Repeater Design for the North Atlantic Link

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Some of the considerations governing the electrical and mechanical design of flexible repeaters and their component apparatus are discussed in this paper. The discussion includes description of the feedback amplifier and the sea-pressure resisting container that surrounds it. Examples are given of some of the extraordinary measures taken to ensure continuous performance in service.

INTRODUCTION

Repeaters for use in the transatlantic submarine telephone cable system had to be designed to resist the stresses of laying, and to withstand the great pressures of water encountered in the North Atlantic route. In anticipation of the need for such a long telephone system in deep water, development work was started over 20 years ago on the design of a flexible repeater that could be incorporated in the cable and be handled as cable by conventional cable ship techniques. Successful completion, in 1950, of the design and construction of the 24-channel Key West, Florida-Havana, Cuba system,[3] led to the adoption of similar repeaters designed for 36 channels for the North Atlantic link discussed in companion papers.[1, 2]

Repeater transmission characteristics determine, to a large extent, the degree to which system objectives can be met. In this repeater, significant characteristics are:

(a) *Noise and Modulation*. These were established by the circuit configuration and by the use of the conservative electron tube[8] developed for the Key West-Havana project.

(b) *Initial Misalignment*, or mismatch of repeater gain and cable loss throughout the transmitted band of frequencies. A match within 0.05 db was the objective. This affected both the design and the precision required in manufacture.

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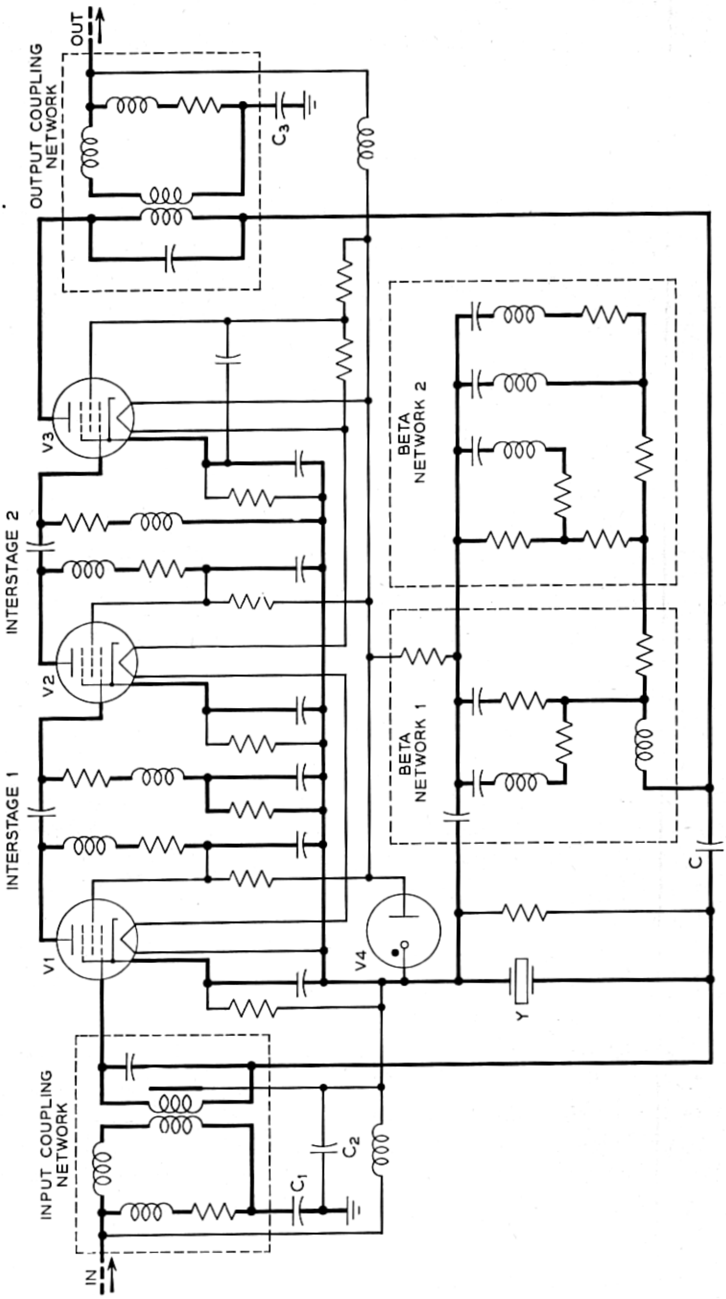


Fig. 1 — Repeater schematic.

(c) *Aging.* As electron tubes lose mutual conductance with age, repeater feedback decreases, repeater gain changes, and misalignment is affected. Decrease in feedback increases the gain at the higher frequencies so that the signal input must be reduced to prevent overloading, resulting in a signal-to-noise penalty. Gain increase is inversely proportional to the amount of feedback; in these repeaters, 33 to 34 db of feedback was the objective to keep this source of misalignment in bounds.

Because repeaters are inaccessible for maintenance, facilities are provided to enable the individual repeater performance to be checked from the shore end. This feature also permits a defective repeater to be identified in the event of transmission failure.

REPEATER UNIT

The repeater, for the sake of discussion, may be divided into two parts, (1) the repeater unit, which contains the electron tubes and other circuit components and (2) the water-proof container and seals which house the repeater unit.

Circuit

The circuit of the repeater unit is shown in Fig. 1. It is a three-stage feedback amplifier of conventional design with the cathodes at ac ground. The amplifier is connected to the cable through input and output coupling networks. Each coupling network consists of a transformer plus gain-shaping elements and a power separation inductor.

The coupling networks directly affect the insertion gain as do the two feedback networks. The design of these networks controls the insertion gain of the amplifier. The required gain (inverse of cable loss) is shown in Fig. 2. The 39 db shaping required between 20 and 164 kc is divided approximately equally among the input and output coupling networks and the feedback networks.

The interstage networks are of conventional design. The gain of the first interstage is approximately flat across the band. The second interstage has a sloping characteristic, the gain increasing with frequency. The gain shaping of these networks offsets the loss of the feedback networks so that the feedback is approximately flat across the band.

Plate and heater power is supplied to the repeater over the cable.[4] The plate voltage (approximately 52 volts) is obtained from the drop across the heater string. The dc circuits are isolated from the container by the high voltage blocking capacitors C_1, C_2 and C_3.

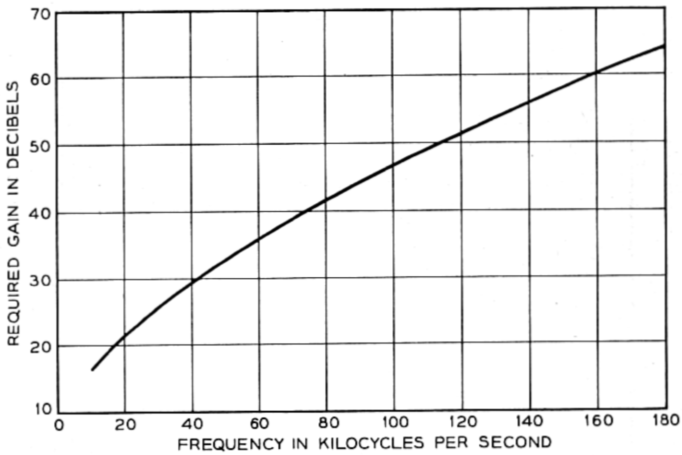


Fig. 2 — Required insertion gain.

Gain Formula

The circuit of Fig. 1 may be represented by a simplified circuit consisting of an input coupling network, a three stage amplifier, an output network and a feedback impedance Z_β as shown in Fig. 3. From this figure it can be shown that the insertion gain of the repeater is given by:[6]

$$e^\theta = \frac{2e^{\theta_1}e^{\theta_2}Z_c}{Z_\beta}\left[\frac{\rho_i\rho_0 g_{mT}Z_1Z_2Z_\beta}{1 - \rho_i\rho_0 g_{mT}Z_1Z_2Z_\beta}\right] \tag{1}$$

when $Z_\beta \ll g_{mT}Z_pZ_gZ_1Z_2 \gg (Z_0 + Z_p)$ and where

$$\rho_i = \frac{Z_g}{Z_i + Z_g} \qquad \text{and} \qquad \rho_0 = \frac{Z_p}{Z_0 + Z_p}$$

are "potentiometer terms". The gain of the input network is defined as $e^{\theta_1} = V/E_i$; where V is the open circuit voltage of the input network with E_i as the source, and the gain of the output network is defined as $e^{\theta_2} = i/I_1$. This expression may be put in familiar form by recognizing that $\rho_i\rho_0 g_{mT}Z_1Z_2Z_\beta$ is $\mu\beta$, the feedback around the loop. Hence

$$e^\theta = \frac{2e^{\theta_1}e^{\theta_2}Z_c}{Z_\beta}\left[\frac{\mu\beta}{1 - \mu\beta}\right] \tag{2}$$

Equation (2) shows that the insertion gain of the repeater is the product of five factors, namely:

(1) e^{θ_1} — the gain of the Input Network
(2) e^{θ_2} — the gain of the Output Network
(3) Z_c — the cable impedance
(4) Z_β — the feedback impedance
(5) $(\mu\beta/1 - \mu\beta)$ — the $\mu\beta$ effect term

It should be noted that a number of simplifying assumptions have been made. For example, the effect of grid plate capacitance has been neglected. In addition the β circuit has been assumed to be a two terminal impedance whereas it is actually a four terminal network. However, in the pass band and over a large part of the outband of the repeater these simplifications give a very good approximation to the true gain of the repeater.

In the pass band $(\mu\beta/1 - \mu\beta)$ is very nearly unity so that the gain controlling factors are e^{θ_1}, e^{θ_2}, and $1/Z_\beta$ assuming that Z_c is fixed.

Coupling Networks

The input and output networks are essentially identical. The networks are of unterminated design and therefore do not present a good termination to the cable at all frequencies which results in some ripple in the system transmission characteristic at the lower edge of the band and makes the repeater insertion gain sensitive to variations in the cable impedance. However, this arrangement has the advantage of maximum

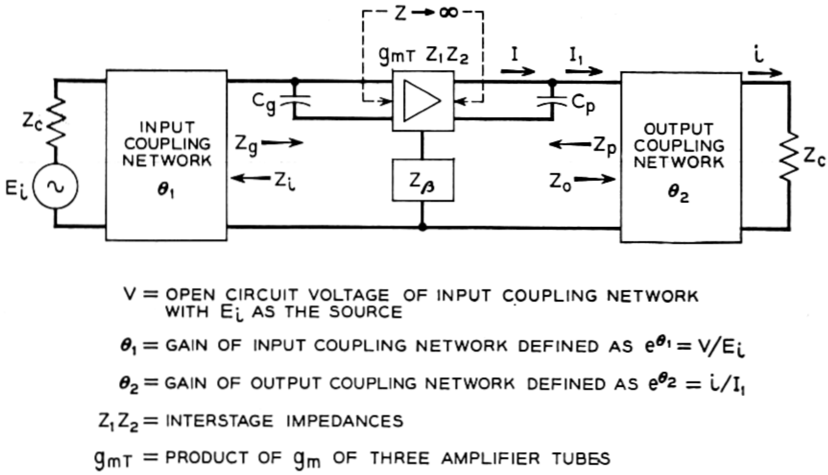


Fig. 3 — Simplified amplifier circuit.

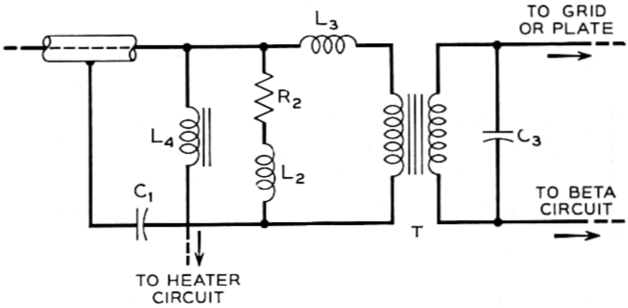


Fig. 4 — Coupling network.

signal to noise performance, highest gain, and most effective shaping with a minimum of elements. A minimum of elements is important in view of the space restrictions imposed by the flexible repeater structure. The sensitivity of the gain to variation in impedance is minimized by close manufacturing control of the cable and networks.

The schematic of a coupling network is shown in Fig. 4 and the equivalent circuit in Fig. 5. Capacitor C_1 and inductor L_4 are part of the power separation circuit. The effect of L_4 in the transmission band is negligible and it has been omitted from the equivalent circuit. However C_1 is in the direct transmission path and has a small effect at the lower edge of the band so that it becomes a design parameter. The combination R_2, L_2 controls the low-frequency gain shaping of the network. Inductor L_3

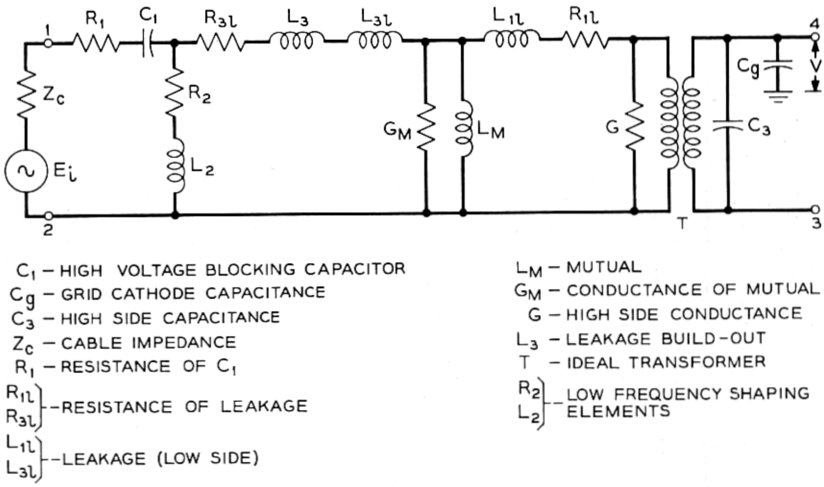


Fig. 5 — Equivalent circuit of coupling network.

builds out the leakage inductance of the transformer and together with capacitor C_3 controls the shaping at the top end of the band. These elements are adjusted during manufacture of the networks to provide the desired shaping.

The equivalent circuit is an approximation to the true transformer circuit. By standard network analysis techniques the ratio V/E_i, the gain of the network, can be obtained. The agreement between measurements and computation is sufficiently close, several hundredths of a db, to insure that the representation is good.

Each coupling network is designed to provide approximately one-third of the total shaping required, or 13 db. While these networks are

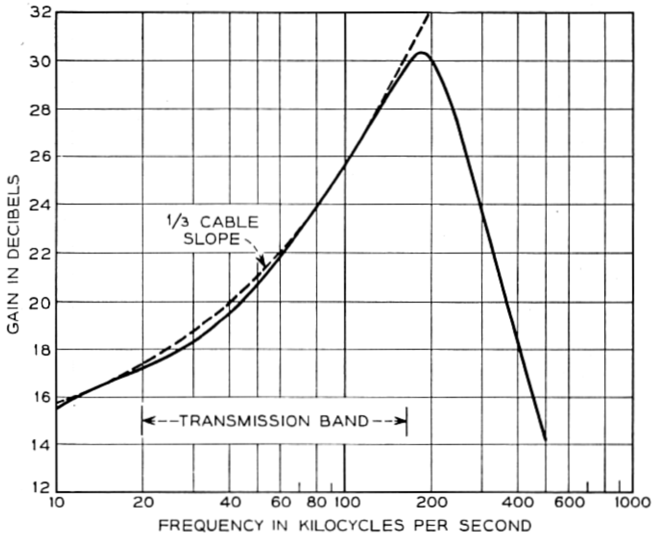


Fig. 6 — Gain of input coupling network.

outside the feedback path, the impedances which they present to the amplifier are important factors in the feedback design. It can be seen from Fig. 3 that at the amplifier input the proportion of the feedback voltage which will be effective in producing feedback around the loop is dependent upon the potentiometer division between the grid-cathode impedance of the first tube and the impedance looking back into the coupling network. The greater the gain shaping of the network, the greater the potentiometer loss. The maximum gain which can be obtained from the coupling network is limited by the capacitance across the circuit. This capacitance cannot be reduced without increasing the

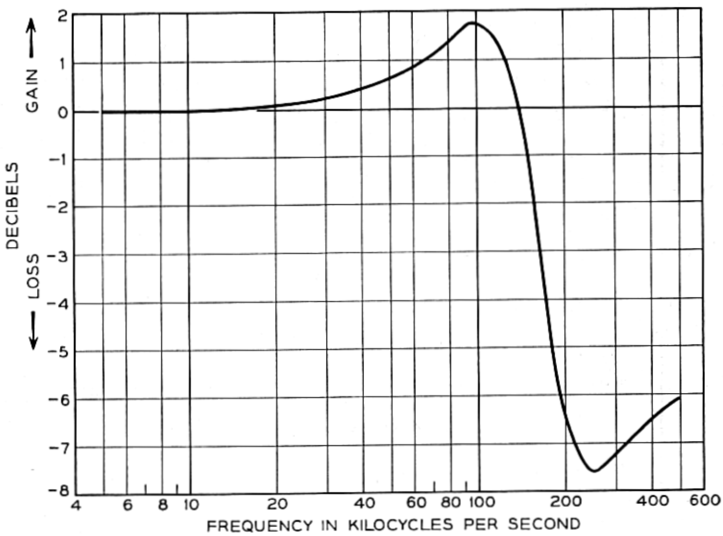


Fig. 7 — Input potentiometer term.

potentiometer loss, and seriously limiting feedback. In this design an acceptable compromise is made when the ratio of network capacitance to grid-cathode capacitance has been fixed at 1.2 as suggested by Bode.[6] The gain through the input network and the deviation from one-third cable shape is shown in Fig. 6. A typical potentiometer term is shown in Fig. 7

Similar considerations apply to the output network with the further restriction that the impedance presented to the output tube should be about 40,000 ohms at the top edge of the band for optimum modulation performance.

The coupling networks have a temperature characteristic which must be taken into account in the insertion gain of the repeater. The characteristic is due to variations in the resistance of C_1 and R_2 with temperature. This amounts to 0.005 db per degree F at 20 kc, decreasing with frequency, becoming negligible above 80 kc.

Beta Circuit

The beta or feedback network is designed to complement the combined characteristics of the input and output coupling networks and mop-up residual effects, such as those due to $\mu\beta$ effect and coupling network temperature coefficients. The network also provides the dc path for the output tube plate current.

The configuration of the beta circuit is shown in Fig. 8. In the pass band it is a two terminal network whose impedance varies from about 300 ohms at 20 kc to 70 ohms at 164 kc. It consists of essentially two parts. The elements to the left of the dotted line provide the major portion of the shaping. With these the repeater is within ±0.7 db of the required gain. The series resonant circuits to the right of the dotted line reduce this to the ±0.05 db set as the objective.

The mopping up elements are connected to the main portion of the beta circuit through a resistance potentiometer R_1, R_2 and R_3. This scales the elements of the resonant circuits to values which would meet mounting space and component restrictions.

Built-in Testing Features

The crystal Y and capacitor C, Fig. 1, in the feedback path provide the means for checking the repeater from the shore station. The crystal is a sharply tuned series-resonant shunt on the feedback path which reduces the feedback at the resonant frequency and produces a narrow peak in the insertion gain characteristic of the repeater. The feedback reduction, and hence the peak gain, is controlled by the potentiometer divider formed by the reactance of the capacitor and the series resonant resistance of the crystal. The crystal and capacitor are chosen so that substantially all the feedback is removed from the repeater. With no feed-

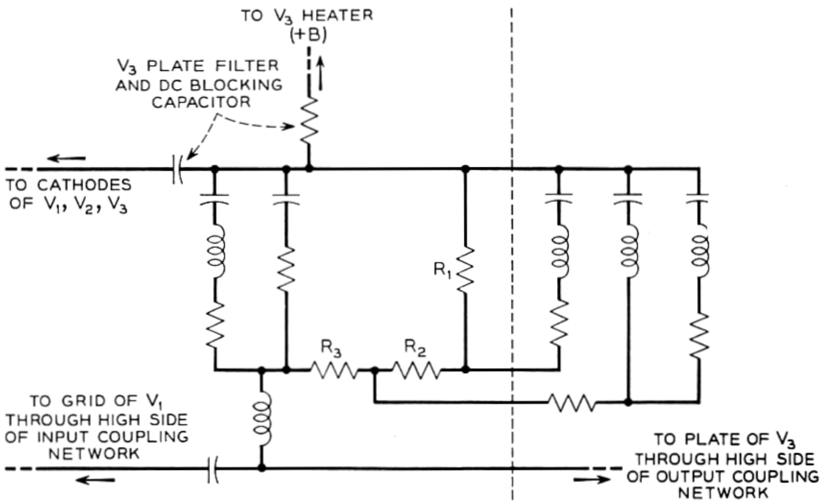


Fig. 8 — Beta network.

back the peak gain is proportional to the mutual conductance of the three tubes.

At frequencies well off resonance the impedance of the crystal is high so that no reduction in feedback results. Periodic measurements of gain at the resonant frequency relative to measurements made at a frequency off resonance will show any changes in the tubes. The crystal frequency is different for each repeater so that by measuring the gain from the shore stations at the various crystal frequencies it is possible to monitor the performance of the individual repeaters.

The increase in gain at the peak is approximately 25 db. The crystal frequencies, spaced at 100-cycle intervals, are placed above the normal transmitted band between 167 and 173.4 kc.

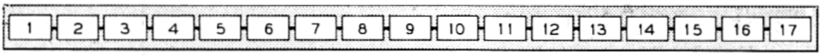
Thermal noise always present at the input to the repeater, is also amplified over the narrow band of frequencies corresponding to the peak gain in each repeater so that at the receiving end of the line there are a series of noise peaks, one for each repeater. Should a repeater fail, the noise peaks of all repeaters between the faulty repeater and the receiving end will be present and those from repeaters ahead will be missing. By determining which peaks are missing the location of the failed repeater can be determined. It is obvious that to locate a faulty repeater the power circuit must be intact. To guard against power interruption owing to an open electron-tube heater, a gas tube V4, Fig. 1, is connected across the heater string as a bypass.

Loop Feedback

The design of the feedback loop follows conventional practice. The restrictions that limit the amount of feedback that can be obtained in the transmitted band are well known.[6] Broadly speaking, the figure of merit of the electron tubes and the incidental circuit capacitances determine the asymptotic cutoff which limits the amount of feedback that can be obtained in the band. With the flexible repeater circuit, capacitances are rather large because of the severe space restrictions and physical length of the structure. Transit time of 1.8° per megacycle per tube and a like amount for the physical length of the feedback loop reduced the available feedback by 2 db.

Margins of 10 db at phase cross-over and 30° at gain cross-over were set as design objectives. While these may seem to be ultraconservative in view of the tight controls placed on components and the mechanical assembly, it should be borne in mind that the repeaters are inaccessible and repairs would be costly.

Modulation and tube aging considerations require a minimum feed-



1 INPUT TERMINAL
2 INPUT BLOCKING CAPACITOR
3 GROUNDING CAPACITOR
4 CRYSTAL
5 INPUT NETWORK
6 VACUUM TUBE (FIRST STAGE)
7 FIRST INTERSTAGE NETWORK
8 VACUUM TUBE (SECOND STAGE)
9 SECOND INTERSTAGE NETWORK
10 VACUUM TUBE (THIRD STAGE)
11 OUTPUT NETWORK
12 BETA NETWORK (1)
13 BETA NETWORK (2)
14 GAS TUBE
15 DRYER
16 OUTPUT BLOCKING CAPACITOR
17 OUTPUT TERMINAL

Fig. 9 — Repeater make-up.

back of 33–34 db. With the restrictions noted above and the effect of the potentiometer terms on the available feedback, the top edge of the band is limited to about 165 kc with the desired feedback.

Mechanical Design

To provide a flexible structure the repeater unit is assembled in a number of longitudinal sections mechanically coupled by helical springs and electrically interconnected by means of bus tapes. The assembly is composed of 17 sections. Figs. 9 and 10 show the repeater make-up and an assembled unit.

The sections consist of the circuit component, or components, mounted in machined plastic forms and enclosed in a plastic container which in turn is enclosed in a housing of the same material.* The sections contain circuit components grouped functionally such as input coupling network, interstage, electron tube, or high voltage blocking capacitor. In the case of the feedback network it was necessary to mount the network in two sections because of the large numbers of components involved. A typical network, container and housing are shown in Fig. 11.

The bus tapes are placed in grooves milled in the outer surfaces of the

* The material used is methyl methacrylate which was chosen for its physical and chemical stability and good machinability.

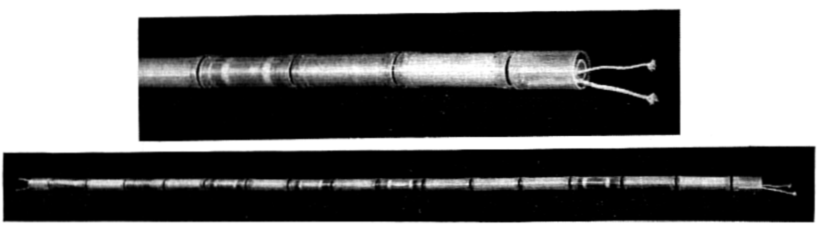


Fig. 10 — Overall view of the repeater unit.

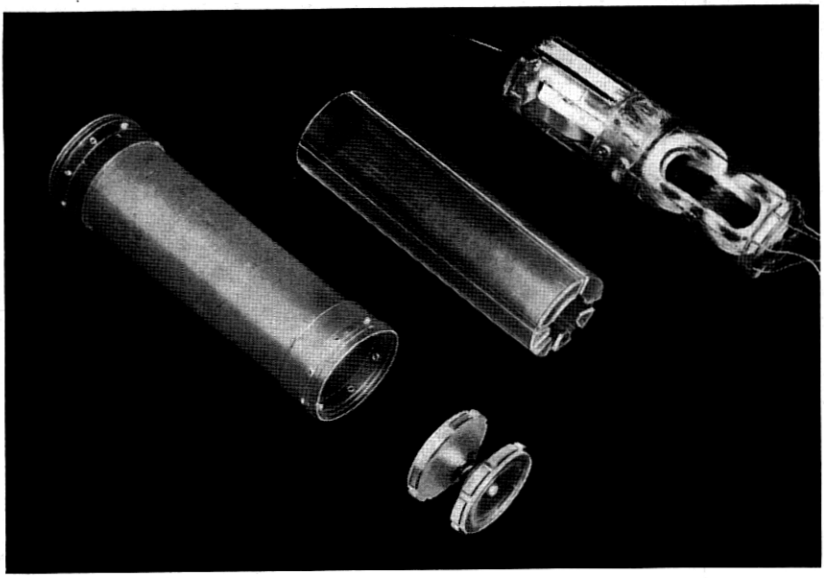


Fig. 11 — Network section.

section containers. Wiring spaces are machined into the ends of the containers for connecting network leads to the bus tapes. The housing is placed over the container and the buses and is closed by a plastic coupler plate which also forms part of the intersection couplers. The coupler plates are fastened to the housing with plastic pins.

Between sections the bus tapes are looped toward the longitudinal axis of the repeater unit. The dimensions of the loop are rigidly controlled so that as the unit is flexed during bending of the repeater, the loops always return to their original location between sections and do not short to each other or the metal outer container. The bus tapes have either an electrical connection or lock at one end of each section to eliminate any tendency of the tapes to creep as the repeater unit is flexed.

The buses consist of two copper tapes in parallel to guard against opens should one tape break. The design of the connections to the buses is such that once the section is closed there can be no disturbance of the tapes or network leads in the vicinity of the electrical connections. The bus-type wiring plan was chosen as the best arrangement for the long structure in keeping with the stringent transmission requirements. Electrically adjacent but physically remote components can thus be interconnected with careful control of the parasitic capacitances and couplings to insure reproducibility from unit to unit in manufacture.

COMPONENTS

The development of passive components for use in the flexible repeater presented a number of unusual problems, the most important being: (1) the extreme reliability, (2) the high degree of stability, (3) the limitations on size and shape and, (4) an environment of constant low temperature.

The repeaters for the transatlantic system contain a total of approximately 6,000 resistors, capacitors, inductors and transformers. If we are to be 90 per cent certain of attaining the objective of 20 years service without failure of any of these components, the effective average annual failure rate for the components must be not more than 1 in a million. To assure this degree of reliability by actual tests would require more than 400 years testing on 6,000 components. Obviously some other approach to insure reliability is required. The most obvious avenue, that of providing a large factor of safety, was not open because of space limitations.

Fortunately, with only one exception, the passive components do not wear out. Thus the approach to reliability could be made by one or more of the following:

1. The use of constructions and materials which have been proved by long use, particularly in the Bell System.
2. The use of only mechanically and chemically stable materials.
3. The use of extreme precautions to avoid contamination by materials which might promote deterioration.
4. Special care in manufacture to insure freedom from potentially hazardous defects.

The philosophy of using only tried and proved types of components dictated the use of wire wound resistors, impregnated paper and silvered mica capacitors and permalloy cores for inductors and transformers. While newer and, in some ways, superior materials are known, none of these possessed the necessary long record of trouble-free performance. In some cases, particularly in resistors, this approach resulted in more difficult design problems and also in physically larger components. While the ambient conditions in the repeater, i.e., low temperatures and extreme dryness, are ideal from the standpoint of minimizing corrosion or other harmful effects of a chemical nature, the materials used in the fabrication of components were nevertheless limited to those which are in-

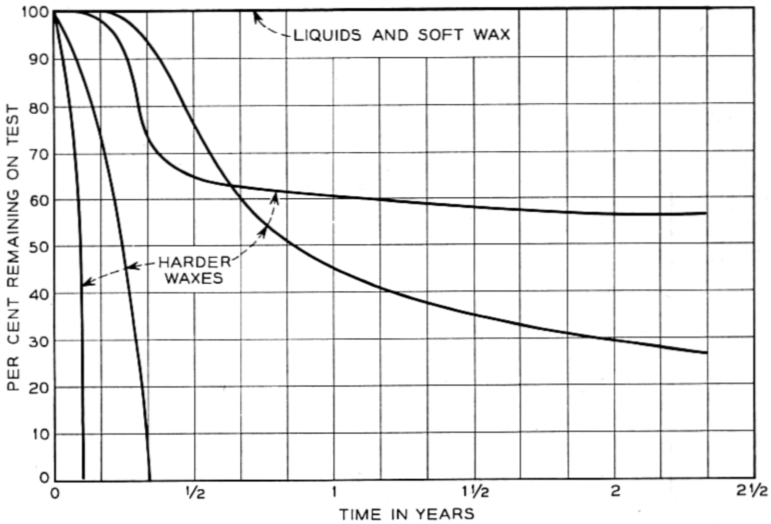


Fig. 12 — Accelerated life tests on paper capacitors with various impregnants at room temperature (60° to 80°F).

herently stable and nonreactive. In addition, raw materials were carefully protected from contamination from the time of their manufacture until they were used, or, wherever possible, they were cleaned and tested for freedom from contaminants just prior to use. Unusually detailed specifications were prepared for all materials.

The effort to achieve extreme reliability also influenced or dictated a number of design factors such as the minimum wire diameters used in wound apparatus, the use of as few electrical joints as possible and the use of relatively simple structures. These limitations resulted in the use of unencased components in most instances. Wherever possible, the ends of windings were used as terminal leads to avoid unnecessary soldered connections. This injected the additional hazard of lead breakage owing to handling during manufacture and inspection. This hazard was minimized in most instances by providing the windings with extra turns which were removed just before the component was assembled in the network. Thus, the lead wires in the final assembly had never been subjected to severe stress. Where this technique was impracticable, special fixtures and handling procedures were used to prevent undue flexing or stressing of lead wires.

As mentioned above there was one type of passive component in which life is a function of time and severity of operating conditions. These are the capacitors, especially those subject to high voltages. Because of this and the fact that the physical and electrical requirements dictated the use of relatively high dielectric stress in these capacitors, a program of study covering a wide range of dielectric materials was undertaken about 1940. This study showed that none of the usual solid or semisolid materials used to impregnate paper capacitors were suitable for continuous use at sea bottom temperatures. Typical results of this program are shown in Figs. 12 and 13. These curves show the performance of capacitors operating at approximately 1.8 times normal dielectric stress at both sea bottom and room temperatures. It is evident that even semisolid impregnants are inferior to liquids at the lower temperature. The need for the maximum capacitance in a given space restricted the field still further, so that the final choice was a design using castor-oil-impregnated kraft paper as the dielectric.

It is well established that the life of impregnated paper capacitors is inversely proportional to the fourth to sixth power of the voltage stress; or

$$\frac{L_1}{L_2} = \left(\frac{V_2}{V_1}\right)^p$$

where p ranges from 4 to 6. This fact permits the accumulation of a large amount of life information in a relatively short time. In order to insure

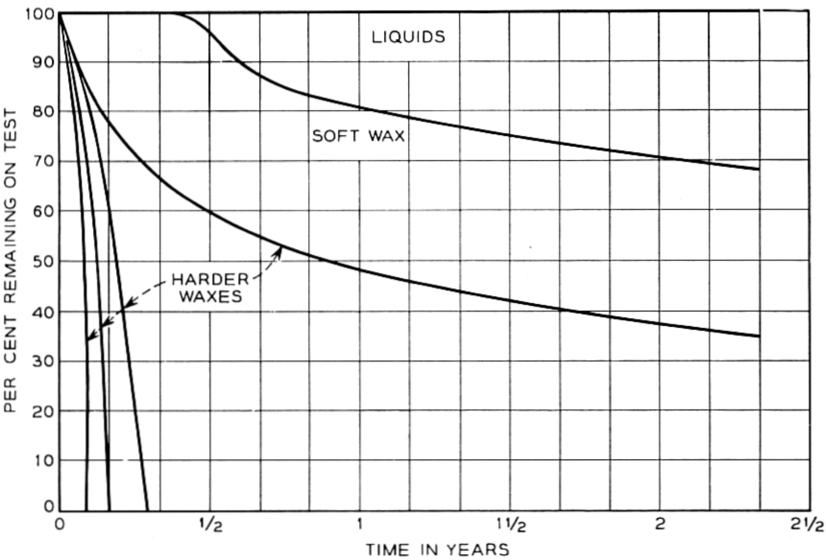


Fig. 13 — Accelerated life tests on paper capacitors with various impregnants at 40°F.

that the capacitor design selected would provide the degree of reliability required, a number of capacitors were constructed and placed on test at voltage stresses ranging from $1\frac{1}{2}$ to $2\frac{1}{4}$ times the maximum stress expected in service. From the performance of these samples, a prediction of performance under service conditions can be made as follows:

The total equivalent exposure in terms of capacitor years at the maximum service voltage can be computed for the samples under test by the following summation:

$$T = N_1T_1\left(\frac{V_1}{V_s}\right)^p + N_2T_2\left(\frac{V_2}{V_s}\right)^p + \cdots + N_rT_r\left(\frac{V_r}{V_s}\right)^p \tag{1}$$

where N_1, N_2, $\cdots$ N_r are the number of samples on test at voltage stresses V_1, V_2 and V_r, T_1, T_2, $\cdots$ T_r are the total times of the individual tests and V_s is the maximum voltage stress under service conditions.

If, as has been the case in the tests described above, there has been only one failure in the total exposure T, we can estimate from probability equations the limits or bounds within which the first failure will occur in a system involving a given number of capacitors operating at a voltage stress V_s. These equations are:

$$\text{probability of no failures in exposure } T = e^{-(T/L)} \tag{2}$$

probability of more than one failure in exposure time T =

$$1 - \left(1 + \frac{T}{L}\right)e^{-T/L} \tag{3}$$

where T is obtained from (1) and L is the total exposure in the same units as T for the service conditions. The solutions of (2) and (3) for L using any desired probability give the maximum and minimum exposures in capacitor-years, within which the first failure may be expected to occur under service conditions.

However, since the voltage on the capacitors varies from repeater to repeater, it is necessary to determine the equivalent exposure of the system in terms of capacitor-years per year of operation at the maximum service voltage in order to estimate the time to the first failure in the system. This is obtained from (1) for one-half of one cable by substituting the supply voltage at each repeater for V_1, V_2, etc., the maximum service voltage for V_s and the number of capacitors per repeater for N. The total exposure for a two cable system is then 4 times this figure. With the data which has been accumulated and the number of capacitors and voltages of the transatlantic system, we estimate with a probability of being correct nine times in ten that the first "wear-out" failure of a capacitor in the transatlantic system will not occur in less than 16 years nor more than 600 years.

There is, of course, the possibility of a catastrophic or early failure due to mechanical or other defects not associated with normal deterioration of the dielectric. Such potential failures are not always detected by the commonly used short-time over-voltage test. Thus, for submarine cable repeaters, all capacitors subjected to dc potentials in service are subjected to at least $1\frac{1}{2}$ times the maximum operating voltage for a period of four to six months before they are used in repeaters. Experience indicates that this is adequate to detect potential early failures. The results of this type of testing on submarine cable capacitors is an indication of the care used in selecting materials and manufacturing the capacitors. Only one failure has occurred in more than 3,000 capacitor-years of testing.

An important aspect of the control of quality of components is the control of the raw materials used in their manufacture. For the transatlantic project, this was accomplished by rigid specifications, thorough inspection and testing, supplemented in some cases by a process of selection.

This can be illustrated by the procedure used for selecting the paper used as the dielectric in capacitors. The Western Electric Company normally inspects many lots of capacitor paper during each year. Those lots which were outstanding in their ability to stand up under a highly accelerated voltage test were selected from this regular inspection process. These selected lots were then subjected to a somewhat less highly accelerated life test. Paper which met the performance requirements of this test was slit into the proper widths for use in capacitors. Sample capacitors were then prepared with this paper and so selected that they represented a uniform sampling of the lot at the rate of one sample for approximately each three pounds of paper. These samples were impregnated with the same lot of oil to be used in the final product. Satisfactory completion of accelerated life and other tests on these samples constituted final qualification of the paper for production of capacitors. Relatively few raw materials were adaptable to such tests or required such detailed and exhaustive inspection as capacitor paper. But the attitude in all cases was that the material be qualified not only as to its primary constituents or characteristics but also as to its uniformity and freedom from unwanted properties.

To a considerable extent, stability of components is assured by the practice of using only those types of structures which have long records of satisfactory field performance. However, in some cases, a product far more stable than usual was required. This was true of the high voltage capacitors where other requirements dictated the use of impregnated paper as the dielectric but where the degree of stability required was comparable to that expected of more stable types of capacitors. In so far as possible, stability was built into the components by appropriate design but, where necessary, stabilizing treatments consisting of repeated temperature cycles were used to accelerate aging processes to reach a stable condition prior to assembly of the repeaters. Temperature cycling or observation over periods up to six months were used also to determine that the components' characteristics were stable.

Exceptional inspection procedures followed to insure reliability and stability are described in detail in a companion paper.[7]

As mentioned earlier, the design and construction of components was simplified by omitting housings or containers, except for oil impregnated paper capacitors. Adequate mountings for the components were obtained in several ways. Mica capacitors were cemented to small bases of methyl methacrylate which were in turn cemented in suitable recesses in network structures. Inductors and transformers were cemented directly into recesses in the network housings. Fig. 14 illustrates some of these structures and their mounting arrangements. On the bottom is a molybdenum permalloy dust core coil in which a mounting ring of methyl

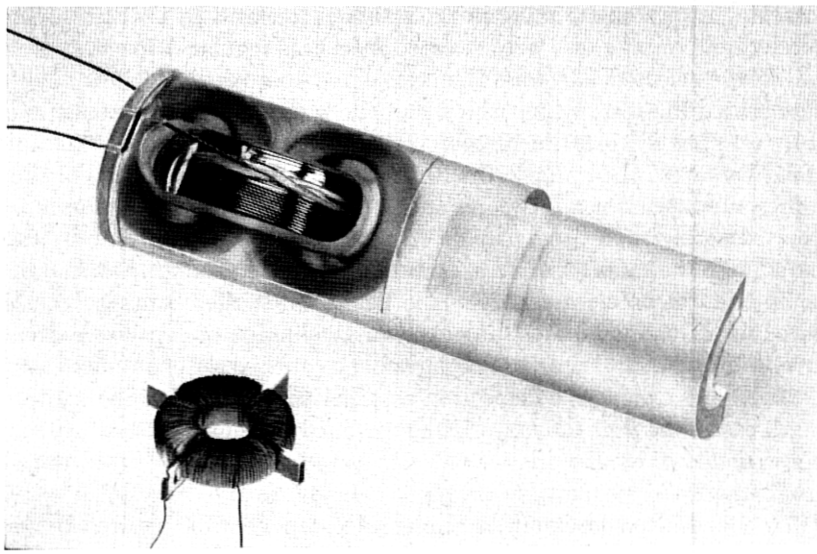


Fig. 14 — Mounting for molybdenum permalloy dust core coils.

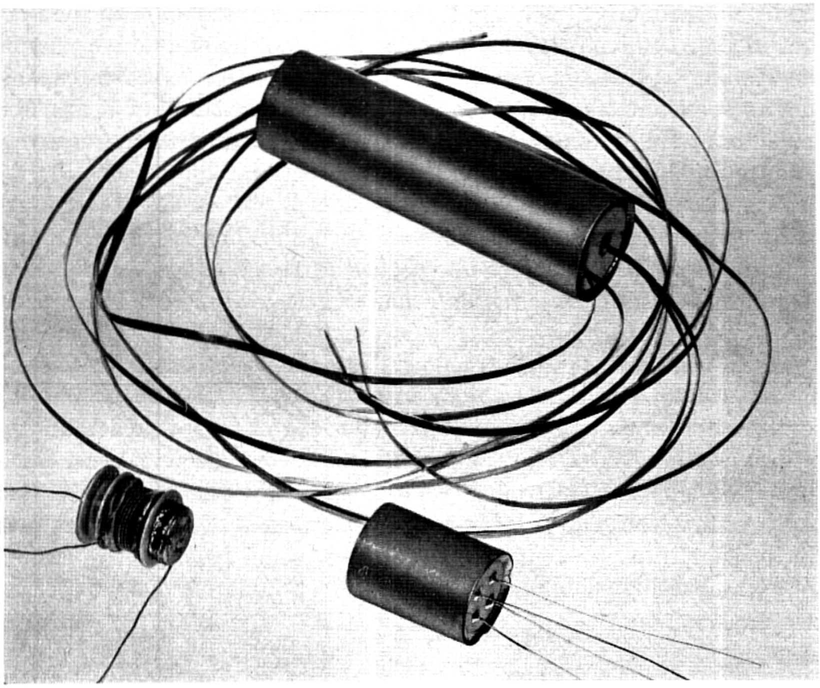


Fig. 15 — Capacitor and resistor capacitor combinations.

methacrylate provided with radial fins is secured around the core by tape and the wire of the winding. Such inductors were mounted by cementing the projecting fins into slots arranged around a recess in the network housing. On top is an inductor which, for electrical reasons, required a core of greater cross-section than could be accommodated in the network when made by the usual toroidal construction. In this case, the effective cross-section of two cores was obtained by cementing the cores in a "figure-8" position and by applying the winding so that it threads the hole in both cores. With these constructions, the cement used to secure the inductors does not come into contact with the wire of the winding which is thereby not subject to strains produced by curing of the cement.

For economy of space and also to reduce the number of soldered connections, many of the components' structures contain two or more elements. Inductors and resistors were combined by winding inductors with resistance wire. Separate adjustment of inductance and resistance were obtained by adjusting turns for inductance and the length of wire in a small "non-inductive" winding for resistance. The inductor on the bottom in Fig. 14 illustrates one type in which the non-inductive part of the winding is placed on one of the separating fins. In some cases, capacitors and resistors were also combined. Fig. 15 shows two of these. The capacitor at the bottom right contains three capacitances and a single resistance in the same container. This construction requires that the resistor parts be capable of withstanding the capacitor drying and impregnation process and also that the resistor contain nothing which would be harmful to the capacitor. The capacitor on the left in this figure is housed in a ceramic container on which is wound a resistor. The capacitor at the top is a high-voltage type which, aside from electron tubes, represents the largest single component used in the repeater. In this capacitor, the tape terminals which contact the electrodes are brought out through the ceramic cover and are made long enough to reach an appropriate point so as to avoid additional soldered connections. Such special designs introduced many problems in the manufacture of the components. However, the improved performance of the repeater and the increase in the inherent reliability of the overall system fully justified the greater effort which was required for the production of such specialized apparatus.

POWER BY-PASS GAS TUBE*

The fault locating means, referred to previously, requires that the power circuit through the cable be continuous. To protect against an open circuit in the repeater, such as a heater failure, an additional device is required to bypass the line current. This bypass must be a high resistance under normal operating conditions since any current taken by this device must be supplied through preceding repeaters. If an open circuit occurs the bypass must carry the full cable current. At full current, the voltage drop should be small to avoid excessive localized power dissipation in the repeater. The device should recover when power is removed so that false operation by a transient condition will not permanently bypass the repeater.

A gas diode using an ionically heated cathode has been used to meet these requirements. By making the breakdown voltage safely greater than the drop across the heater string, no power is taken by the tube under normal repeater operation. In the event of an open circuit in the repeater, the voltage across the tube rises and breakdown occurs. Full cable current is then passed through the gas discharge. Removal of power

* Material contributed by Mr. M. A. Townsend.

from the cable allows the tube to deionize and recover in the event of false triggering by transients. The cathode is a coil of tungsten wire coated with a mixture of barium and strontium oxide. A cold cathode glow discharge forms when the tube is first broken down. This discharge has a sustaining voltage of the order of 70 volts. The glow discharge initially covers the entire cathode area. Local heating occurs and some parts of the oxide coating begin to emit electrons thermionically. This local emission causes increased current density and further increases the local heating. The discharge thus concentrates to a thermionic arc covering only a portion of the coil. The sustaining voltage is then of the order of 10 volts.

Mechanically the tube was designed to minimize the possibility of a short circuit resulting from structural failure of tube parts. Fig. 16 shows the construction of the tube. The glass envelope and stem structure which had previously been developed for the hot cathode repeater tubes were used as a starting point for the design. The anode is a circular disk of nickel attached to two of the stem lead wires. To provide shock resistance the supporting stem leads are crossed and welded in the center. To protect against weld failure, a nickel sleeve is used at each end of the cathode

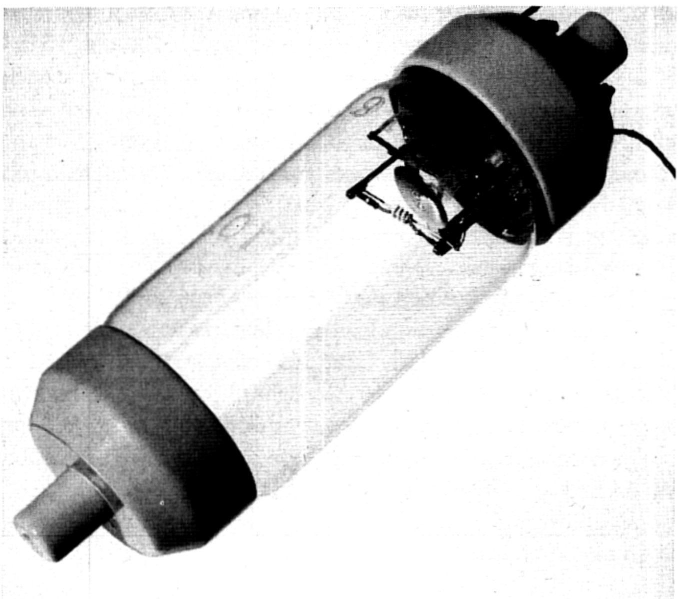


Fig. 16— The power by-pass gas tube.

coil. It is crimped to hold the coil mechanically in place and then welded at the end for electrical connection. At the end of the coil as well as in all other places where it is possible, a mechanical wrap is made in addition to spot welding. An additional precaution is taken by inserting an insulated molybdenum support rod through the center of the cathode coil. The filling gas is argon at a pressure of 10 mm Hg. To provide initial ionization, 1 microgram of radium in the form of radium bromide was placed on the inside of the tube envelope. All materials were procured in batches of sufficient size to make the entire lot of tubes and carefully tested before being approved for use. The tubes were fabricated in small groups and a complete history was kept of the processing of each lot.

For detailed study of tube performance, a number of electrical tests were made. These involved measurements of breakdown voltage, operating voltage as a glow discharge at low current, current required to cause the transition to a thermionic arc, the time required at the cable current to cause transition to the low voltage arc, and the sustaining voltage at the full cable current.

All tubes were aged by operating at 250 milliamperes on a schedule which included a sequence of short on-off periods (2 min. on, 2 min. off) followed by periods of continuous operation. A total of 150 starts and 300 hours of continuous operation were used. Following this aging schedule the tubes were allowed to stabilize for a few days and then subjected to a 2-hour thermal treatment or pulse at 125°C. It was required that no more than a few volts change in breakdown voltage occur during this thermal pulse before a tube was considered as a candidate for use in repeaters.

After aging and selection as candidates for repeaters, tubes were stored in a light-tight can at 0°C. Measurements were made to assure stability of breakdown voltage and breakdown time.

The quality of each group of 12 tubes was further checked by continuous and on-off cycling life tests. The fact that none of these tubes has failed on the cycling tests at less than 3,500 hours and 1,500 starts and no tube on continuous operation has failed at less than 4,200 hours gives assurance that system tubes will start once and operate for the few hours necessary to locate a defective repeater. Long-term shelf tests of representative samples at 70°C and at 0°C give assurance of satisfactory behavior in the system.

CONTAINER AND SEALS

The design of the flexible enclosure for the flexible repeater unit is basically the same as it emerged from its development stages in the

1930's. It is virtually identical to the structure of the repeaters manufactured by the Bell Telephone Laboratories for the cables laid in 1950 between Key West and Havana.[3]

The functions of the enclosure are to protect the repeater unit from the effects of water at great pressure at the ocean bottom; to provide means of connecting the repeater to the cable before laying; and to be slender and flexible enough to behave like cable during laying. How these functions are met in the design may be more readily understood by reference to Fig. 17.

The repeater unit, described earlier, is surrounded by a two-layer carcass of steel rings, end to end. The rings are surrounded in turn by a copper tube $1\frac{3}{4}$ inches in diameter and having a $\frac{1}{32}$-inch wall.

When a repeater is bent during laying by passing onto the cable-ship drum, the steel rings separate at the outer periphery of the bend and the copper tube stretches beyond its elastic limit. As the repeater leaves the drum under tension the rings separate and the copper stretches on the opposite side, leaving the repeater in a slightly elongated state. At the ocean bottom, hydraulic pressure restores the repeater to its original condition with rings abutted and the copper tube reformed.

The system of seals in each end of the tube consists of (1) a glass-to-Kovar seal adjacent to the repeater unit, (2) a rubber-to-brass seal seaward from the glass seal, and (3) a core tube and core sleeve seal seaward from the rubber seal.

The glass seal, although capable of withstanding sea bottom pressures, is primarily a water vapor barrier and a lead-through for electrical connection to the repeater circuit. In service it is normally protected from exposure to sea pressures by the rubber seal.

The rubber seal, capable of withstanding sea bottom pressures, is indeed exposed to these pressures for the life of the repeater, but is not exposed to sea water. It is likewise a lead-through for electrical connection from the cable to the glass seal.

The core sleeve seal is an elastic barrier between sea water on the outside and a fluid on the inside. This fluid, polyisobutylene, is a viscous honey-like substance, chemically inert, electrically a good insulator, and a moderately good water vapor barrier. It fills the long thin annular space outside the cable core and inside a copper core tube and thus becomes the medium of transmitting to the rubber seal the sea pressure exerted on the core sleeve. It can be seen that the core sleeve seal has nominally no pressure resisting function and no electrical function.

The same fluid is also used to fill the space between the glass and rubber seals. Voids at any point in the system of seals are potential hazards to long, trouble-free life. Empty pockets, for instance, lying between the

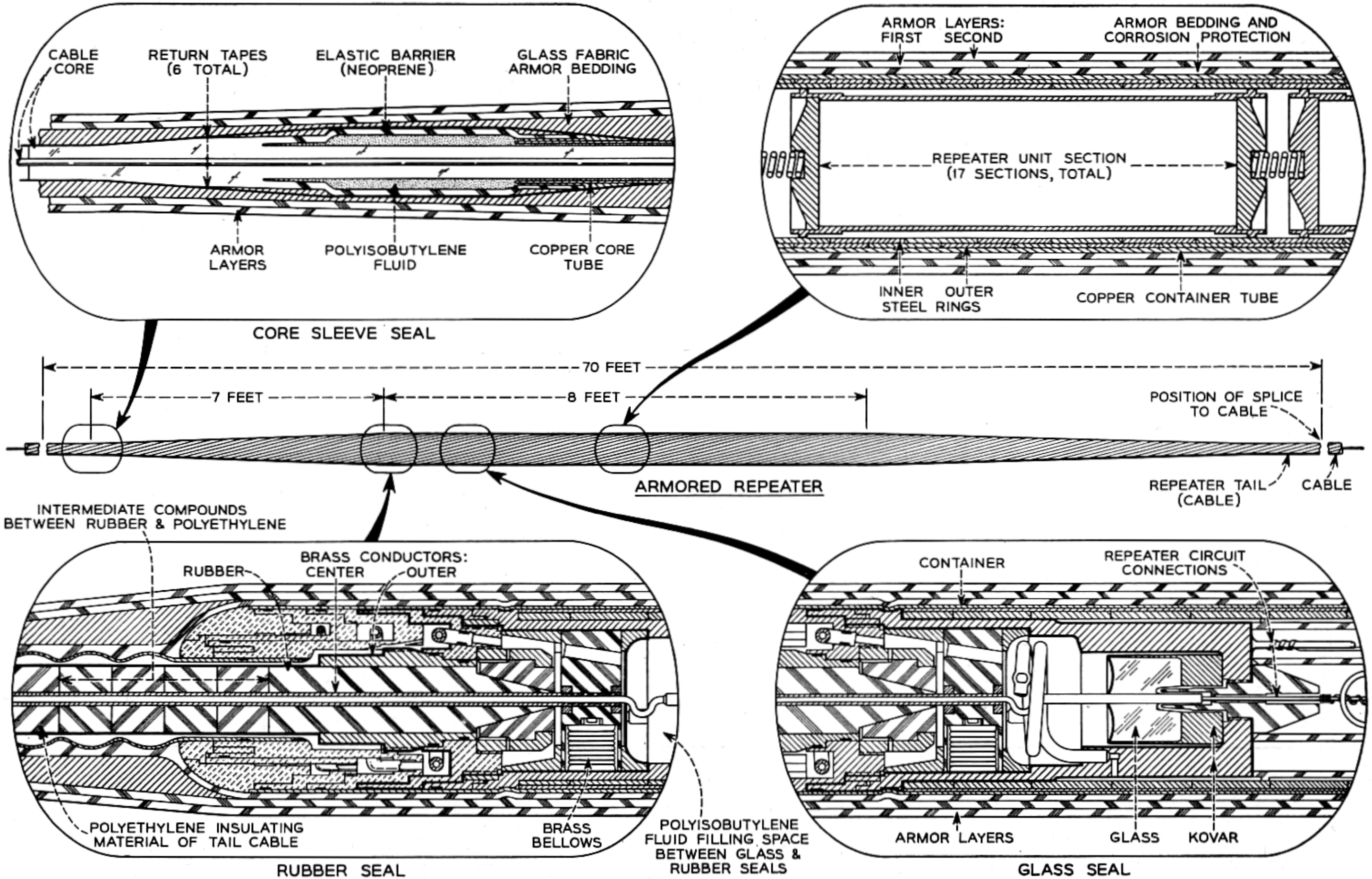


Fig. 17 — Details of container and seals.

central conductor and the outer conductor, or container, are capable of becoming electrically conducting paths if filled with water vapor. As pointed out in companion papers,[2, 4] the voltage between the repeater (and cable) central and outer conductors is in the neighborhood of 2,000 volts at the ends of the transatlantic system.

The filling of the seal interspace with a liquid would defeat one function of the rubber seal if special features were not provided in the rubber seal design. Very slight displacement of the rubber seal toward the glass seal because of sea pressure, or resulting from reduction in volume owing to falling temperature, would otherwise build up pressure in the liquid and on the glass seal. We avoid this by providing a kind of resilience in the interspace chamber. Three small brass bellows, partly compressed, occupy fixed cavities in the chamber. They can compress readily and maintain essentially constant conditions independent of external pressures and temperatures.

The entire repeater assembly enclosed in copper is approximately 23 feet long. Tails of cable at each end make the total length about 80 feet before splicing. The central conductor of each cable tail is joined to the rubber seal central conductor, with the insulation molded in place in generally the same manner as in cable-to-cable junctions elsewhere in the system. The outer-conductor copper tapes of the cable tails are electrically connected to the copper core tubes.

The copper region is coated with asphalt varnish and gutta percha tape to minimize corrosion. Over this coating bandage-like layers of glass fabric tape are built up to produce an outer contour tapering from cable diameter at one end up to repeater diameter and back down to cable diameter at the opposite end. The tape covering is saturated with asphalt varnish. This tape is primarily a bedding for the armor wires that are laid on the outside of both cable tails and repeater to make the repeater cable-like in its tensile properties and capable of being spliced to cable.

In the region of the repeater proper where the diameter is double that of cable, extra armor wires are added to produce a layer without spaces. Also, to avoid subjecting the repeater to the torque characteristically present in cable under the tensions of laying, a second layer of armor wires of opposite lay is added over the first layer. This armoring process is so closely related to the armoring of cable core in a cable factory that it is performed there.

Materials

Following the same design philosophy applied to the repeater components, the materials of construction of the repeater container and seals were chosen for maximum life, compatibility with each other, and for best adaptability to the design intent. Specifications particularly adapted to this use were set up for all of the some 50 different metals and non-metals employed in the enclosure design. In general, the methods established for proving the integrity of the materials are more elaborate than usual commercial practice. In most instances, such as that of copper container tubes, the extraordinary inspection for defects and weaknesses with its resulting rejection rate, resulted in high cost for the usable material.

TESTING

A substantial part of the development work on the repeater enclosure was concerned with devising tests that give real assurance of soundness and stability. It is beyond the scope of this paper to discuss how each part is tested before and after it is assembled but certain outstanding tests deserve mention.

Steel Ring Tests

Each of the inner steel rings, before installation, is required to pass a magnetic particle test to find evidence of hidden metallurgical faults. Each ring is later a participant in a group test under hydraulic pressure simulating the crushing effect of ocean bottom service but exceeding the working pressures. The magnetic particle test is repeated.

Helium Leak Tests

Both glass and rubber seal assemblies, before being installed in repeaters, are required to undergo individual tests under high-pressure helium gas. Helium is used not only because its small molecules can pass through smaller leaks than can water molecules but because of the excellent mass spectrometer type of leak detectors commercially available for this technique. While helium is applied at high pressure to the outer wall of the seal, the inner wall is maintained under vacuum in a chamber joined with the leak detector. The passage of helium through a faulty seal at the rate of 10^{-9} milliliters per second can be detected. Stated differently, this is 1 milliliter of helium in 30 years. The relation of water-leak rate to helium-leak rate is dependent on the physical nature of the leak, but if they were assumed to be equal rates, the amount of water which might enter a tested repeater in 20 years would be 0.66 grams. A desiccant within the repeater cavity is designed to keep the relative humidity under 10 per cent if the water intake were five times this amount.

After glass seals are silver brazed into the ends of the copper tube of the repeater the helium test is repeated to check the braze and to recheck the seal. For this test the entire repeater must necessarily be submerged in high pressure helium. Obviously, in order to sense a possible passage of the gas from the outside to the inside, the leak detector vacuum system must be connected to the internal volume of the repeater. For this and other reasons a small diameter tube that by-passes the seal is provided as a feature of the seal design. After the leak integrity of the repeater is established by this means for all but the access tube, this tube is then used as a means of vacuum drying the repeater and then filling it with extremely dry nitrogen. Following this, the tube is closed by welding and brazing. This closure is then the only remaining leak possibility and is checked by a radioisotope leak test.

Radioisotope Leak Test

Of various methods of detecting the passage of very small amounts of a liquid or a gas from the outside to the inside of a sealed repeater, a scheme using a gamma-emitting radioisotope appeared to be the most applicable.

The relatively small region of the welded tube referred to above is surrounded by a solution of a soluble salt of cesium^{134}. With the entire repeater in a pressure tank, hydraulic pressure in excess of service pressures is applied for about 60 hours. The repeater is removed from the tank, the radioactive solution is removed and the test region is washed by a special process so as to be essentially free from external radioactivity. A special geiger counter is applied to the region. If there has been no leak the gamma radiation reads a low value. If an intake has occurred of as much as one milligram of the isotope solution, the radiation count is about four to five times greater than that of the no-leak condition. The rate of leak indicated is an acceptable measure of soundness of the repeater closure.

The helium and subsequent isotope leak tests are made on a repeater not only when its glass seals are installed but are performed again on each rubber seal after it is brazed in place.

Electrical Tests

Prior to assembly into the repeater the various networks are tested under conditions simulating as nearly as is feasible the actual operating

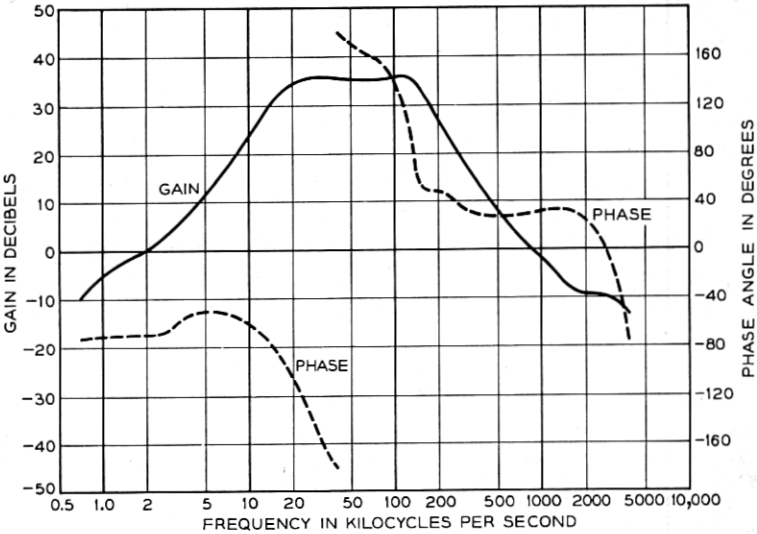


Fig. 18 — Mu Beta gain and phase.

conditions of the particular network. The input and output coupling networks and the beta networks enter directly into the insertion gain and hence are held to very close limits. To ensure meeting these limits elements which go into a particular network are matched and adjusted as a group before assembly into the network.

Repeater units are tested for transmission performance both before and after closing. These tests consist of; mu-beta measurements (simultaneous measurements of gain and phase of the feedback loop); noise; modulation; insertion gain at many frequencies; exact frequency of the fault location crystal and crystal peak gain. Modulation and crystal frequency measurements are made with the repeater energized at 225 milliamperes cable current and also at 245 milliamperes as a check on the ultimate performance of the whole system initially and after aging.

PERFORMANCE OF REPEATERS

The phase and gain characteristics of the feedback loop of the repeater are shown in Fig. 18. It will be noted that at the upper edge of the band the feedback is a little less than the 33–34 db set as the objective. Additional elements could have been used in the interstages to increase the feedback but the return per element is small. Since any element is a potential hazard, the lower feedback is acceptable.

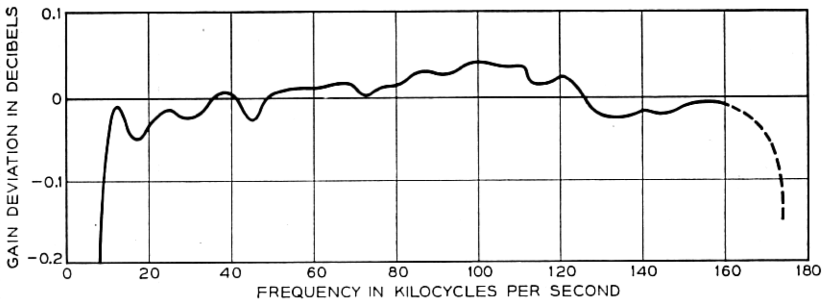


Fig. 19 — Repeater deviation from 36.9 NM design cable.

The deviation of the insertion gain of the repeater from the loss of 36.9 nautical miles of design cable[5] at sea bottom is shown in Fig. 19. This is well within the objective of ±0.05 db.

It has been pointed out that the repeater input and output impedance do not match the cable impedance. This results in ripples in the system frequency characteristic due to reflections at the repeater. These are shown in Fig. 20.

The noise performance of the repeater is determined by the input tube and the voltage ratio of the input coupling network. Amplifier noise referred to the input is shown in Fig. 21. At the upper frequencies the

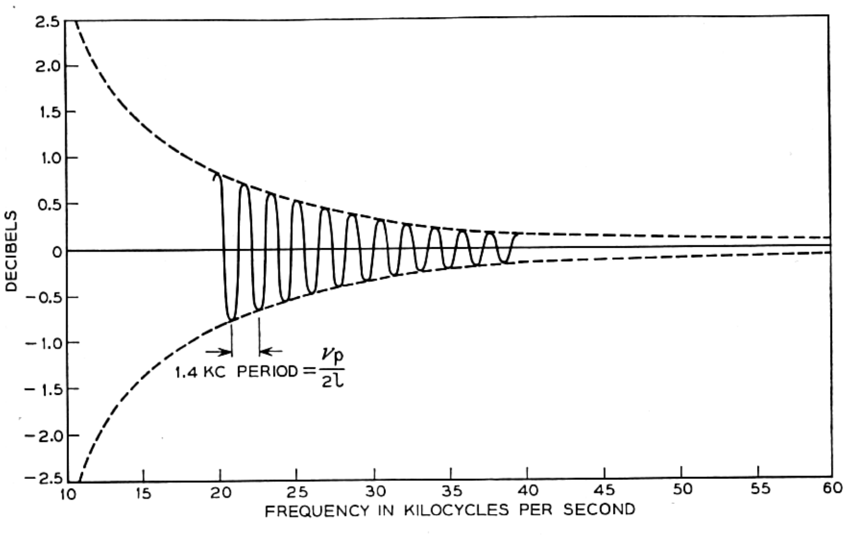


Fig. 20 — Interaction ripple for TAC system.

repeater contribution to cable noise is very small. At the lower frequencies, while the repeater noise is considerably greater than thermal noise, this does not degrade performance because of the lower cable attenuation at these frequencies.

MANUFACTURING DRAWINGS

Because of the extraordinary nature of many of the manufacturing problems associated with undersea repeaters it was determined at the outset that a so-called single-drawing system would be used. For this reason, considerably more information is supplied than is normal. The effect is illustrated best in the rather large number of drawings that consist of text material outlining in detail a specific manufacturing technique. Such drawings specify the devices, supplies and work materials needed to perform an operation, and the step-by-step procedure. Of course, these papers are by no means a substitute for manufacturing skill. Primarily they insure the continuance of practices proved to be effective with the Havana-Key West project.

REPAIR REPEATER

The "repair repeater," used to offset the attenuation of the excess cable which must be added in making a repair, is basically the same general design as the line repeater. It employs a two-stage amplifier, designed to match the loss of 5.3 nautical miles of cable to within ± 0.25 db. The larger deviation compared to the line repeater is permissible since few repair repeaters are expected to be added in a cable. The input

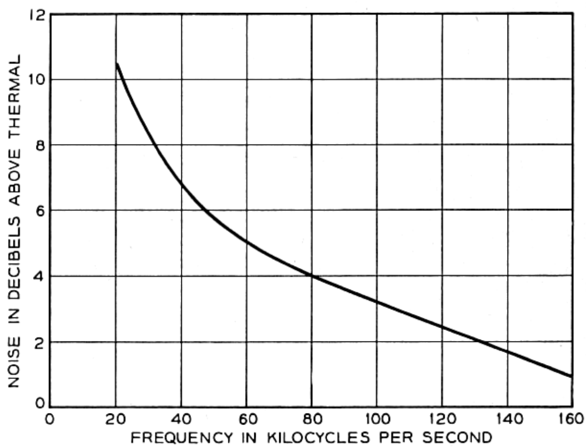


Fig. 21 — Repeater noise.

and output impedances match the cable. As in regular repeaters a crystal and gas tube are provided for maintenance testing. The crystals give approximately 25 db increase in gain and are placed between 173.5 and 174.1 kc so as not to duplicate any frequencies used in the line repeaters. The crystal frequency spacing is 100 cycles.

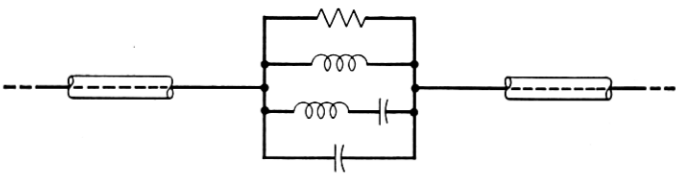
Wherever possible the same components and mechanical details are used in the repair repeaters as in the line repeaters. When changes in design were necessary, these were modifications in the existing designs rather than new types. Capacitors are like those of line repeaters. Except for the length of the container, the enclosure is identical to the line repeater.

Noise and overload considerations restrict the location of a repair repeater to the middle third of a repeater section.

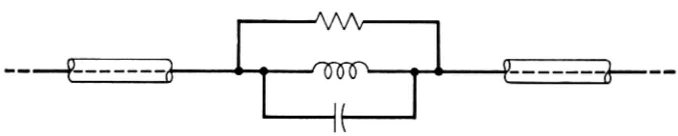
UNDERSEA EQUALIZERS

Even though the insertion gain of the line repeater matches the normal loss characteristic of the cable rather closely, uncertainties in the knowledge of the attenuation of the laid cable can lead to misalignment which, if uncorrected, would seriously affect the performance of the system. Misalignment which has cable loss shape can be corrected by shortening or lengthening the cable between repeaters at intervals as the cable is laid. Other shapes, however, require the addition of networks or equalizers in the line.

With these factors in mind a series of undersea equalizers were designed. The loss shapes were chosen on the basis of a power series analysis of expected misalignments. The designs were restricted to series im-



(a)



(b)

Fig. 22 — (a) Schematic of Type IV equalizer. (b) Schematic of Type V equalizer

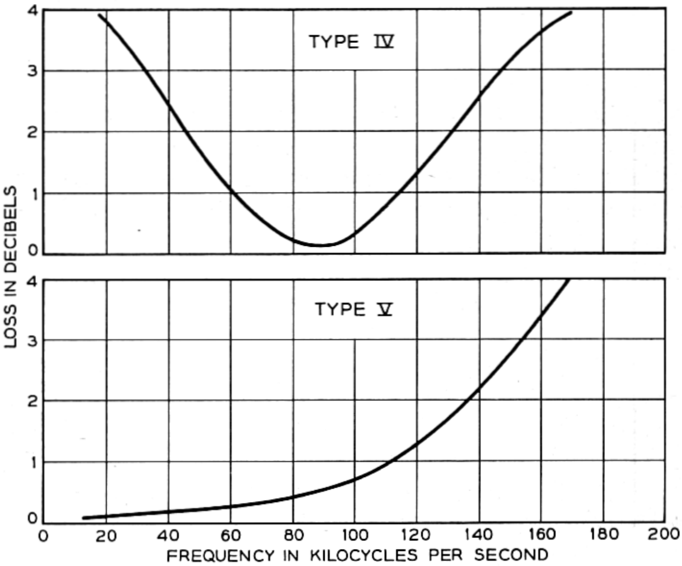


Fig. 23 — Equalizer loss characteristics.

pedance type equalizers to avoid the necessity for shunt arms and the accompanying high-voltage blocking capacitor required to isolate the cable power circuits. This restriction confines the ultimate location of the equalizers to the middle portion of repeater sections to minimize the reaction of the poor repeater impedance on the equalizer characteristic. The dc resistance of equalizers is low so that material increase of the system power supply voltage is not required.

The configuration of two of the equalizers are shown in Fig. 22. The loss characteristics are shown in Fig. 23. Each equalizer has a maximum loss spread in the pass band of about 4 db which represents a compromise between keeping the number of equalizers low and at the same time keeping the misalignment within tolerable limits.

The components used are modifications of the repeater components. The mechanical construction is identical to the repeater except that with the smaller number of elements, the container is materially shorter than a repeater.

ACKNOWLEDGMENTS

Scores of individuals have contributed to the development of these repeaters, some leading to basic decisions, some creating, adapting and

perfecting both electrical and mechanical designs. Many of these people have furnished the continuing drive and enthusiasm that are so essential for a team of engineers and scientists having divergent interests. It is nearly impossible to assign relative importance to the work of transmission engineers, apparatus designers, mathematicians and research scientists in the fields of materials and processes. Equally difficult is any realistic appraisal of the work of all of the technical aides and shop personnel whose contributions are so significant to the final product. The authors of this paper, in reporting the results, therefore acknowledge this large volume of effort without listing the many individuals by name.

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