuits are not seriously degraded by the employment of independent drives. Should a multi-vibrator cease to be controlled, due to loss of the control signal or to any other fault, the working multi-vibrators and associated selectors are replaced by the corresponding standby equipment. This changeover is controlled by the loss of synchronism unit. In the event of a failure of the output from the frequency selectors, the working multi-vibrators and associated selectors are replaced by the standby equipment. Standby power amplifiers are switched into service on the failure of the carrier output from the working amplifiers.

Loss of Synchronism Unit.

Should any of the multi-vibrators at one terminal cease to be controlled by the master oscillator, the loss of synchronism is detected by this unit and the necessary changeover made to standby equipment. The design is based on the fact that loss of synchronism in any multi-vibrator is reflected in the 5 kc.p.s. multi-vibrator. An output from the 100 kc.p.s. selector is fed to a tuned circuit connected across the grid and filament of a triode (Fig. **33**) and a crystal resonator, of series resonant frequency 100 kc.p.s., is paralleled with the tuned circuit. The anode current of the triode under static conditions is biassed to the cut-off point. When the incoming frequency is precisely 100 kc.p.s. the crystal effectively short-circuits the tuned circuit, the grid input voltage is almost zero and no anode current will flow. Should the carrier frequency differ by even a few cycles from **100** kc.p.s. then, by virtue of the low dissipation constant of the equivalent circuit of the crystal, it ceases to act as a short-circuit, a radio frequency input is applied across the grid circuit, anode current commences to flow and the anode relay is operated. In turn the changeover relay is operated and the

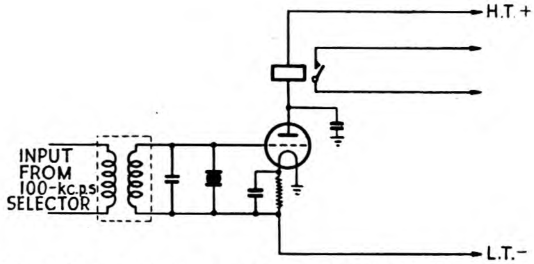


FIG. **33**.—CIRCUIT OF LOSS-OF-SYNCHRONISM UNIT.

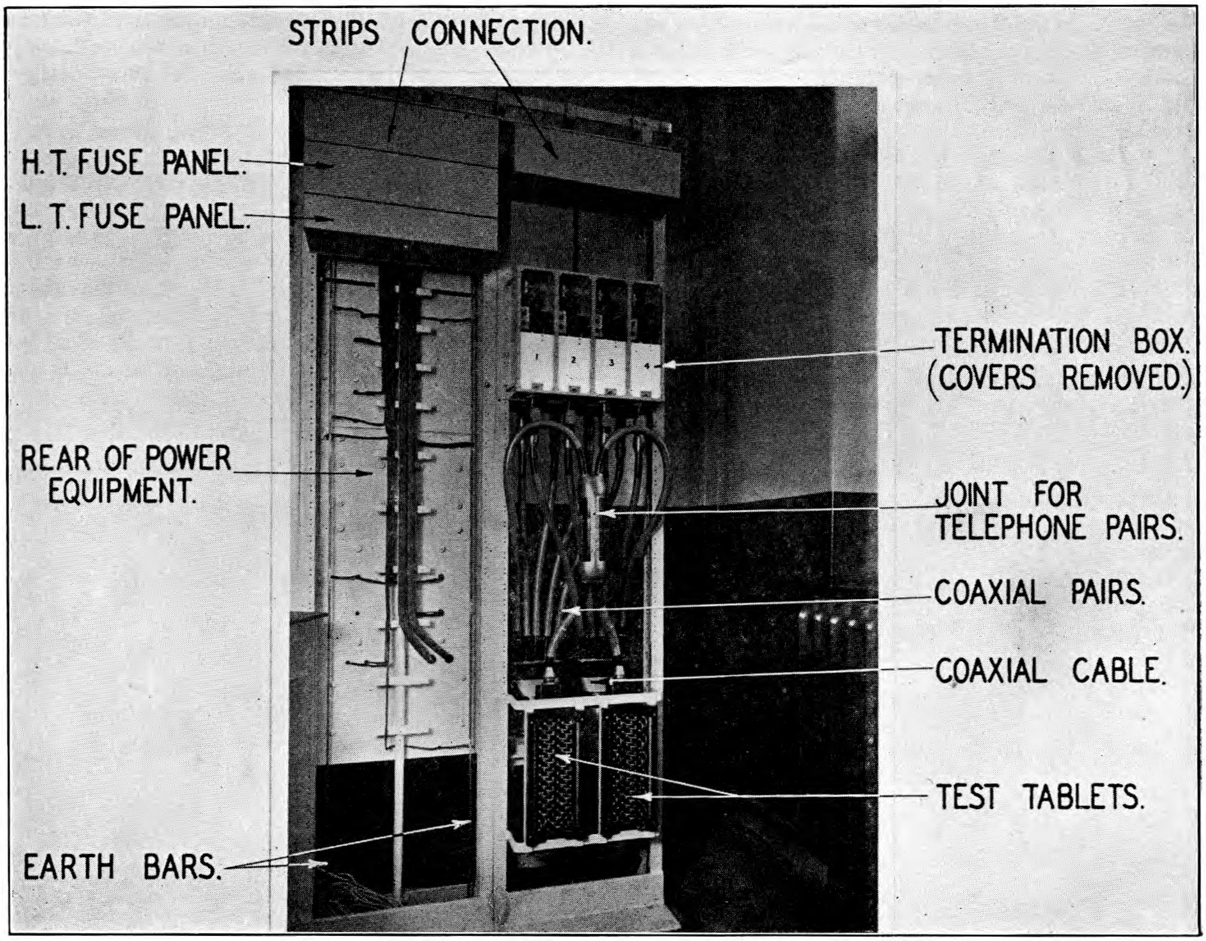


FIG. **34**.—CABLE TERMINATION AT REPEATER STATION.

faulty multi-vibrators and associated selectors are replaced. The frequency variation which may be permitted without operation of the relay is adjustable within limits.

Repeater Station Equipment.

The repeater station equipment includes all the apparatus connected directly in the path between the modulating equipment at the two terminal stations. In all, there are 19 repeater stations, two being positioned in the respective terminal stations. Each station contains equipment similar to that at any other, apart from minor differences associated with the provision of a power supply over the coaxial pairs and the supervisory facilities at the terminal repeater stations.

A photograph of a cable termination at a typical repeater station is shown in Fig. **34**. The four coaxial pairs from each of the London and Birmingham sides of the main cable and the power supply connections to the repeating equipment are led into a termination box. In the lower half of this box, protected by a sliding partition, are located the various filter networks associated with the transmission of power over the cable ; details of the networks have been given in an earlier section. Access to the cable terminations, on which relatively high power supply voltages may be present, can only be obtained by raising the sliding partition. Mechanical interlocks prevent this partition being raised before the power supply connections have been removed and an earth applied to the coaxial pair. The various factors involved in the design of the repeater station equipment having been outlined earlier, the more important parts of this apparatus will now be described in some detail.

The High Frequency Repeater and Equaliser.

The repeater designed for use on the London-Birmingham route comprises an input transformer followed by four stages of amplification with an output transformer (Fig. **35**). The first stage is provided with a small degree of feedback from the bias resistor. The coupling between the first and second stages consists of a equaliser network providing the equalisation required for a 6-mile length of cable. The last three stages have feedback from output to input and also individual feedback on each stage.

The valves employed are high slope indirectly heated pentodes with a maximum anode dissipation of 10 watts at 250 volts. The heaters require 2 amps at 4 volts. The input capacitance is 16 $\mu\mu$F, the output capacitance 16 $\mu\mu$F and the residual grid to anode capacitance 0.6 $\mu\mu$F, which can be reduced to 0.2 $\mu\mu$F by means of a screening cap. The working mutual conductance is 10 milliamps per volt $\pm$ 10 per cent. Much of the success of the amplifier is due to the excellence of the valve characteristics ; a development which has been accelerated by broadcasting requirements. The voltage stability is such that a 5 per cent. change in H.T. or L.T. causes a change not exceeding 0.1 db. The overall maximum gain of the repeater at 2.1 Mc.p.s. is 55 db., sufficient for a repeater section of 8 miles including the loss in the subsidiary equaliser, connected before the amplifier proper, which compensates for the length in excess of 6 miles.

A photograph of the repeater is shown in Fig. **36**, which illustrates the type of screen assembly adopted. The components and wiring of the repeater are attached to aluminium screens in such a manner that after unsoldering the input and output coaxial cables, the high and low tension leads and removing a few screws, the whole repeater can be removed from the panel. This method of construction simplifies the wiring and permits of a ready interchange of units. It will be appreciated that the design has been arranged so as to minimise to the utmost interstage wiring. An aluminium cover is fitted over the compartments in addition to the standard dust cover.

The Spare Repeaters.

A spare repeater is automatically switched in if the main repeater fails. This is effected as follows : a control tone having a frequency of 2.2 Mc.p.s. is transmitted on each pair and selected from the output of each main repeater. After amplification and rectification it operates a relay circuit which switches in the spare repeater if the tone ceases to appear at the output of the main repeater. The changeover time is less than 30 milliseconds. A

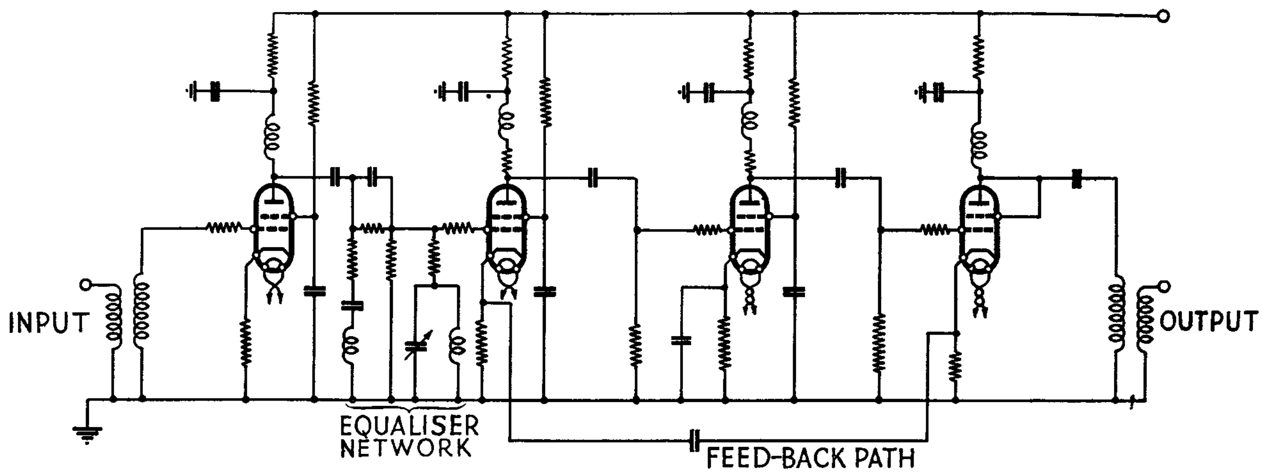


Fig. 35.—High Frequency Repeater and Equaliser.

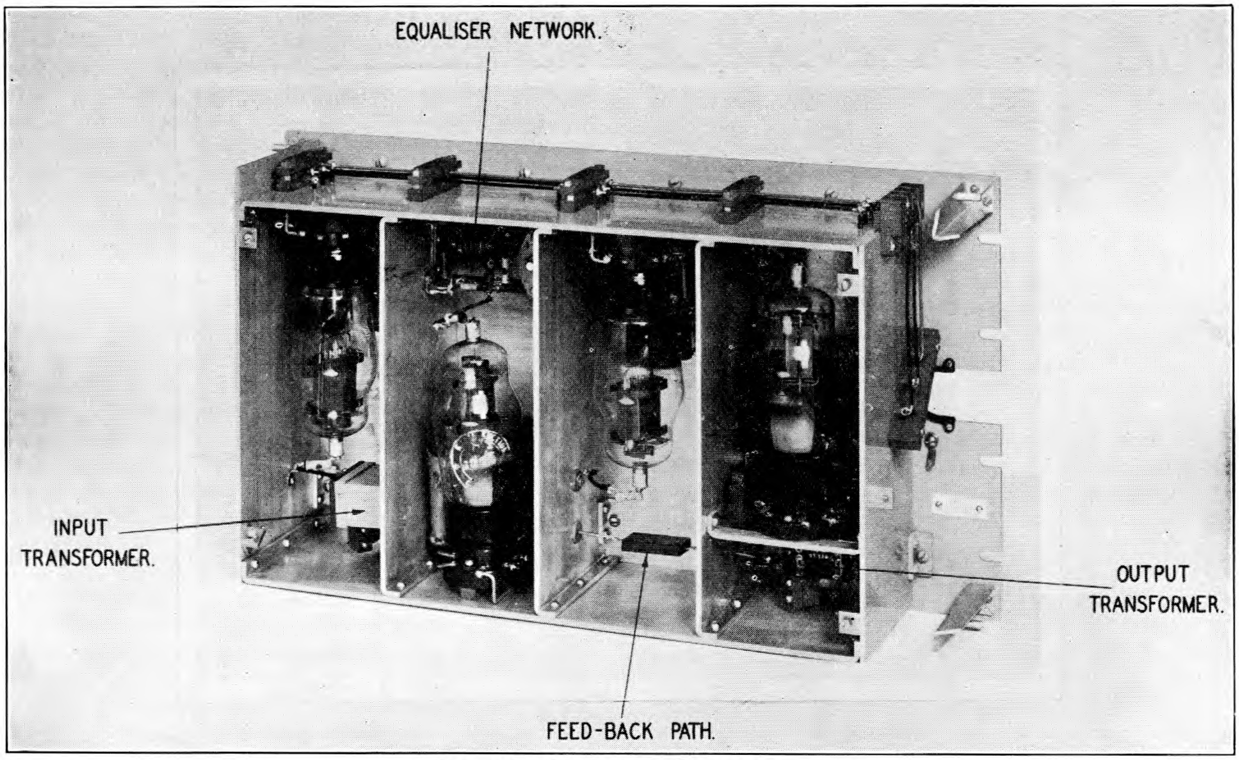


FIG. **36**.—FEED-BACK REPEATER.

similar selector panel is also required across the output of the spare repeater.

Features of the scheme are :—

(*a*) Only the spare repeater on the appropriate coaxial pairs at the station affected is switched into circuit.

(*b*) While the spare repeater is not in circuit it operates under reduced high and low tension voltages. When switched into circuit the voltages are increased to normal and the repeater gives the required gain immediately but does not give the required reduction of inter-modulation products until the cathode has reached the proper operating temperature. By this means valve life in the spare repeater is prolonged and immediate continuity of service, although of a lower standard, ensured with a low power consumption during the inoperative condition.

(*c*) In the event of a cessation of the control tone at any point in the system all stations failing to transmit the tone, automatically test to see whether the use of the spare repeater on the particular pair affected will restore the tone. Restoration of the tone, possibly by the automatic replacement of a faulty repeater, automatically causes all the subsequent main repeaters in the system to be tested before allowing any further spare repeaters to come into actual operation at any later station. Thus a spare repeater only remains in circuit if its main repeater is found to be faulty.

(*d*) An indicator at London makes it possible to see at a glance which stations are operating on their spare repeaters and thus enables the central control to issue the maintenance instruction and inform them automatically of the restoration of the main repeater to service.

Compensation of Attenuation Changes due to Temperature Variation.

It has been pointed out earlier that the maximum total variation in attenuation from London to Birmingham per year due to temperature will be about 33 db. at 2.2 Mc.p.s. and 12 db. at 0.4 Mc.p.s. From recorded temperature measurements on a section of the cable it appears that any compensation for the most severe temperature changes encountered need not be applied more frequently than once a fortnight and over the greater part of the year the interval will be considerably longer. A much longer period of observation will, however, be necessary before definitely assuming that this will be adequate.

It has been decided to operate the circuit initially with manual control and leave the automatic compensation to be applied later. A small compensating network, forming part of the subsidiary equaliser, is provided on each coaxial pair at each station, and can be switched into or out of circuit. All temperature changes will be taken up as required at the main attended repeater stations, except twice each year when certain of the intermediate station networks will have to be switched ; further control for the next six months can then be effected at the main stations.

Speaker and Supervisory Circuits

The provision of adequate and efficient speaker and supervisory circuits forms an integral part of any transmission scheme involving unattended repeater stations. The speaker and supervisory circuits are provided on the unloaded paper insulated pairs contained within the make-up of the complete cable. These are repeatered and equalised at main stations by means of single stage feedback repeaters, having a gain of about 40 db. The valves used for the repeaters and for almost all supervisory and test equipment are indirectly heated high slope H.F. pentodes.

In the present system the supervisory and test equipment can be sub-divided into low frequency tone operated and D.C. operated circuits.

(*a*) L.F. Tone Operated Supervisory Circuits. Each station on the route is associated with a particular frequency which is continuously generated from an L.F. oscillator at that station. The frequencies employed are the same as those used in V.F. telegraphy and consist of odd multiples of 60 c.p.s. commencing at 420 c.p.s. One function of these tones is to provide positive indication at London of the failure of a main repeater at any station. The tones are normally transmitted from each station over a common repeatered pair to London where they are selected and used to operate supervisory equipment. Failure of a repeater suppresses the associated tone at the transmitting point thereby giving an indication in London.

The main repeater station oscillators are also used for calling London or Birmingham on the speaker circuit and the two terminal stations can bring in any main station by means of a 6-frequency ringing oscillator.

(*b*) D.C. Operated Supervisory Circuits. Supervision at London is obtained of other causes of failure, e.g. L.F. repeater, supply failure, cable breakdown, etc. by means of a D.C. bridge circuit operating on two of the telephone pairs.

By these two supervisory systems it is possible to identify and locate most of the important sources of failure that might occur on the coaxial cable system without delay.

The Power Bay

The power required at each station to operate the H.F. repeater and switching equipment for the four coaxial pairs and test, supervisory and L.F. repeater equipment for the telephone pairs is about 800 watts. As explained earlier, power for these purposes is transmitted over the coaxial pairs from the main to the intermediate repeater stations. A local power supply is used for lighting and inspection at all the intermediate stations.

The power supply at every main repeater station is stepped up to 350 volts and all power equipment is designed to operate from 280–350 volts. Power at 350 volts is supplied (*a*) to the " up " or " down " coaxial pairs as required for transmission to the intermediate stations, (*b*) to a 4-volt transformer for filament heating and (*c*) to a transformer which supplies the Westinghouse rectifier unit yielding a 250 volt D.C. supply ; this transformer also carries a small tertiary winding supplying a small rectifier giving a 40 volt D.C. supply for energising relay circuits.

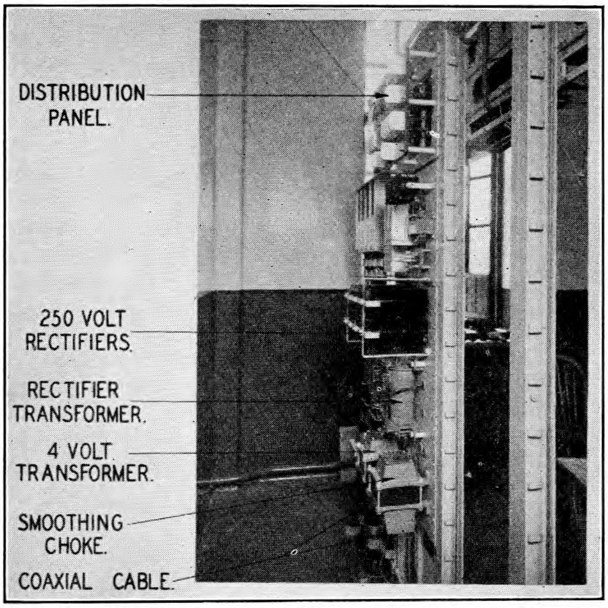


FIG. **37**.—POWER BAY AT REPEATER STATION (COVERS REMOVED).

The power bay equipment is completely enclosed by two expanded metal covers, affording adequate ventilation and ensuring protection against electric shock. The design of the power bays at the intermediate stations is similar to the main stations excepting that the transformer for supplying power to other stations is omitted. A photograph of a typical main repeater station power bay is shown in Fig. **37**.

Test Equipment.

Each repeater station is provided with the following panels of test equipment.

(*a*) Valve Test Panel.

This is used for a rapid test on anode current and mutual conductance of the various valves. Its use necessitates the removal of the valve from its normal working position.

(*b*) L.F. and D.C. Test Panel.

For measuring H.T. volts and current to every panel, setting up selector detector circuits and measuring L.F. voltages.

(*c*) H.F. Test Panel.

This comprises an oscillator having a constant output characteristic working over the range 0.35 to 2.3 Mc.p.s. and yielding various fixed output levels of 0 to 40 db. relative to 1 mW in steps of 5 db. It also includes a wide range calibrated receive element for measuring levels.

Part III.—Layout of Equipment and Test Results

THE terminal stations are located in Faraday Building, London, and Telephone House, Birmingham. Where no building existed that could suitably be converted into a repeater station, sufficient ground was purchased to enable small brick built buildings of the U.A.X. type, 14 ft. by 10 ft. by 8 ft. 6 ins. high, to be erected. Twelve such buildings have been provided along the route. Accommodation for the other five stations has been provided in telephone exchanges or normal repeater stations.

The rack layout plan adopted in London and Birmingham is shown in Figs. **38** and **39** respectively.

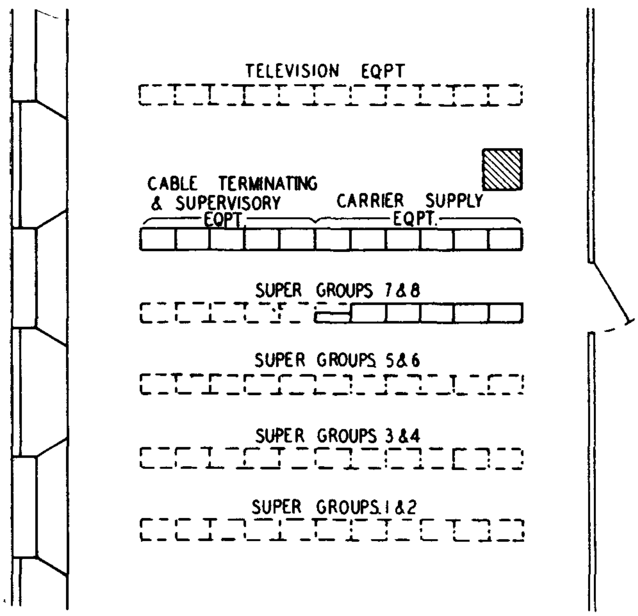


FIG. **38**.—RACK LAYOUT, LONDON TERMINAL STATION.

In view of the extension of the cable through to Manchester and the definite allocation of certain super-groups to the London-Manchester traffic it will probably be unnecessary to bring the through circuits down to audio frequency at Birmingham and the corresponding super-groups will have to be deleted from the floor plan ; the absence of a break-in facility at Birmingham on these particular super-groups will obviously very materially reduce the cost of the London-Manchester circuits.

Modulating Equipment.

In associating various units the policy has been to make groups and super-groups self contained as far as possible, and to associate corresponding transmitting and receiving equipment closely.

Each of the five groups occupies both sides of a 10 ft. 6 in. bay, one side being devoted to transmitting equipment and the other to receiving equipment. The super-group modulators and various subsidiary units involved in the combination of the five groups to form a super-group are mounted on one side of a sixth bay. The other side of the latter bay is occupied by similar equipment for a second super-group while the seventh to eleventh bays are used for the groups constituting this second super-group. A plan view showing the way in which the bays are associated is given in Fig. **38** and elevations of the group and super-group bays are given in Fig. **40**. This arrangement of apparatus possesses several advantages from the point of view of circuit requirements in addition to the following facilities which make the equipment flexible :—

(*a*) The groups are entirely self contained and can therefore be used for certain other purposes without alteration, e.g. extension of the range of existing 12-channel equipment ; multiplexing an ultra short wave transmitter.

(*b*) The layout of all super-groups is exactly the same.

(*c*) The bays carrying the super-group modulators etc. are independent of the group bays and may therefore be used with certain modifications for translating super-groups from one frequency band to another for the purpose of diverting blocks of circuits.

It will be seen from Fig. **40** that blank panels have been fitted where the additional modulator and demodulator units will be required when the channel spacing is reduced from 5 to 4 kc.p.s. corresponding to an increase in channels per group from 8 to 10.

In the course of maintenance it will occasionally be necessary to isolate various major units for test purposes, or it may be desired to insert special equipment for experimental work. Facilities have, therefore, been provided for breaking into the circuit at various points. The terminals of the various units of audio frequency equipment are connected to sockets mounted on one of several test tablets, the normal circuits being completed by U links. In view of the possibility of cross-talk this practice has not been extended to radio frequency equipment but sockets and U links are mounted on the various units underneath the dust covers.

The equipment is designed to work directly from the normal repeater power supplies of 24 and 130 volts.

Carrier Generating Equipment.

The working and standby sets are mounted on opposite sides of six standard 10-ft. 6-in. bays, the

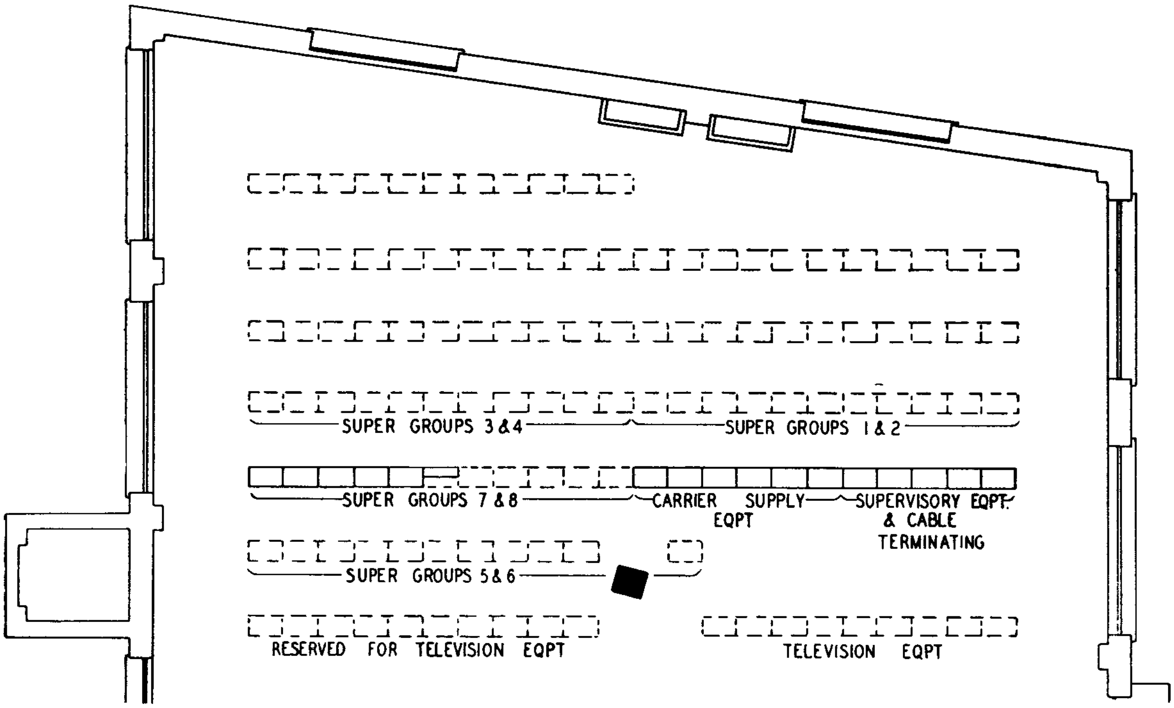


FIG. 39.—RACK LAYOUT, BIRMINGHAM TERMINAL STATION.

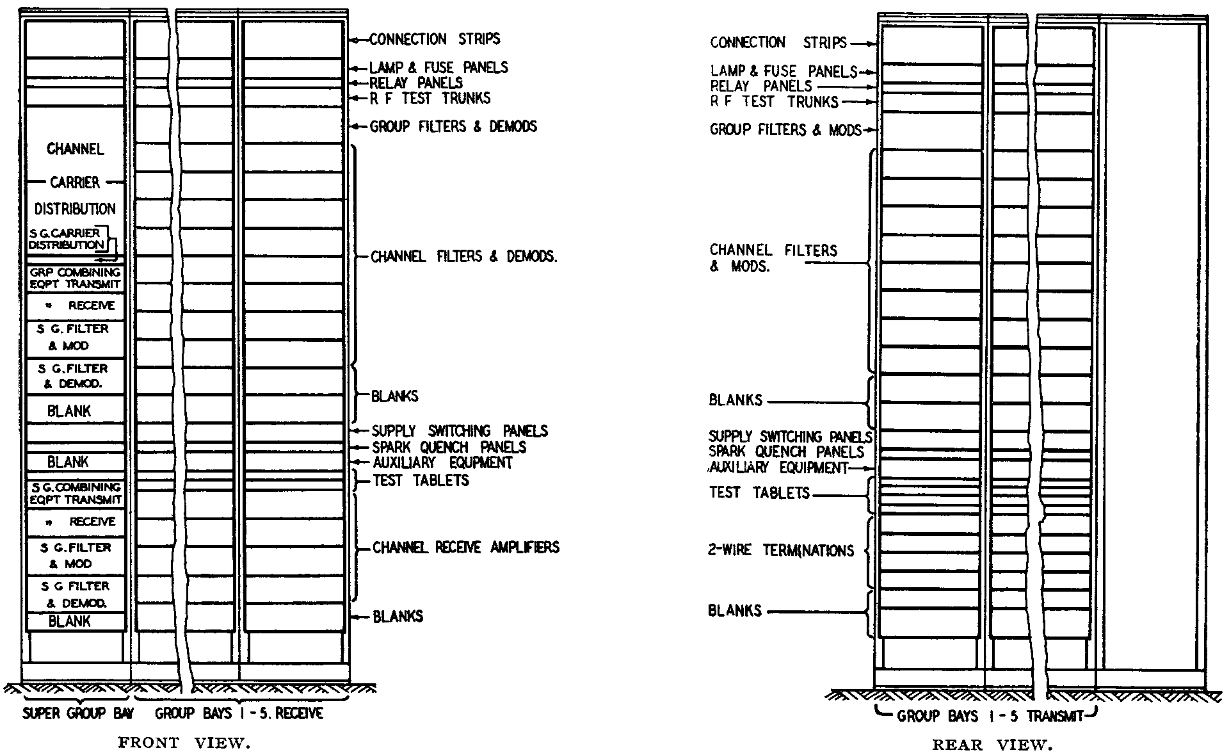


FIG. 40.—TERMINAL EQUIPMENT.

one set being an approximate mirror image of the other. Standard unit construction is employed, each unit being protected by a 6-in. dust cover. The arrangement is given in detail in Fig. **41**, the blank

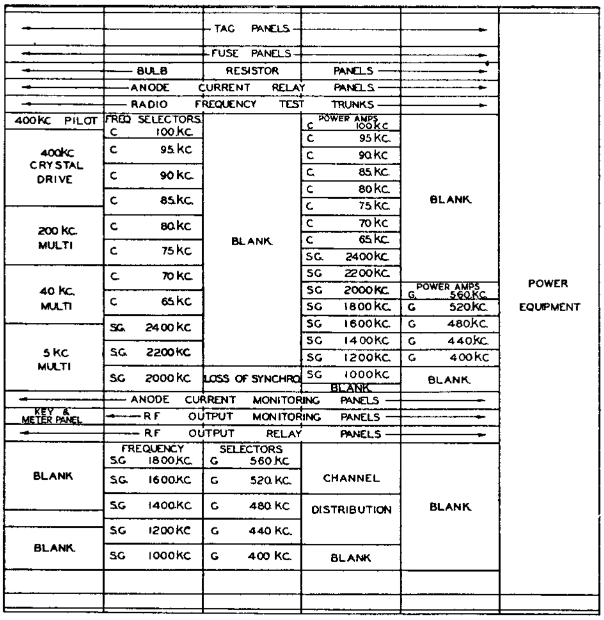


FIG. **41**.—CARRIER GENERATION EQUIPMENT.

panels occupying space reserved for additional equipment when the channel spacing is modified.

Three standard types of valve are used and each valve anode circuit is fed through a jack shunted by a fixed resistor and through a relay coil. The valve anode current is measured in terms of the volts drop across the resistor and the relay contacts are connected to a lamp and bell to give warning of a valve failure. The input voltage to each amplifier stage may be measured across a screened socket connected across the grid input circuit and the outputs of the selectors and power amplifiers are monitored in the rectifier circuit associated with each of these units.

In addition to the normal repeater power station supplies, **4** and **240** volt A.C. supplies are obtained from a power bay similar in design to the repeater station power equipment.

Repeater Station Equipment

Each repeater station is fitted with four **7**-ft. **6**-in. double-sided bays arranged for single-sided panel mounting. All panels are provided with 6-in. deep dust covers and a standard grey paint finish has been adopted throughout. Particular attention has been devoted to earthing arrangements since the presence of very small mutual impedances in the earth leads can cause serious interference. All panels are directly earthed to a $\frac{1}{4}$-in. diameter copper rod which is fixed inside the channel verticals.

The " up " and " down " coaxial cables are, in general, brought through a floor chase or duct to one end bay of the rack where the coaxial pairs and the interstice pairs are separated out at a sleeve. The coaxial pairs are brought up to two termination filter boxes mounted near the top of the bay and the telephone pairs looped in to trunk test tablets mounted near the bottom of the bay. The second bay carries the power equipment on the back and miscellaneous test, speaker and supervisory equipment on the front. The third bay carries all the H.F. equipment required for repeating the two coaxial pairs carrying the multi-channel telephone circuits. The fourth is to be used for the apparatus required for television transmission.

The front and rear views of the bays in a typical station are given in Figs. **42** and **43**.

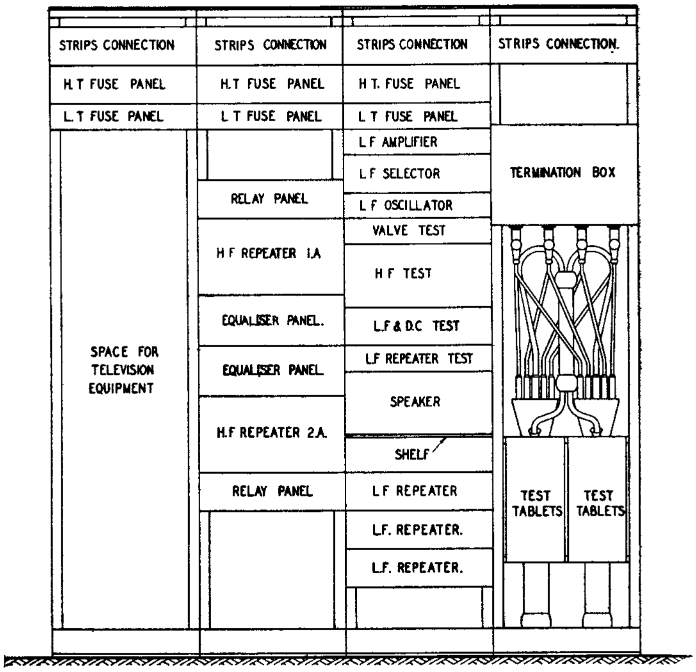


FIG. **42**.—LAYOUT OF RACKS IN MAIN REPEATER STATION. FRONT VIEW.

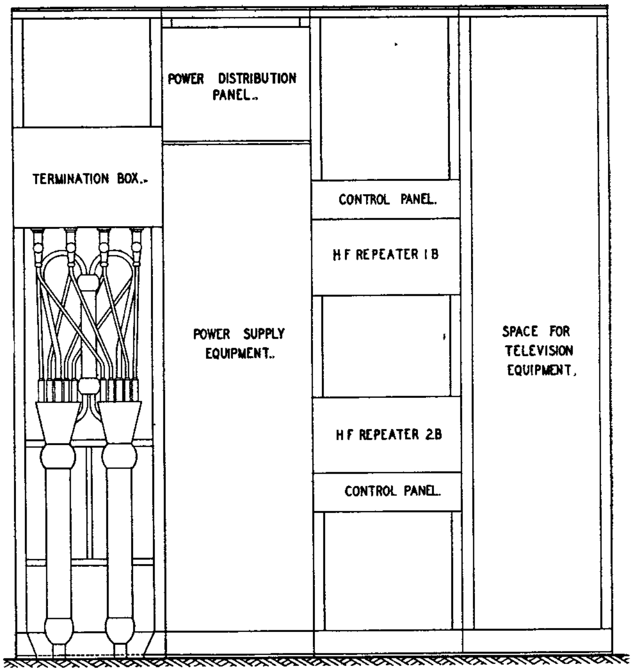


FIG. **43**.—LAYOUT OF RACKS IN MAIN REPEATER STATION. REAR VIEW.

Measured Characteristics of the Cable

The major problems encountered in the development of the coaxial cable system for the provision of circuits between London and Birmingham have been discussed and many details of the equipment given. Obviously there are many points of interest to which no reference has been made ; for instance the provision of through circuits to more distant points than Birmingham, for the cable is already well beyond Birmingham, without reducing the through signals to audio frequency at Birmingham. As the experiment is not completed,[1] detailed results are not yet available. A brief outline of the results, obtained to date follows:

Propagation Constant and Velocity.

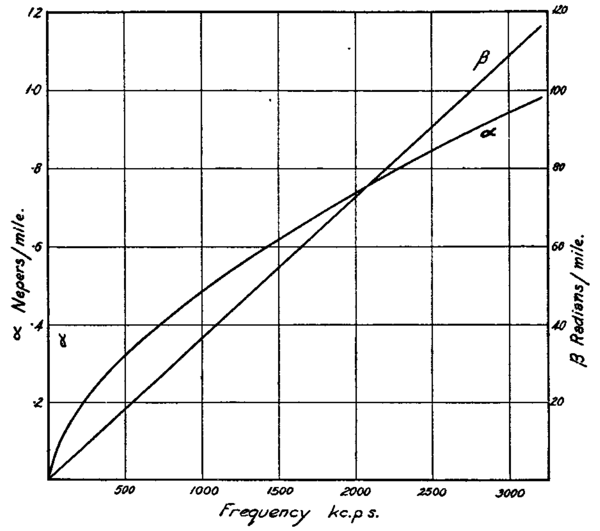


Fig. **44**.—Attenuation (α) and Wavelength (β) Constants per Mile.

Fig. **44** shows the attenuation and phase constants per mile. The phase constant is nearly proportional to frequency, the phase velocity increasing slightly with increasing frequency and approximating to about 93 per cent. of the velocity of electro-magnetic radiation in free space.

Characteristic Impedance.

Between 500 and 2,100 kc.p.s. the value is approximately 74.0 ohms, increasing slightly as the frequency decreases. At 2,100 kc.p.s. the small negative reactance component is 0.4 ohm increasing with decrease of frequency until at 500 kc.p.s. it amounts to 1.0 ohm.

Capacitance and Inductance.

The capacitance is constant apart from an apparent gradual decrease from 0.0789 microfarads per mile at 100 kc.p.s. to 0.0783 at 400 kc.p.s.

At 2,100 kc.p.s. the inductance is 0.425 millihenries per mile, increasing with a decrease in frequency and following closely the value derived from theoretical considerations.

Resistance and Leakance.

The resistance of the cable is 86 ohms/mile at 2,100 kc.p.s. and varies directly as the square root of the frequency over the band covered by the transmissions. This measured resistance is some 8 per cent. higher than the theoretical value—assuming the interleaved copper tapes to be replaced by a solid copper tube and neglecting the lead sheath—and it would appear that this difference is due to the manner in which the copper sheath is made up.

The measurements on leakance indicate a dielectric power factor, practically independent of frequency, equal to 0.0044.

Table 2.

Attenuation Measurements on the Various Repeater Sections

Repeater Section	*Average attenuation of the four coaxial pairs for each repeater section expressed in db. per mile.* Frequency kc.p.s. 200	400	800	1,200	1,600	2,000	2,400
1. Faraday Bldg., London–Gladstone Exch.	$1{\cdot}70_9$	$2{\cdot}47_1$	$3{\cdot}65_6$	$4{\cdot}61_4$	$5{\cdot}40_7$	$6{\cdot}17_9$	$6{\cdot}88_2$
2. Gladstone–Elstree	$1{\cdot}72_1$	$2{\cdot}49_6$	$3{\cdot}69_6$	$4{\cdot}61_8$	$5{\cdot}44_3$	$6{\cdot}25_0$	$6{\cdot}91_2$
3. Elstree–St. Albans	$1{\cdot}70_7$	$2{\cdot}49_0$	$3{\cdot}68_1$	$4{\cdot}59_6$	$5{\cdot}38_5$	$6{\cdot}20_0$	$6{\cdot}85_5$
4. St. Albans–The Kennels	$1{\cdot}70_6$	$2{\cdot}47_1$	$3{\cdot}58_8$	$4{\cdot}57_6$	$5{\cdot}34_3$	$6{\cdot}13_5$	$6{\cdot}80_6$
5. The Kennels–Streatley	$1{\cdot}70_2$	$2{\cdot}45_5$	$3{\cdot}62_4$	$4{\cdot}55_9$	$5{\cdot}36_0$	$6{\cdot}13_9$	$6{\cdot}80_9$
6. Streatley–Haynes West End	$1{\cdot}72_1$	$2{\cdot}47_7$	$3{\cdot}62_9$	$4{\cdot}58_0$	$5{\cdot}38_4$	$6{\cdot}17_9$	$6{\cdot}83_9$
7. Haynes West End–Bedford	$1{\cdot}71_1$	$2{\cdot}45_5$	$3{\cdot}60_4$	$4{\cdot}56_3$	$5{\cdot}37_0$	$6{\cdot}15_2$	$6{\cdot}80_4$
8. Bedford–Turvey	$1{\cdot}69_4$	$2{\cdot}45_2$	$3{\cdot}62_6$	$4{\cdot}53_3$	$5{\cdot}33_1$	$6{\cdot}13_2$	$6{\cdot}79_3$
9. Turvey–Yardley Hastings	$1{\cdot}69_8$	$2{\cdot}44_1$	$3{\cdot}60_0$	$4{\cdot}55_4$	$5{\cdot}32_5$	$6{\cdot}10_2$	$6{\cdot}80_1$
10. Yardley Hastings–Northampton ..	$1{\cdot}68_5$	$2{\cdot}43_2$	$3{\cdot}70_5$	$4{\cdot}54_8$	$5{\cdot}33_2$	$6{\cdot}13_2$	$6{\cdot}82_9$
11. Northampton–Upper Heyford	$1{\cdot}69_8$	$2{\cdot}48_7$	$3{\cdot}67_3$	$4{\cdot}62_5$	$5{\cdot}42_3$	$6{\cdot}12_3$	$6{\cdot}88_6$
12. Upper Heyford–Daventry	$1{\cdot}75_0$	$2{\cdot}52_7$	$3{\cdot}66_4$	$4{\cdot}74_3$	$5{\cdot}50_2$	$6{\cdot}20_0$	$6{\cdot}95_0$
13. Daventry–Willoughby	$1{\cdot}75_0$	$2{\cdot}53_5$	$3{\cdot}67_3$	$4{\cdot}69_4$	$5{\cdot}51_3$	$6{\cdot}23_9$	$7{\cdot}00_3$
14. Willoughby–Stretton-on-Dunsmore ..	$1{\cdot}76_9$	$2{\cdot}54_8$	$3{\cdot}77_1$	$4{\cdot}77_1$	$5{\cdot}58_9$	$6{\cdot}30_3$	$7{\cdot}05_6$
15. Stretton-on-Dunsmore–Coventry ..	$1{\cdot}78_5$	$2{\cdot}54_1$	$3{\cdot}79_8$	$4{\cdot}78_3$	$5{\cdot}61_3$	$6{\cdot}37_5$	$7{\cdot}11_2$
16. Coventry–Meriden	$1{\cdot}76_1$	$2{\cdot}54_4$	$3{\cdot}75_3$	$4{\cdot}72_1$	$5{\cdot}58_0$	$6{\cdot}36_0$	$7{\cdot}08_8$
17. Meriden-Sheldon..	$1{\cdot}77_5$	$2{\cdot}58_3$	$3{\cdot}77_4$	$4{\cdot}75_1$	$5{\cdot}59_5$	$6{\cdot}31_1$	$7{\cdot}09_8$
18. Sheldon-Birmingham	$1{\cdot}76_4$	$2{\cdot}57_6$	$3{\cdot}80_8$	$4{\cdot}82_0$	$5{\cdot}64_8$	$6{\cdot}36_2$	$7{\cdot}18_7$
Average attenuation db/mile for all sections	$1{\cdot}72_9$	$2{\cdot}49_9$	$3{\cdot}68_4$	$4{\cdot}64_7$	$5{\cdot}45_2$	$6{\cdot}21_9$	$6{\cdot}92_9$
Extreme variations from the average values in db.	$+0{\cdot}05_6$ $-0{\cdot}04_4$	$+0{\cdot}08_4$ $-0{\cdot}06_7$	$+0{\cdot}12_4$ $-0{\cdot}09_6$	$+0{\cdot}17_3$ $-0{\cdot}09_4$	$+0{\cdot}19_6$ $-0{\cdot}12_7$	$+0{\cdot}15_6$ $-0{\cdot}11_7$	$+0{\cdot}25_8$ $-0{\cdot}12_8$

[1] March 1938

Attenuation.

An attenuation-frequency characteristic for a typical repeater section has been given in Fig. **2**. Table 2 summarises in some detail the attenuation characteristics of the various repeater section lengths. The variation in attenuation among the four coaxial pairs in any one section was found to be within the limits of experimental error in making the measurements but the variation between various sections was definitely outside these limits. A general tendency should be noted for the attenuation per mile to be lower in the sections nearer London. Between Upper Heyford and Birmingham the attenuation per mile at 400 kc.p.s. was about 3.5 per cent. higher than between Upper Heyford and London, while at 2,000 kc.p.s. it was about 2.2 per cent. higher. This difference can only be accounted for to the extent of about 1 per cent. by temperature changes during the progress of the tests and the remaining difference must be due to non-uniformity in manufacture. D.C. resistance measurements on the central conductors indicate that the difference is not due to the central conductor being thicker in the sections nearer London.

Crosstalk.

The near-end crosstalk frequency characteristic of a repeater section fluctuates considerably. At frequencies above 400 kc.p.s. the near-end crosstalk was always greater than 140 db. The far-end crosstalk frequency characteristics were smooth curves showing increasing crosstalk ratios with increasing frequency. The average values at 400 kc.p.s. were about 128db between adjacent cores and 119 db. between opposite cores.

Voltage Test.

All the coaxial pairs of the several repeater sections successfully withstood an alternating (50 c.p.s.) test voltage of 2,000 V R.M.S. for 2 minutes.

Improved Types of Coaxial Cable

Since the original type of cable was designed development work by the manufacturer has been continuous. The Birmingham-Manchester coaxial cable has " super-cotopa " in place of cotopa cords for positioning the inner conductor in the tube. The result of this modification is that, although the inner and outer conductor diameters remain unaltered, the attenuation has been decreased appreciably due to a reduction in dielectric loss. In fact, this cable has the same attenuation at 2.5 Mc.p.s. as the London-Birmingham coaxial cable at 2.1 Mc.p.s. Another modification has been the substitution of mild steel tapes for the lead sheath surrounding each coaxial pair, thereby reducing crosstalk in the cable by some 10 db.

A more noticeable modification has occurred in the Manchester-Newcastle coaxial cable, the make-up of a sample of this cable being illustrated in Fig. **45**. It will be seen that the inner conductor is now positioned in the centre of the tube by means of rubber discs, spaced at intervals of about 1.25 in. This modification has reduced the dielectric loss to such a low figure that it has been found possible to reduce the dimensions of the pair to approximately 80 per cent. of their original values, at the same time retaining the same loss at 2.5 Mc.p.s. as the Birmingham-Manchester type of cable or 2.1 Mc.p.s. for the London-Birmingham design ; this reduction in size has necessarily been reflected in the cost of the cable.

Present Position (April, 1938).

Early in the development of the system it was decided that its possibilities could only be fully explored by transmitting a complete super group, i.e. 40 circuits, over the cable and arrangements were made for the construction of the required terminal and repeater station equipment ; the super group to occupy the frequency band 1,100-1,200 kc.p.s. In

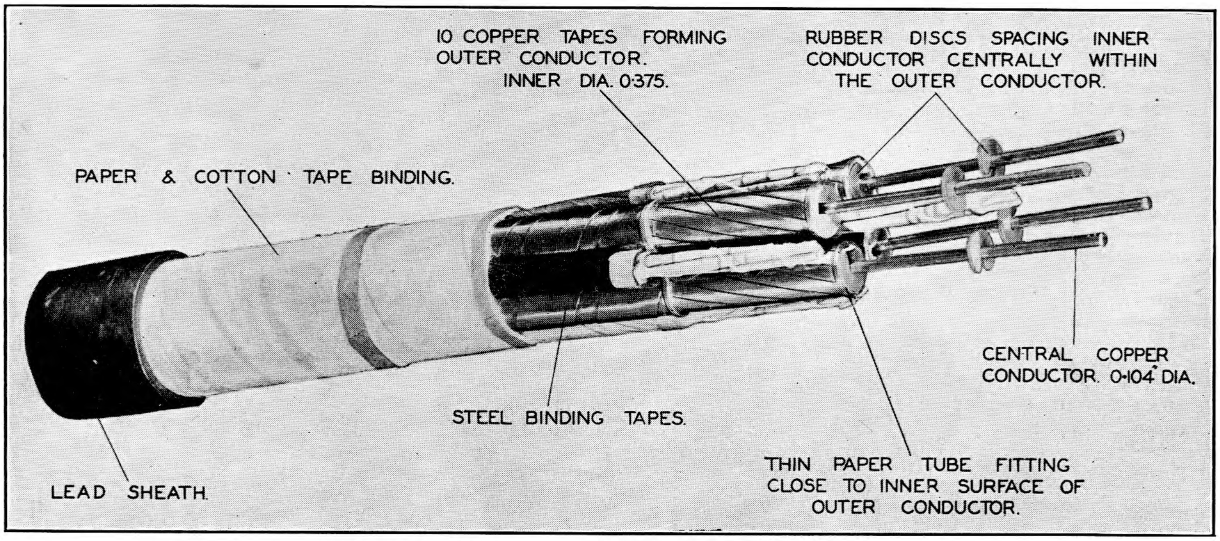


Fig. **45**.—Manchester-Newcastle Coaxial Cable.

view of the complexity of the system, it is essential that standby equipment, as outlined earlier in this paper, should always be available during commercial operation and arrangements have been made for the provision of this standby equipment so that the circuits may be handed over to and tested on traffic as early as possible. Certain preliminary overall tests of limited scope were made in mid-January of this year[2] pending the completion of the equipment.

In these tests one coaxial pair, complete with repeaters and associated equalisers, was set up in the direction London to Birmingham. For convenience, arrangements were made to transmit the signals arriving at Birmingham from London back to London at audio frequency over order wires, formed from the interstice pairs available in the complete cable; the interstice pairs are unloaded. The " looping back " of the circuit is not, of course, a normal arrangement and no attempt was made to preserve the balance of the pairs and so avoid mutual interference between the pairs and/or the coaxial pairs. Actually during the demonstration a slight amount of hum was present due to pick-up on these interstice pairs from the power supplies which are transmitted over the coaxial pairs.

The first test consisted in making a two-way conversation, both talkers being located in London, over a 4-wire circuit, the go and return channels each consisting of a coaxial channel up to Birmingham, thereby including 19 high frequency feedback repeaters, and an audio channel to bring the signals back to London, the audio frequency channel including 6 audio frequency (feedback) repeaters. Thus the talkers were separated by 250 miles of circuit. Sufficient time was not available to enable the circuit to be adjusted to have zero loss, the actual transmission equivalent being some 3 db. The demonstration was successful in every respect, the good quality and complete absence of echo being particularly noticeable.

[2] 1938

The next test was for crosstalk between the two channels. For this test tone was applied to one channel at a level 6 db. above the level that is equivalent to the volume of the loudest speech that is ever likely to be transmitted, and this will only happen, according to present evidence, in one case out of a hundred.

The level of crosstalk under these conditions was only just discernible to an experienced observer. It is probable that the crosstalk that was audible arose on the audio frequency portions of the circuit, i.e. the interstice pairs, since these are not balanced for crosstalk.

The final test consisted in connecting in tandem the go and return channels used in the two way test, so as to provide a single channel 500 miles long, having a loss of some 6 db. This set-up included approximately 250 miles of coaxial cable and corresponding repeater equipment and is equivalent to transmitting signals from London to Leeds. During this test 38 high frequency repeaters and 12 audio frequency repeaters were operating in series. A slight degradation of quality was observed due no doubt to the extra audio frequency pairs and terminal equipment, which would not normally be used. For instance, signals from London to Leeds over the coaxial cable will not normally be reduced to audio frequency at any intermediate point on the system.

Since these early tests both coaxial pairs, complete with repeaters and associated equalisers, have been set up and all the carrier generating and frequency translating equipment for 40 circuits installed and adjusted. Details of the further test results obtained will be given in a subsequent article.

Part IV.—Test Results and Commercial Operation

Introduction.

HAVING completed the installation of the apparatus panels that were essential for the transmission of a complete super-group, it was decided to make an immediate test of the simultaneous operation of 40 circuits. Thus the gains of the various modulators and amplifiers were adjusted approximately to their correct values and no attempt was made to equalise the characteristics of individual circuits, the overall loss of each circuit being left at about 3 db. This article describes this first test of a complete super-group and the work that was carried out before staging a demonstration some weeks later when the initial troubles, which are inevitable in a new system, had been remedied and the individual circuits equalised.

The First Test of a Super-Group.

This test was held on March 11th[1] and was arranged in the following manner. Thirty-five of the circuits were connected at each end to telephones adjacent to the terminal equipment, the five remaining circuits being connected to telephones located in situations relatively free from room noise. Separate tests showed that for the normal talker the telephones delivered on the average an output of approximately 8 db. below R.T.P. Since the telephones were connected directly to the 2-wire sides of the hybrid transformers terminating the coaxial circuits, it is to be expected that the power delivered by these telephones during the test was approximately 6 db. above the average value that would be encountered under traffic conditions. The thirty-five circuits first mentioned were loaded by conversations between female switchboard operators and the remaining five were reserved for the use of persons especially concerned with the test.

Briefly, the results of the test were as follows:

(*a*) The articulation on the circuits was considered to be good and there was a complete absence of echo as such; it is certain that an appreciable echo must have been present, but owing to the high velocity circuits employed it appeared merely as side tone and could not be detected.

(*b*) A slight amount of crosstalk was observed which, it was suspected, would have been intelligible if its level had been higher. There was, however, no trace of babble when the operators were conversing normally or when all the operators at one end were talking very loudly.

(*c*) A certain amount of noise was present having the characteristics of A.C. power interference and D.C. generator noise combined.

(*d*) The operators, except one at London and another at Birmingham, expressed the opinion that the circuits were better than the trunk circuits on which they were normally employed.

[1] 1938

Modifications Made as a Result of this Test.

Subsequent to the preliminary test the work of preparing the coaxial equipment for traffic was resumed. At the same time an investigation into the sources of noise and crosstalk observed during the demonstration was made with the following results.

The crosstalk was found to be occurring in the audio-frequency bay wiring and was overcome by earthing one side of each of the pairs concerned.

Further, it was found that the noise was introduced into the system at the two terminal stations. Part of the noise was due to direct magnetic induction into the channel receive amplifiers from the power equipment on the carrier supply and repeater bays, and this was overcome by substituting sheet-metal covers for the expanded metal guards protecting the power transformers and chokes mounted on these bays.

The remainder of the noise observed during the test was due to the fact that at London, and to a minor extent at Birmingham, there is a considerable ripple voltage between the "rack" and "silent" earths, affecting both the modulating and carrier-generating equipment. The trouble was overcome by using appropriate earths at various key points in the equipment. Thus it was necessary to insulate the cases of transformers from the panel in certain parts of the equipment; it was subsequently discovered that this practice is normally followed at Faraday Building, London, but not at Telephone House, Birmingham, presumably due to the ripple voltages prevalent at Faraday Building being greater.

The coaxial channels were then equalised with the result that the overall transmission lay, with a few exceptions, between the limits of $\pm$ 1 db. of the value at 1,500 c.p.s., for frequencies ranging from 250 to 3,100 c.p.s.; the characteristics of the channels which came outside these limits will be improved at a later date.

Interference.

A day or two previous to the main demonstration it was found that a 1,000 c.p.s. tone of comparatively low level, more than 50 db. below reference level, was present on one of the circuits during the transmissions of the London National broadcasting station, working frequency 1,149 kc.p.s. A preliminary investigation indicates that the high frequency carrier wave of this station is probably being picked up at one or more of the intermediate repeater stations and demodulated at the terminal stations along with the wanted signals. While the point is being thoroughly investigated, narrow band elimination filters will be used to remove the unwanted signal from this particular circuit.

Characteristics of the Equipment and System.

Channel Filters.—The channel filters incorporated in the terminal equipment include quartz crystal resonators in addition to inductors and capacitors. The characteristics of the network are such that it is necessary to manufacture the individual elements to relatively close limits, and the adjustment of a complete filter is a process calling for considerable precision although it has not been found difficult to train junior staff to carry out the adjustment. As variations in temperature must alter the values of the filter elements to some extent it was considered possible that the performance of the filters in service might prove to be affected materially by changes in ambient temperature. In an investigation of the point, the insertion loss characteristic of certain channel filters was measured, while the temperature of the filter was varied over a range of 18° C., an adequate time interval being allowed during the test to allow the complete filter to attain the extreme limits of temperature. The results showed that, at least over the range of temperature over which measurements were made, temperature had little effect on the performance of these filters. There was no appreciable change in the frequencies at which peak attenuation occurs, but in the pass band there was a slight increase in the average attenuation with increase of temperature and a tendency for small irregularities of attenuation to increase. The increase in attenuation is probably due to a small rise in the power factor of the inductors and the increase in magnitude of the small irregularities is no doubt due to very small changes in the effective reactance of the elements comprising the filter. It was satisfactory to observe that the behaviour of the filters was substantially cyclic. A temperature range of 18° C. is considerably in excess of that likely to be encountered in practice and it is confidently anticipated that the variations of temperature occurring under working conditions will have a negligible effect on the performance of the channel filters.

In view of the fact that the crystal plates are supported in their holders solely by two pairs of contacts pressing on opposite sides along the nodal plane of the plate, it was thought possible that the performance of the filters might be adversely affected by vibration. The effect of vibration was checked to some extent by transporting a number of filters, fairly carefully packed in strong wooden cases, over a distance of 230 miles in a commercial 2-ton van, the characteristics of the filters being measured before and after the journey. The modifications which occurred in the characteristics were so small as to be of negligible importance; they were in fact of the same order of magnitude as the variations in performance among a number of filters of the same type immediately after they have been adjusted; thus vibration should have a negligible effect if the filters are handled with reasonable care.

It is preferable to give the limits, within which lie the characteristics of all the units comprised in a certain part of any system, rather than the characteristics of a few selected isolated samples, the latter method merely showing the degree of perfection

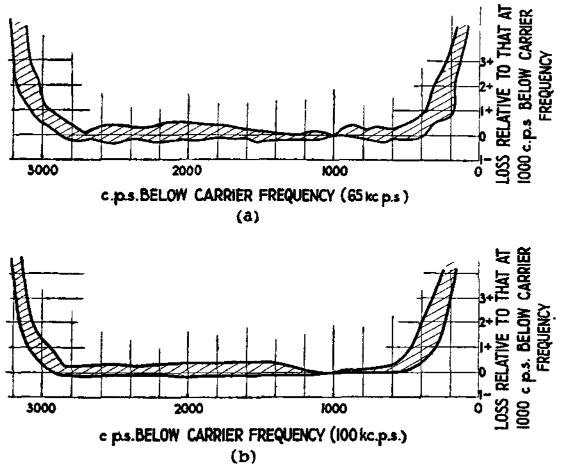


FIG. 46.—ENVELOPE OF FREQUENCY/LOSS CHARACTERISTICS OF TWO SETS OF CHANNEL FILTERS.

attained in any particular characteristic without giving any indication as to how closely the remainder of the units approach this sample. The former method has been adopted here and the limits presented in the form of an envelope, within which the actual characteristic of any particular unit is contained, the reference point being clearly specified. For instance, Fig. **46** shows the envelope of the frequency/loss characteristics of two sets of 22 channel filters, 20 working and two spare in each set, used in connection with the 60-65 and 95-100 kc.p.s. channels in either the first modulation or the final demodulation process; the losses being measured with respect to the loss at the frequency 1,000 c.p.s. below the carrier frequency.

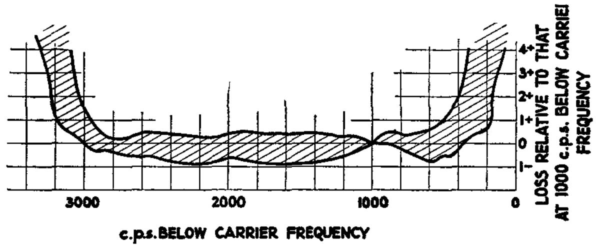


FIG. 47.—ENVELOPE OF FREQUENCY/LOSS CHARACTERISTICS OF CHANNEL FILTERS IN FIRST SUPER-GROUP.

Fig. **47** is the envelope of the frequency/loss characteristics of all the channel filters made for this first super-group, irrespective of the carrier frequency, the frequency/loss curves of each individual filter being made to coincide at a point 1,000 c.p.s. below the actual carrier frequency of that particular channel. It demonstrates the closeness to which the various sets of channel filters, used in the group combination, have been designed, as well as the constancy of reproduction of characteristics during manufacture and adjustment. It will also be seen that the spread of the envelope does not exceed 2·2 db. at any frequency between 400 and 3,000 c.p.s. below the actual carrier frequencies.

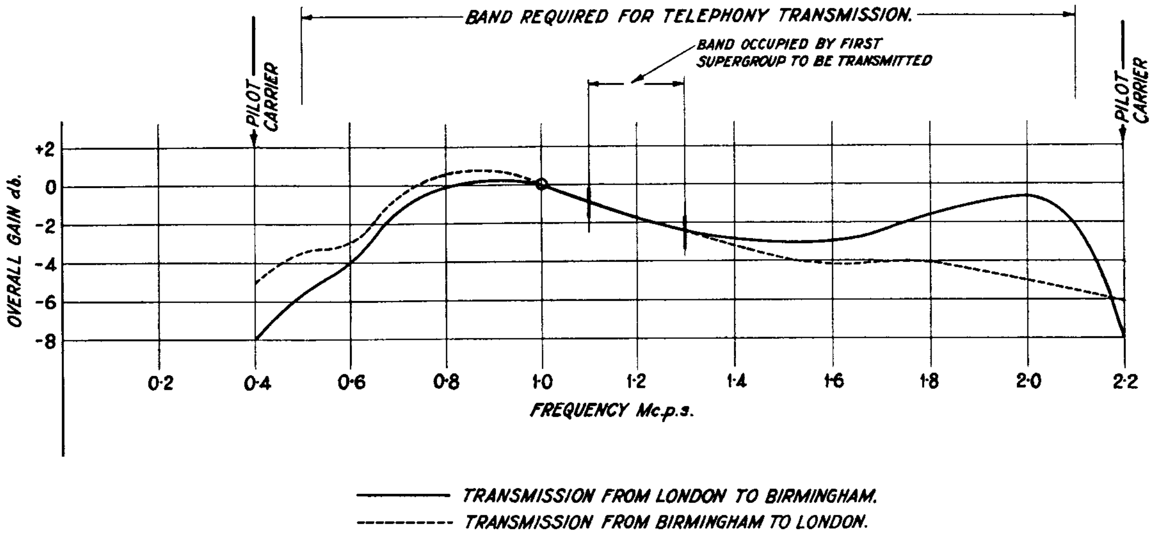


FIG. 48.—OVERALL GAIN/FREQUENCY CHARACTERISTIC OF THE COAXIAL LINE AND REPEATERS (APRIL 23rd, 1938).

The Equalised Line.—The overall characteristics of the coaxial lines, repeaters and associated equalisers between London and Birmingham are shown in Fig. **48**, although it must not be inferred that this represents the ultimate characteristic since, as explained earlier, the experimental work is still continuing. It will be seen that the overall characteristic over the frequency band 0·5 to 2·1 Mc.p.s. lies within ± 3 db. of the value at the midband frequency; the variation over the band occupied by the first super-group imposed on the system being 1·5 db. Some variation of the characteristic must be expected due to the effect of temperature changes and a possible lack of perfect compensation by the temperature compensation equalisers; the present data is far too meagre to discuss the point further.

Overall Gain/Frequency Characteristics of the Audio Channels.—Envelopes of the transmission characteristics, 2-wire—2-wire, of the London to Birmingham channels separated into the five groups forming the super-group are shown in Fig. **49**; the envelopes of the return channels are very similar to those illustrated. It will be seen that a high degree of uniformity in design and adjustment of the various parts of the systems has already been achieved, and yet an improvement, both in the degree of uniformity and width of frequency response for a reduced channel separation, is already envisaged.

Fig. **50** shows the characteristic of the complete super-group of London–Birmingham channels, 2-wire—2-wire, previously considered in Fig. **49** on a group basis, measured with respect to (*a*) 800, (*b*) 1,000, (*c*) 1,500 c.p.s. The specified limits were expressed relative to the gain at 800 c.p.s. and an inspection of Fig. **50** (*a*) will show that the channels comply with the specification. As a matter of some interest, the anticipated transmission characteristic, first disclosed over a year ago, has been superimposed on the envelope. For the 800 c.p.s. reference point, the anticipated curve has proved to be the mean of the envelope.

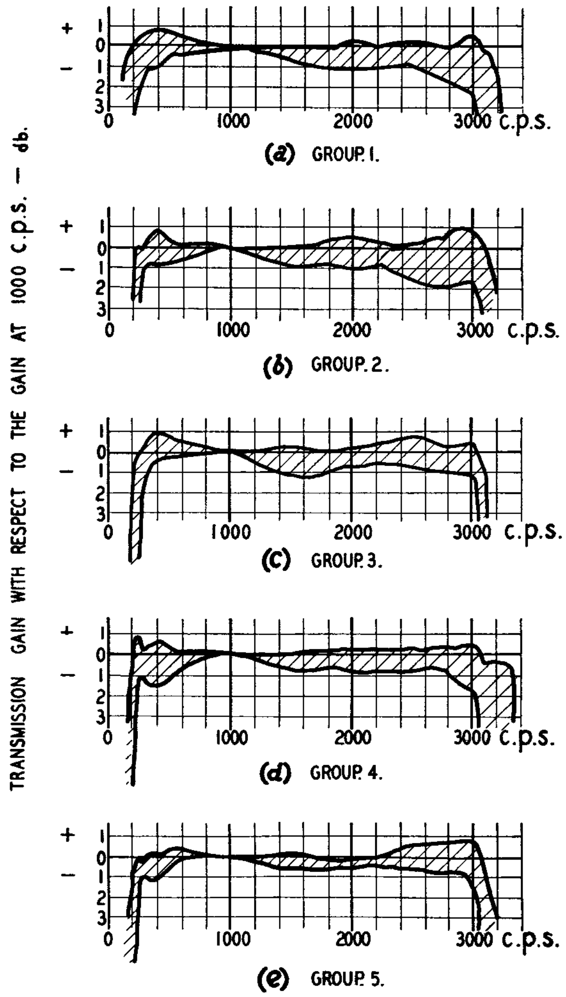


FIG. 49.—ENVELOPE OF THE TRANSMISSION CHARACTERISTICS (2-WIRE—2-WIRE) OF THE CHANNELS COMPRISED IN THE VARIOUS GROUPS.

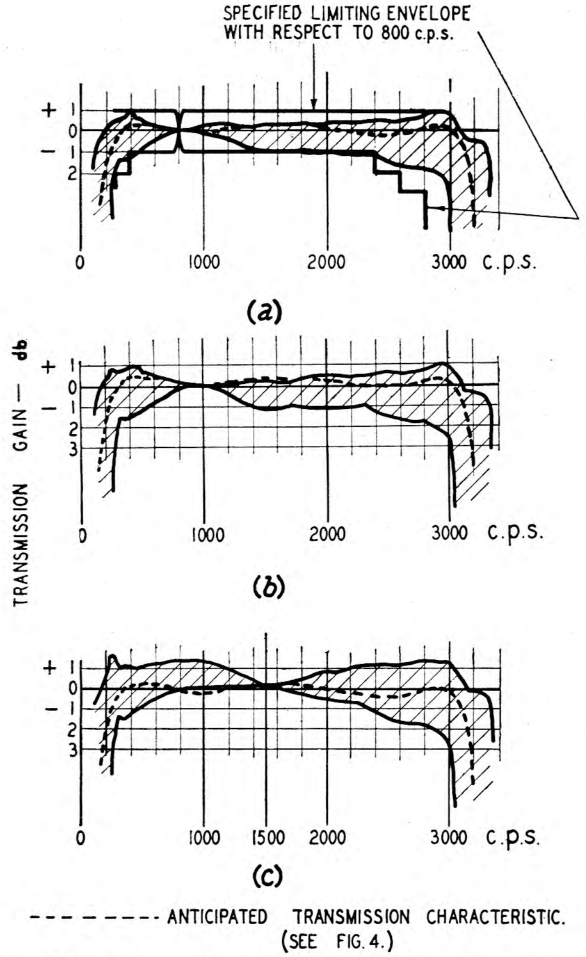


FIG. 50.—ENVELOPE OF TRANSMISSION CHARACTERISTICS OF THE 40 LONDON-BIRMINGHAM CHANNELS (2-WIRE—2-WIRE) WITH RESPECT TO (*a*) 800 C.P.S., (*b*) 1,000 C.P.S., (*c*) 1,800 C.P.S.

The Main Demonstration.

The main demonstration was given on April 11th, 1938, and was carried out on the same general lines as those of the previous test; the circuits being adjusted to have a transmission loss of approximately 1 db. The circuits were quiet, the articulation good, crosstalk and babble completely absent. Certain observers stated they experienced a feeling of confidence in the stability of the circuits in speaking over them which they felt was lacking when using the normal low loss trunk circuits. This is no doubt due to a subconscious reaction against the changing conditions of a normal circuit brought about by the operation of the echo suppressors. As has already been pointed out for a coaxial circuit the echo merges completely with the side tone and echo suppressors are not used.

Towards the end of the demonstration seven circuits were connected in series to form a single circuit some 800 miles long; thus the speech in each channel went through 42 modulation processes and in effect some 133 high frequency repeaters, using 532 valves. The performance of this circuit was good although slightly inferior to that of the single-length London–Birmingham circuit. There was still

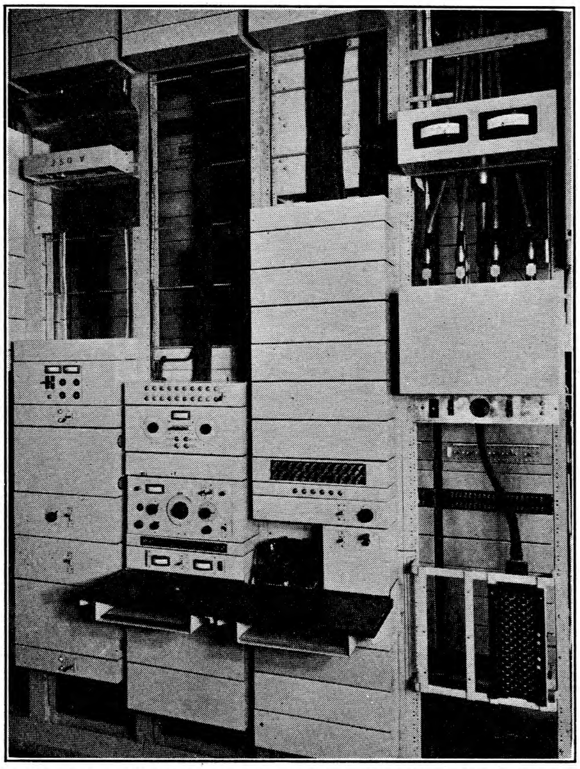


FIG. 51.—TERMINAL REPEATER STATION, LONDON.

no noticeable echo, the transmission time between the two ends of the complete circuit still being less than 5 milliseconds. The degradation on performance was obviously due to the six intervening points at which

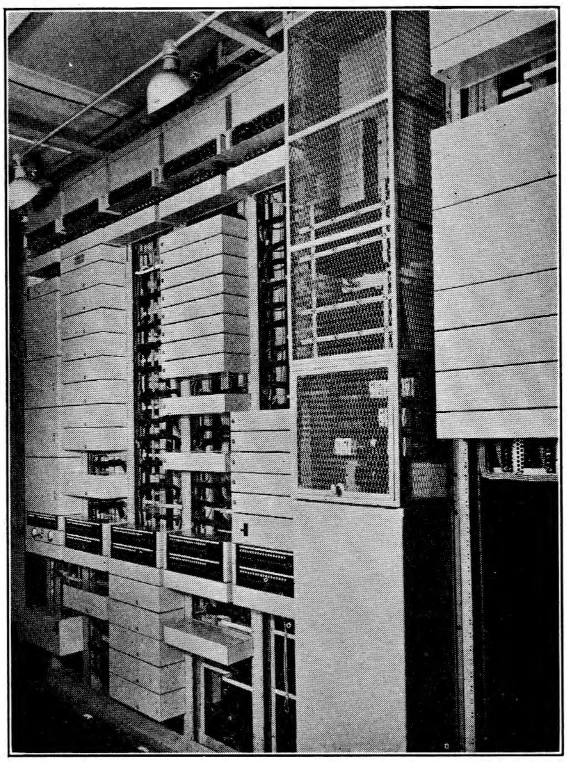


FIG. 52.—CARRIER GENERATING EQUIPMENT, LONDON.

limiting, modulation and demodulation occurred, the majority of which would not normally be present in a commercial circuit of that length.

Commercial Operation.

In accordance with a previous agreement the circuits were handed over for part-time traffic (week-days, 9.30 a.m.–4.30 p.m.) on the day following the main demonstration, i.e. April 12th, 1938. The circuits are at present[2] working traffic very successfully on this basis without the supervisory and repeater standby equipment which is now being installed and adjusted; thus an appreciable risk of breakdown must be faced by the Traffic Group utilising the circuits. The commercial operation is, however, most valuable, since it enables data to be accumulated under the actual conditions of operation at an early stage of the installation, forming an indispensable check upon the previous calculations. It is anticipated that the adjustment of the outstanding equipment will be completed within the next few months.

Figs. **51** and **52** show portions of the completed equipment installed in the London Terminal Repeater Station.

[2] July 1938.

Acknowledgments.

In conclusion, it is desired to thank Messrs. Standard Telephones & Cables, Ltd., the contractors responsible for manufacturing most of the equipment, for their ready assistance in many matters, and also the author's colleagues who have assisted not only in the preparation of this series of articles but also in the development, design and adjustment of the equipment. Obviously, there are many who have contributed materially to the development described but who cannot be mentioned individually. The author would, however, like to mention and thank individually the nucleus, Messrs. R. F. J. Jarvis, C. F. Booth, H. Stanesby and R. A. Brockbank, around whom the team responsible for this work has been built. The remainder of the team know and can rest assured that their efforts are valued and appreciated and will perhaps accept this public expression of thanks as an acknowledgment of their efforts.

Finally, the team desire to record their appreciation of the encouragement and advice received from the Engineer-in-Chief, Sir George Lee, his deputy, Col. Angwin, and Mr. A. J. Gill, under whose immediate direction this work has been carried out.

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