Repeaters and Equalizers for the SD Submarine Cable System

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An equivalent four-wire repeater and an adjustable equalizer are described. The repeater incorporates a low-aging design to reduce the effect of electron tube gain changes. The equalizer contains a number of bridged-T networks, some of which can be switched in or out by a selector.

The high-pressure container which houses either unit is made up of a beryllium copper cylinder with welded dome covers. Electrical connections are made through polyethylene-metal seals.

I. INTRODUCTION

The decision to replace the flexible repeater of the SB submarine cable system[1] with a rigid structure of more conventional length-to-diameter ratio permitted the design of a repeater of increased bandwidth with equivalent four-wire operation. The objectives relating to stability and reliability remained the same as for the SB repeater.

In the design of repeaters for submarine cable systems, attention must be paid to the smallest detail, and long testing programs are required to realize the stability and reliability objectives. Generally, basic circuit and mechanical concepts are well proven, but must be refined to an extremely high order of perfection to meet the system transmission and life requirements.

The SD system[2] for which this new repeater was designed operates over a frequency range of 108-504 kc (low band) and 660-1052 kc (high band). The repeaters are spaced at 20-nautical mile (nm) intervals. The repeater gain matches the cable section loss within $+0.30$ or -0.10 db in the low band and ± 0.10 in the high band. Excess gain or loss of a repeater section is called misalignment. To avoid a substantial buildup of misalignment, equalizers are inserted every 10 repeater sections. This keeps the misalignment down to ± 0.20 db per 192 nm. The equalizers also compensate cable loss changes that occur during laying. For this purpose they are adjustable from outside their housings until a short time prior to overboarding.

II. REPEATER CIRCUIT

The repeater block schematic, Fig. 1, shows the feedback amplifier, the two sets of directional filters, and the two power separation filters. The cable connects to the power separation filter, which directs the dc cable current to the electron tube heaters and the high-frequency signals to the directional filters. These filters combine both low-band and high-band signals entering from opposite power separation filters and connect them to the amplifier input. After amplification the two bands are split again by the directional filters and sent out through the proper filters to the cable.

2.1 *Power Separation Filters*

The power separation filters (PSF) shown in Fig. 2 are of a series high-pass, low-pass design. A coaxial choke is inserted in the signal path between the PSF and the directional filters to avoid ground loop couplings. The gas tube is shunted across the signal path output to protect components from high-voltage surges in cases of an accidental cable short. The dc output lead of the PSF connects to the repeater unit con-

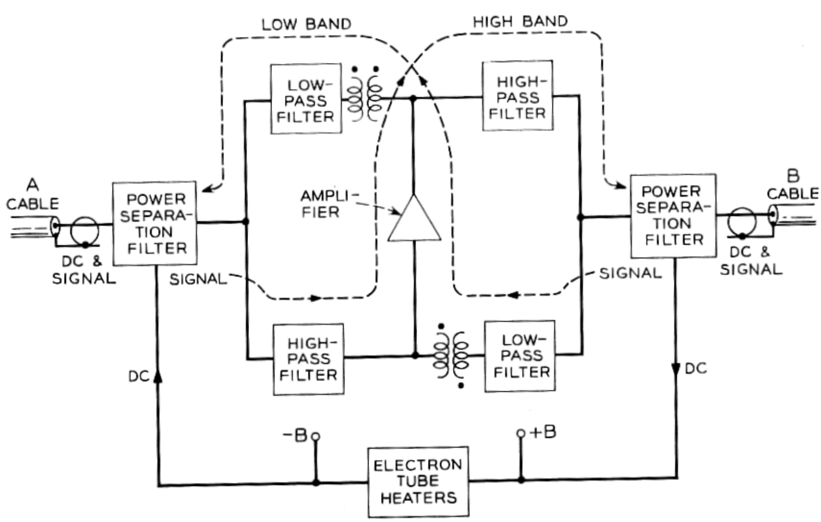


Fig. 1 — Repeater block schematic.

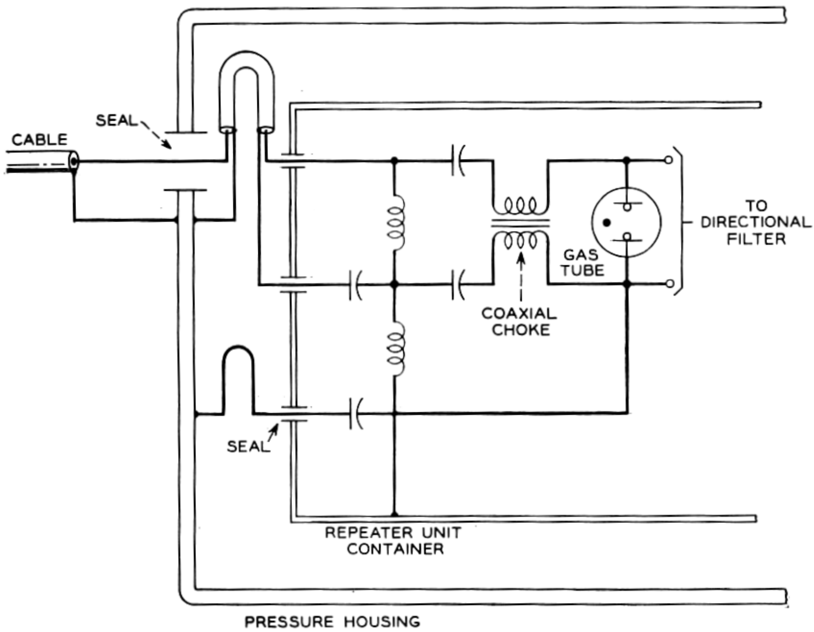


Fig. 2 — Power separation filter.

tainer. As a result, this container is at the potential of the cable inner conductor.

2.2 *Directional Filters*

The directional filters are designed as a constant-resistance four-port network.[3] Special high-Q, adjustable air core inductors are used. Design and adjustment of these filters is critical, since there will be many filters in tandem in a long system. It is important that in-band transmission variations be held to a very small value.

The power separation filters and the directional filters create several spurious feedback paths around the amplifier that would affect the repeater gain characteristic were it not for the high loop losses. The directional filter loop (see Fig. 1) is made up of two symmetrical paths; a 1:1 transformer appears in one path, and a 1: −1 transformer in the other. Ideally then, the two unwanted signals cancel at the amplifier input port. This balance, however, can be maintained only if all ports are terminated by good impedances. Therefore all filter and amplifier impedances exceed a minimum return loss of 27 db.

2.3 *Amplifier*

The amplifier (Fig. 3) is a three-stage, double-μ circuit, feedback device. Major features of interest are the double-μ circuit and the low-aging design.

The input and output coupling networks are identical. The gain is shaped by means of a shunt *RL* network which attenuates low frequencies and by a transformer resonance which peaks at high frequencies. The gain slope of each network is 10 db. The high-side impedance is 3200 ohms at 1 mc, which is the optimum impedance for maximum power output with single-μ circuit operation. An impedance balancing network is used with the hybrid type transformer to provide good amplifier input and output impedances.

The β network is essentially a two-terminal network consisting of one *RL* and five *RLC* branches in parallel. Its impedance varies from about

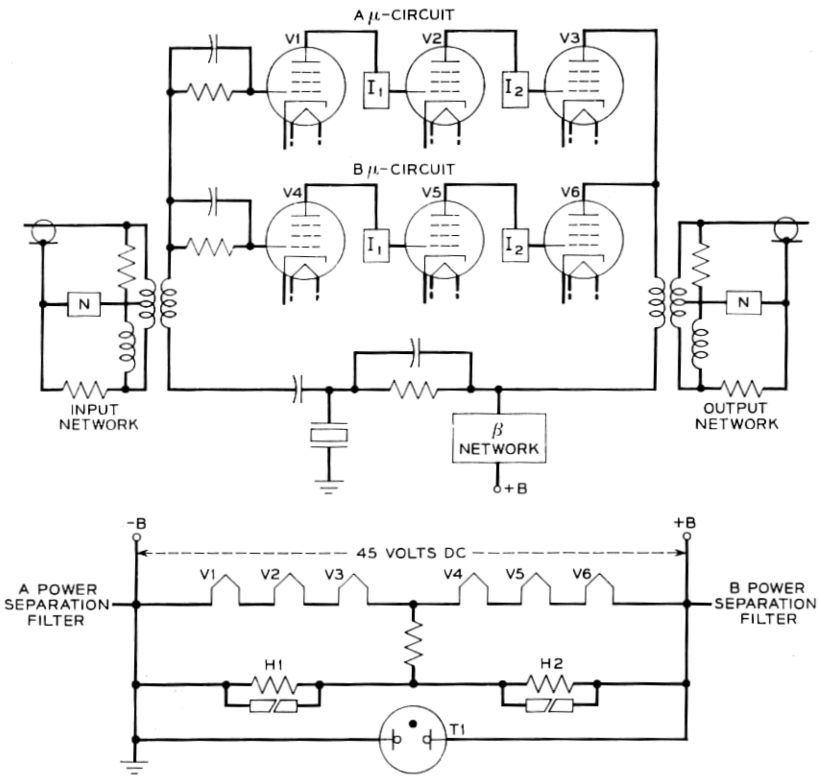


Fig. 3 — Amplifier circuit.

70 ohms at 100 kc to 7 ohms at 1100 kc. The *RL* branch carries the plate current to the two output tubes. The high side of this network connects through a resistor in parallel with a capacitor to a resonant quartz crystal. As in the SB repeater, this crystal permits monitoring of μ circuit gain changes and identification of a defective amplifier.

The amplifier in-band feedback design takes advantage of phase control to minimize the effect of electron tube aging on amplifier gain. In the gain expression μ appears as $(\mu\beta)/(1 - \mu\beta)$ or $1/(1/\mu\beta - 1)$. The absolute value of the denominator $[(1/\mu\beta) - 1]$ is a function of both magnitude and phase of $\mu\beta$ or

$$\left| \frac{1}{\mu\beta} - 1 \right| = \sqrt{1 - \frac{2}{|\mu\beta|} \cos\theta + \frac{1}{|\mu\beta|^2}}\,.$$

For example, the $\mu\beta$ effect[4] of an amplifier with 40 db of feedback has the same value as that of an amplifier with only 20 db of feedback provided $\mu\beta$ phase is 86.9° in both cases. Therefore, by controlling the phase of $\mu\beta$, a substantial reduction in the sensitivity of the $\mu\beta$ effect to a decrease of tube transconductance can be achieved. Based on currently available electron tube aging data, system misalignment from this source over a

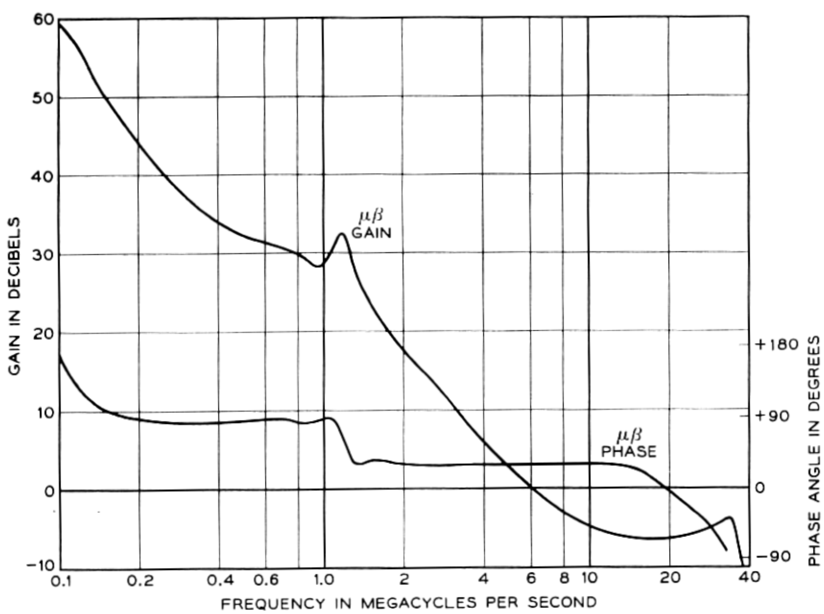


Fig. 4 — Amplifier feedback characteristics.

20-year period is expected to be not more than 4 db for a 200-repeater system.

A special feature of the high-frequency feedback cutoff (Fig. 4) is the loop gain peak at 34 mc. At this frequency, the β network resonates with the parasitic capacitance of the β loop. The resulting favorable phase at lower frequencies makes it possible to achieve maximum available feedback at band edge. The minimum stability margins are: 5 db gain margin at phase crossover and 25° phase margin at gain crossover. Transit time is 2.7° per mc for the whole loop including electron tubes.

The double-μ circuit is used to improve amplifier reliability as far as electron tube failures are concerned. The most likely tube failures are open heaters and electrode shorts. Therefore, to realize the full advantage of this redundancy, it is necessary to be able to operate a functional μ circuit after its twin has failed. Grid-to-cathode shorts, if they occur, will not disable the functional μ circuit, because they are either isolated by grid isolation networks in the first stage or completely independent in the second and third stages.

An open heater, on the other hand, will disable the amplifier, since the gas tube will fire and remove power from the undamaged string. After the repeater in question has been identified by measurements of the crystal noise peaks, power can be turned down to extinguish the gas tube. The current can then be raised to 140 ma. At this point, the amplifier voltage is not sufficient to fire the gas tube. However, under these conditions sufficient heat is generated in the heat coil to melt solder that bridges its resistance (see Fig. 3). Thus a resistor previously not carrying current is substituted for the heaters of the failed amplifier circuit. The equivalent space current of one amplifier circuit is carried by the intact heat coil.

III. REPEATER PERFORMANCE

The SD repeater is primarily characterized by its insertion gain (Fig. 5), its noise figure, and its power output (Fig. 6). As already pointed out, the insertion gain closely matches the cable loss.

Since high frequencies are attenuated by the cable considerably more than low frequencies, they are more vulnerable to noise originated at the repeater input. For this reason both repeater noise figure and power output capabilities are optimized at high frequencies.

During the manufacture of components, networks, filters, and amplifiers, great control is exercised to make sure not only that requirements are met, but also that the averages do not wander beyond tolerable limits. Fig. 5 shows the manufacturing deviations of the repeater insertion gain based on 80 units.

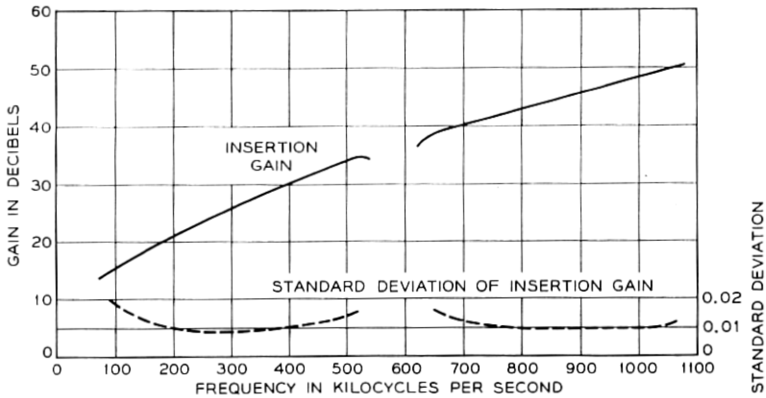


Fig. 5 — Repeater insertion gain.

IV. COMPONENTS

The majority of the electrical component types used in the SD repeater are similar to those used in the SB repeater. However, to fill new needs and meet new requirements several new types of components were introduced after extensive testing. In all cases, similar designs had been used satisfactorily over long periods of time in regular telephone plant applications. The new component types are: polystyrene capacitors, composition resistors, heat coils, and ferrite cores.

Polystyrene capacitors are used in most low-voltage applications for

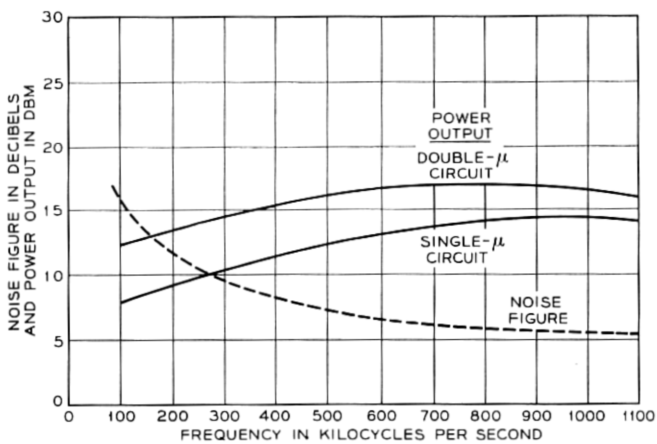


Fig. 6 — Repeater power output and noise figure.

values of capacitance above 5000 pf, where Q and tolerance requirements would not permit the use of paper capacitors.

The composition resistors are used for resistance values above 2000 ohms, where tolerances are liberal. Although these resistors are manufactured by conventional processes, special precautions are taken to produce a uniform product of the highest quality. They are subjected to further screening and stabilization before use in a repeater.

The heat coil is a new device used in the power path to bypass an open heater circuit. It consists of two insulated masses of lead-antimony alloy arranged inside a vitreous enameled resistor so that when sufficient power is applied, the masses of alloy melt, thereby shorting the resistor.

Ferrite cores are used on the control grid and screen grid leads of all electron tubes to provide adequate margin against high-frequency sing of an individual tube.

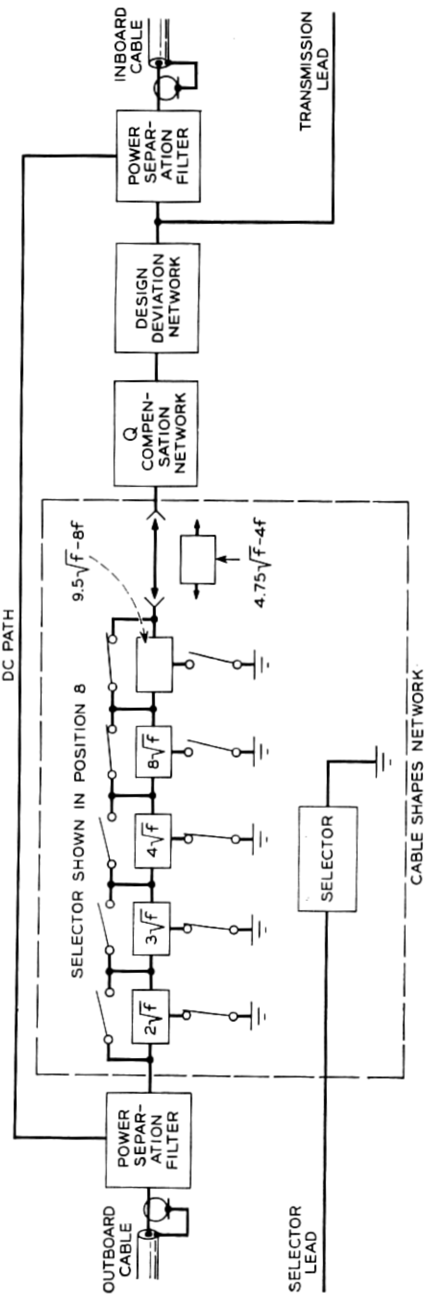
V. EQUALIZER CIRCUIT

Block-end equalizers are located at the end of every group of 10 repeaters. They are inserted between two cable sections, each 6 nm in length. The difference in loss between the nominal 20-nm section and this 12 nm of cable provides the equalizer loss range (constant loss and adjustable loss). The equalizers are designed to compensate the misalignment which has accumulated over 10 sections because of differences in average characteristics of cable and repeater; they also provide an adjustment to compensate the cable laying effect of the block, that is, the difference between predicted and measured sea-bottom cable loss.

The equalizer (see Fig. 7) uses PSF's to bypass the cable current; the inner housing in this case is at sea ground. Since all networks are designed to cover the frequency range of both transmission bands, directional filters are not required. All equalizing networks consist of one or more bridged-T constant-R sections.

5.1 *Design Deviation Network*

This network compensates the mismatch between the average repeater and the average cable section at average depth and temperature. The objective is to keep this misalignment within ±0.2 db per block. It is more practical as well as more economical to do this in the equalizer than to tighten repeater requirements to ±0.02 db.



NETWORK SECTIONS	SELECTOR POSITIONS										
	1	2	3	4	5	6	7	8	9	10	32
$2\sqrt{f}$	0	1	1	0	0	0	1	1	1	0	0
$3\sqrt{f}$	0	0	1	1	1	0	0	1	1	1	0
$4\sqrt{f}$	0	0	0	0	1	1	1	1	1	1	0
$8\sqrt{f}$	0	0	0	0	0	0	0	0	1	1	0
$9.5\sqrt{f}-8f$	0	0	0	0	0	0	0	0	0	0	1

0 = SECTION OUT
1 = SECTION IN

Fig. 7 — Ocean-block equalizer.

5.2 *Directional Filter Q-Compensation Network*

The directional filter inductors are the only repeater components whose manufacturing variations regarding dissipation exceed the limits that system requirements impose. It is for this reason that three Q-section networks are available, one for low-, one for average-, and one for high-Q inductors.

Directional filters are assigned to particular repeaters before the repeaters are assembled. Their insertion losses are added and compared to an objective for the 10-repeater block. Depending on the magnitude and the sign of the deviation, a high-, average- or low-Q section compensating network is picked for the equalizer at the end of this block. Any residual deviation is taken into account in the next equalizer.

5.3 *Cable Shapes Network*

This network consists of five switchable sections and one section that is wired in on an optional basis. The switchable sections can be switched in or out in any combination by a 32-position selector,[5] activating five contact pairs, with a make and a break contact in each pair. Each contact pair controls one network. The make contact is in series with the shunt branch of a bridged-T section and the break contact is in parallel with the series branch. In the nonoperated state, the network is therefore removed from the circuit.

The dominant contributors to the loss of the cable are conductor resistance and dielectric loss. Loss due to conductor resistance varies as the square root of frequency; dielectric loss varies directly with frequency. The bulk of cable loss is $\sqrt{f}$. The linear component of loss is small by comparison and is dependent on the power factor of the polyethylene, a parameter which is difficult to measure and control. The procedure for equalization during laying calls for equalizing a linear f characteristic with $\sqrt{f}$ loss until the value of the former has built up to a considerable magnitude. This will tend to produce a misalignment shape of the form $\pm K_1 f \mp K_2\sqrt{f}$. The equalizer is designed to handle $\pm K_1 f \mp K_2 \sqrt{f}$ or $K_3\sqrt{f}$ shapes. $K\sqrt{f}$ means a loss of K db at 1 mc with a $\sqrt{f}$ shape, and Kf has an analogous meaning.

The nominal characteristics of the six sections are $2\sqrt{f}$, $3\sqrt{f}$, $4\sqrt{f}$, $8\sqrt{f}$, $9.5\sqrt{f} - 8f$, and $4.75\sqrt{f} - 4f$. The last is supplied on an optional basis. The range of $\sqrt{f}$ provided corresponds to ± 3.3 nm or $1\frac{3}{4}$ per cent of the loss in a block. The range of linear shape provided is sufficient to cover a variation of ± 80 per cent in the nominal conductance loss. With these shapes and step sizes, both $\sqrt{f}$ and linear cable loss deviation can be equalized to ± 1 db at 250 kc and ± 0.5 db at 1 mc. This is consistent with the rule for making the tolerances over the band roughly inversely proportional to $\sqrt{f}$.

The nominal setting of the cable shapes network ideally is $13.25\sqrt{f} - 4f$. Since this shape is not available, a nominal block would be equalized by inserting $9\sqrt{f}$. It should be noted that such a nominal block would be left with a residual misalignment of $-4.25\sqrt{f} + 4f$. At the end of a second nominal block this would be wiped out by using $17.5\sqrt{f} - 8f$. The misalignment introduced by the equalizer in the case of nominal cable is necessary to make it possible to handle linear misalignment of either sign using only one switchable section having linear frequency loss. In order to be in a position to handle linear factory deviations if they occur, the optional $4.75\sqrt{f} - 4f$ section is provided. It can be included or omitted at the time the equalizer is assembled in the factory.

Two leads are brought out of the equalizer in addition to the cable leads. One of these connects to the solenoid which operates the selector. The other bridges onto the transmission path between the networks and the inboard power separation filter. It is used to measure transmission during the laying. Both leads are sealed after equalizer adjustment and prior to overboarding.

VI. REPEATER MECHANICAL DESIGN

There are basically three major facets to the physical realization of the SD repeater circuit. These are the repeater unit, the pressure housing, and the cable-to-repeater coupling. (See Fig. 8.) The nature of the individual requirements was such that each could be developed independently as long as there was sufficient coordination to complete an over-all integrated design.

6.1 *Pressure Housing*

The development started at the outside, the rigid repeater housing. At the time, circuit proposals were not complete enough to permit active work on component layouts. However, previous experience with broadband amplifiers permitted a fair judgment of the volume requirements. Since maximum compactness was desirable from many standpoints, a cylindrical design was chosen with the largest diameter which seemed practical for handling in factories and on shipboard. The final length was adjusted to the requirements of the circuit configuration.

Proper and economical design of the housing is important. It must not leak over the expected life span. It must not be overstressed at the

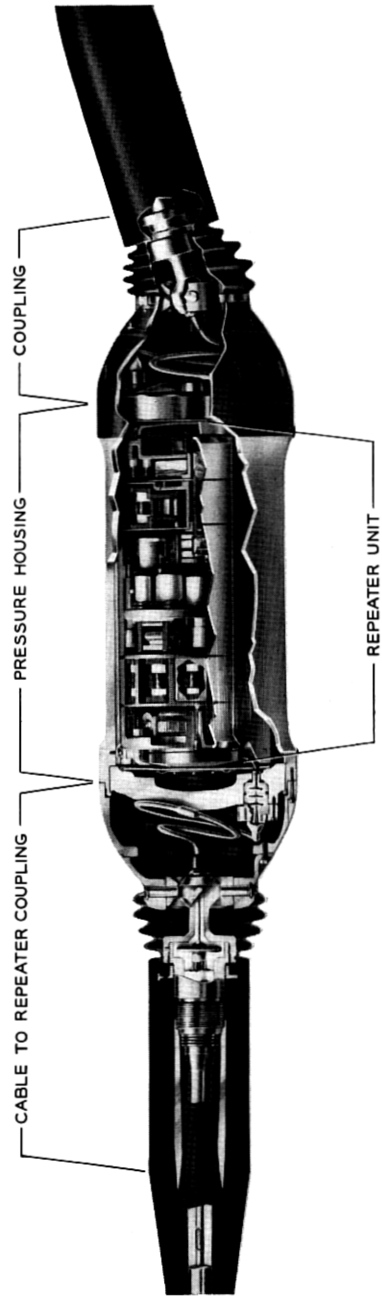


Fig. 8 — Repeater — cutaway drawing.

greatest expected ocean depths, but it must have a minimum factor of safety so that it will not become unmanageable. Exposure of organic materials to sea water pressure must be kept at a minimum. The housing finally utilized to meet these needs consists of a cylinder and two domed end covers, as in Fig. 9.

A variety of materials were considered for use in the pressure housing. In 1955 the list was narrowed to two: steel and a heat-treated copper beryllium alloy. Steel has a slight strength advantage over copper beryllium but has the great disadvantage of a high corrosion rate. If steel is used, protective coatings of some kind must be provided. If the galvanic protection of zinc were utilized, the coating would necessarily be applied after all machining operations and any metal joining operations which might be performed in final closure. The integrity of such a zinc coating could not be reliably ascertained. Furthermore, any joints between the copper return tapes in the cable, or other copper or copper

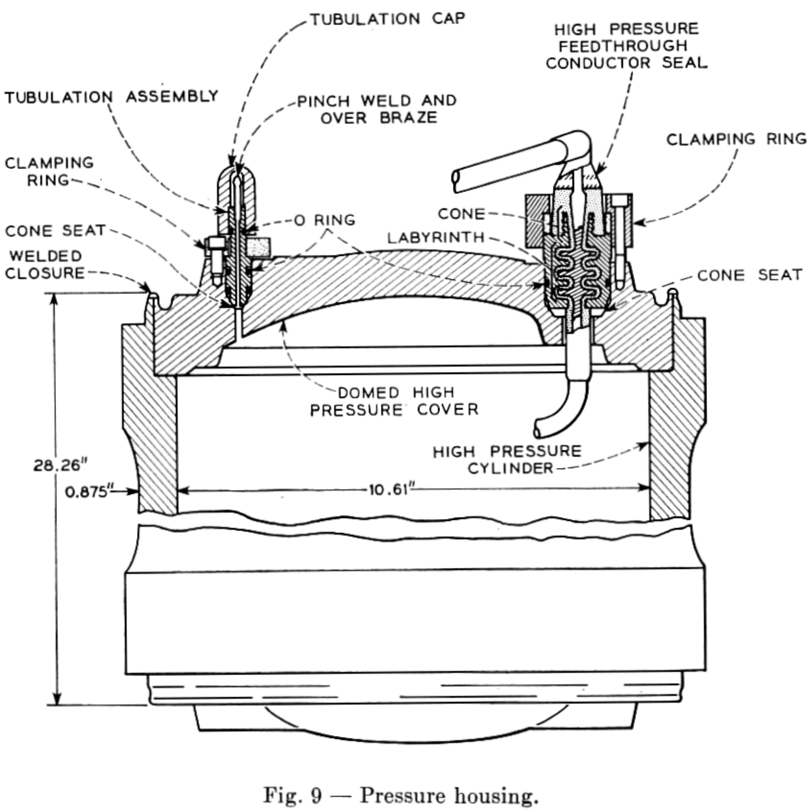


Fig. 9 — Pressure housing.

alloy parts would need to be carefully protected from electrolysis due to copper-steel couples. The most satisfactory protection for the steel would therefore result from a complete skin of copper, or copper alloy, sealed against the entry of sea water. A protective skin of any type would be subjected to abrasion on shipboard and sea bottom and would probably require mechanical protection from such abuse.

Machining costs of steel would not be less than those for copper beryllium, so that the only economy would be in the cost of the material itself. Such economy would be more than offset by complications in assembly to afford corrosion protection.

Further consideration of steel was abandoned in favor of a new copper beryllium alloy specifically developed to meet the special requirements of this application. This alloy has been demonstrated to have the low initial corrosive rate of 0.001 inch per year in salt water, decreasing as patina develops. It is abrasion resistant, and when heat treated to a Rockwell hardness of C-36 develops strength equivalent to many of the steels which could have been chosen. This material can be cast by several methods, it can be wrought, and it can be readily welded. However, unless special techniques are employed, casting processes result in a dendritic grain structure which is not necessarily impervious to helium or water vapor.

6.2 *Cylinder*

The cylinder is fabricated from a semicontinuous cored cast billet, which is forward extruded into a cylinder approximating final dimensions. The extrusion process is performed through special dies at proper temperature in a hydraulic press. Press thrust is in the order of 7000 tons, resulting in a wrought cylinder of high strength and reliability.

The machining operation provides a lip used for final closure welding, a means for attaching cable terminations, and an internal shoulder which accommodates the thrust load of the end covers. The allowable stress for this material in the wrought condition is 120,000 psi at the 0.01 per cent yield point. The design was based on a calculated combined stress value of 100,000 psi under a hydraulic load pressure of 12,000 psi (4400 fathoms). Strain gauge examination of several models indicated the actual combined stress to be 93,000 psi, satisfactorily confirming the analytical work.

6.3 *Cover*

The domed covers used to close the cylinder ends are made of the same copper beryllium alloy as the cylinder. In this case, however, the method of fabrication is different in that another special casting technique is used. This process, known as pressure casting or liquid forging, consists of closing shaped dies under high pressure on molten metal which has just begun to freeze, resulting in a dense casting of approximate size and shape. The force used to form these covers is in the order of 500 tons.

The design of these covers is specially tailored to meet the needs of the final welded assembly. The inner surface is made up of a large spherical radius in the center, blended into a smaller radius at the outside. The outer surface is made up of a large spherical radius in the center blended into a smaller but upturned radius at the outside. The two large radii are not parallel, but are arranged to produce a tapered wall thickness with the thinnest point at the center.

This design was not amenable to straightforward analysis because of the discontinuities associated with feedthrough seals. Therefore a "best approximation" was used to build early models. These were made of aluminum, and the results of strain gage examination and destruction testing were extrapolated to predict copper beryllium performance. The final copper beryllium design had a maximum bending area about half the distance from center to rim. This minimizes any expansion due to bending from hydraulic pressure. The allowable stress for this material in a pressure cast condition at 0.01 per cent yield is 105,000 psi and design objectives were set at 85,000 psi. The measured maximum combined stress in the final copper beryllium models was 49,000 psi under a hydraulic load of 12,000 psi. A greater amount of conservatism was acceptable in the cover design, as any change would be of a minor consequence in the size or weight of the repeater. Furthermore, in this complex configuration it was not certain that strain gauge examination accurately disclosed all points of high stress.

Machining produces a close fit of the cover in the cylinder bore (maximum clearance on the diameter 0.007 inch) and a flat rim to seat on the shoulder in the cylinder. A welding lip to match that in the cylinder is also provided.

Both cylinder and cover must, as stated above, be impervious to water vapor. The practical measurement of the leak-proof quality is by means of helium gas and a mass spectrometer type of leak detector. Each part must meet a maximum leak rate requirement of 5×10^{-8} std. cc of helium per second at any pressure to 12,000 psi.

6.4 *Welding*

The cover design minimizes bending and distortion at the edges. Thus the cover and cylinder lips which are matched and adjacent in assembly may be welded together for final closure in an edge weld virtually free of either tensile or shear stresses (see Fig. 10). The fully automated weld process employs an inert-gas-shielded, nonconsumable electrode, arc technique. No filler material is added; thus only parent metal appears in the weld. Welding is done at a speed of 12 inches per minute with a welding current of 290 amperes. The welder is fed from a balanced-wave ac power supply to minimize the effect of oxidation. The gas shield is argon supplied at the rate of 15 cf/h. An automatic head with slope control up and down minimizes the effect of puddle build-up and eliminates arc blow.

Although the process yields a reliable and quite consistent weld, there are times when, at spots, the required weld depth of 0.06 inch is not attained. Thin spots are not detectable by leak detection or radiographic methods, and it is therefore required that each weld be examined by ultrasonic scanning to accurately determine actual weld depth penetration. A transducer alternately transmits and receives ultrasonic pulses (5 mc) at a rate of 1000 pps to measure reflections.

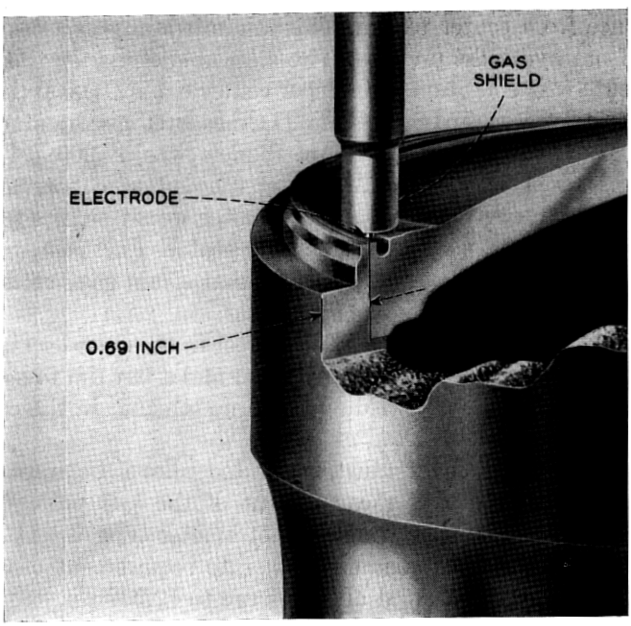


Fig. 10 — Weld process.

6.5 *Feedthrough Seals*

Unfortunately for the mechanical designer, the very function of the repeater housing requires the provision of feedthrough conductor seals. Seals must be free of corona noise at voltages as high as 6000 volts dc and must meet the same leak rate requirements as the rest of the parts making up the pressure housing.

Preferably, the seal should be of a vapor barrier type made of glass or ceramic. Anticipated difficulties with glass at these voltages and pressures, plus complications necessary to effect a transition between the basic seal and the polyethylene insulation of the cable, made the development of a polyethylene seal an attractive prospect. While it is impossible to prevent the diffusion of water vapor through an organic material such as polyethylene, it was felt that a low rate of diffusion would be acceptable if a second barrier could be provided to protect the circuit components. The use of a soft plastic material such as polyethylene presents a further problem: a design with low leak and diffusion rates will still extrude unless a method is devised which distributes the high sea bottom pressure load properly.

The high-pressure seal design (see Fig. 9) consists of a conical load section on the high-pressure side, followed by a labyrinth in which three antiextrusion disks are set in series. These disks are of phosphor bronze and form an integral part of the center conductor. The labyrinth is made up of a series of split machined rings set into an over-all copper beryllium casing. With the center conductor held in proper relation to the casing, the polyethylene insulation is molded directly into the cavity under pressures of about 9000 psi.

Molding polyethylene into a fixed cavity of this type inevitably results in shrinkage of the material away from the cavity walls during the subsequent cooling cycle. Thus it was impossible during the early development stages to produce a seal that did not leak at low pressures. To overcome this difficulty a new bonding process was developed, taking advantage of the ability of polyethylene to bond to a copper oxide under proper pressure, time and temperature conditions.

Bonding is limited to certain critical areas of the cavity in order to establish satisfactory electrical performance. The configuration of [illegible] design is such that bonding is required only at low pressures. At [illegible] pressures the self-energizing qualities take over the sealing fu[illegible]

High-pressure seals of the current design do not extrude [illegible] pressures, they meet a leak requirement of 5×10^{-8} std. [illegible] second, and they perform satisfactorily electrically designed to assure that no direct leakage paths, such as cracks or incomplete polyethylene-to-metal bonds, exist. Even in the absence of cracks, there is some water permeating the polyethylene. This phenomenon, called "diffusion," is largest in shallow tropical waters. Under these conditions, the water diffusion rate has been found to be one order of magnitude lower than the over-all water leakage corresponding to the final helium leak test requirement on the assembled repeater. Under deep-sea conditions, the effect of the lower temperature on the water permeability of polyethylene, and on the water vapor pressure, as well as the compression of the polyethylene by the high hydrostatic pressure, reduces the water diffusion rate by at least another order of magnitude.

The seal casing is set into a counterbore in the end cover, coned at the bottom. The casing is machined with a conical end differing in angle by one degree from that in the cover. This arrangement provides a metal-to-metal cone seat, in a manner regularly used for high-pressure piping. The conical seat is protected from corrosion by an O ring on the sea water side. Preloading of the cone seal is accomplished by a clamping ring and bolt circle, while the O ring assures further loading from sea bottom pressures.

Each repeater housing must be leak tested after final closure over the entire pressure range up to 12,000 psi before leaving the factory. The leak rate requirement is 5×10^{-8} std. cc of helium per second. This rate has been chosen for the over-all assembly as well as individual parts as the limit of meaningful sensitivity obtainable in mass spectrometers. It corresponds to a water leak rate of at most 3×10^{-12} grams per second under deep-sea conditions, which would raise the relative humidity within the repeater housing by about 15 per cent over a 20-year period.

To provide access of leak detector sensing to the inside of the housing while the outside ... mall tubulation is mounted in one ... separate assembly mounted in the ... eals. After completion of the leak ... he tubulation itself is tested by the ... sotope and subsequent searching ... milar to that used for the flexible ... so that less than a thimbleful of ... be safely made a more sensitive ... ssible.

... With this material, test time is ... s as well as manufacturing costs. ... e design of the tubulation, which

After isotope testing, the pinch welded tubulation is overbrazed and finally protected against corrosion and mechanical damage by an O-ring sealed cap.

6.6 *Repeater Unit*

The purpose of the repeater housing is to provide a means whereby the circuit components can operate at atmospheric pressure and low humidity indefinitely. Certain requirements, such as shock absorption, electrical shielding, and the provision of a second barrier to water vapor diffusion, dictated the provision of a helium-tight metallic inner housing for the equipment.

Copper would have been best electrically for the inner housing but was abandoned primarily because of the cost of forming it in the complex patterns required by the design layout. The heavy weight of a housing of copper was also a factor.

It was found that plaster mold castings of aluminum made by the Antioch process* could be reliably expected to be helium-tight without additional treatment. The aluminum alloy used is known commercially as 355 alloy and is heat treated to a T5 condition. Castings to this specification are dimensionally stable and subject to little or no creep with age.

All castings used are tested at one atmosphere of helium and must meet a maximum leak rate of 5×10^{-8} std. cc He/sec. Stress was not an important factor since minimum wall thickness permitted by the casting process resulted in a unit easily capable of withstanding pressures of 100 psi. The normal pressure load in service is 3 psi positive pressure within the housing.

The complete inner unit, called a repeater unit, is made up of five convenient subassemblies, each with a major circuit function: two similar power separation filters, two similar directional filters and an amplifier, as shown in Fig. 11.

6.7 *Amplifier*

The amplifier is the most critical of these major designs and requires very careful layout. The redundancy of the circuit design, with two paralleled μ circuits and a common β circuit, pointed to a preferred basic layout of two similar chassis separated by a space required for the β

* A proprietary process involving special methods for handling plaster and sand for the molds. In addition to gas tightness, this process results in castings of die cast quality with respect to surfaces and dimensional accuracy, requiring very little machining.

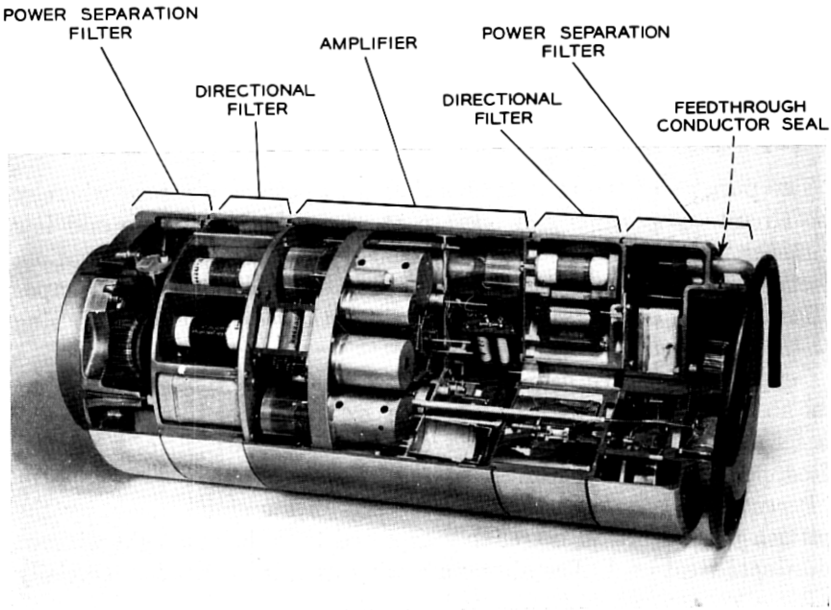


Fig. 11 — Repeater unit — cutaway view.

network. The space thus created is utilized to accommodate other components, such as large bypass capacitors. In manufacture, the basic layout permits separate assembly of each amplifier chassis with a maximum of accessibility and inspectability. Fig. 12 shows the two amplifier chassis before assembly into a complete amplifier, shown in Fig. 13.

Maximum reliability and uniformity have been designed into the amplifier based on the following rules: components must not be lead supported; component leads must not be bent, as the bending process could result in nicks or strains and therefore incipient ultimate breakage; components as well as wiring must be held in position; and their locations must be fixed and uniform from assembly to assembly. To meet these requirements, all amplifier networks, such as interstage and coupling networks, are of the "cordwood" design, with each component supported between two cavities in molded plastic plates. Wiring strips of known quality and thickness are used to interconnect components. All wiring strips are spaced 0.080 inch away from the plastic plates to afford visibility for the inspection of both sides of the soldered joints and to minimize burning hazards to the plastic during soldering. The strips are plated with 40 microinches of gold to facilitate soldering with a minimum of flux.

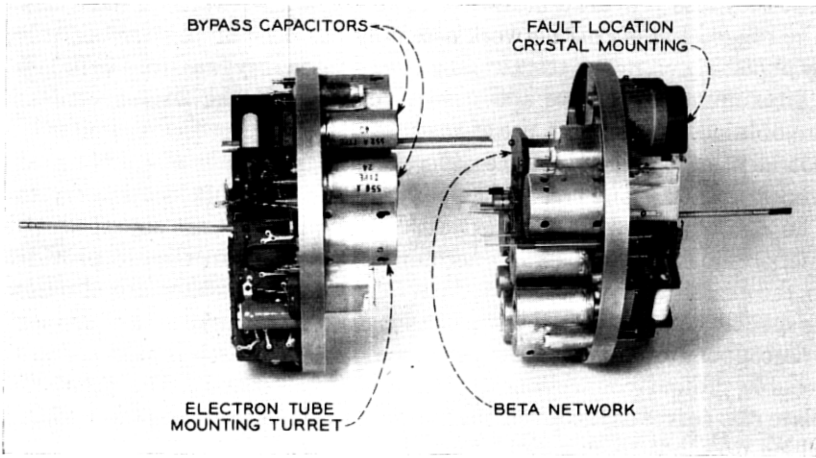


Fig. 12 — Amplifier before final assembly.

The plastic material, diallyl phthalate, used for the network plates was chosen for best combined mechanical and electrical properties and a minimum amount of corrosive outgassing, a necessary attribute for the protection of components in a closed housing for extended periods of time. Spacers are aluminum, and in many cases are dual purpose in

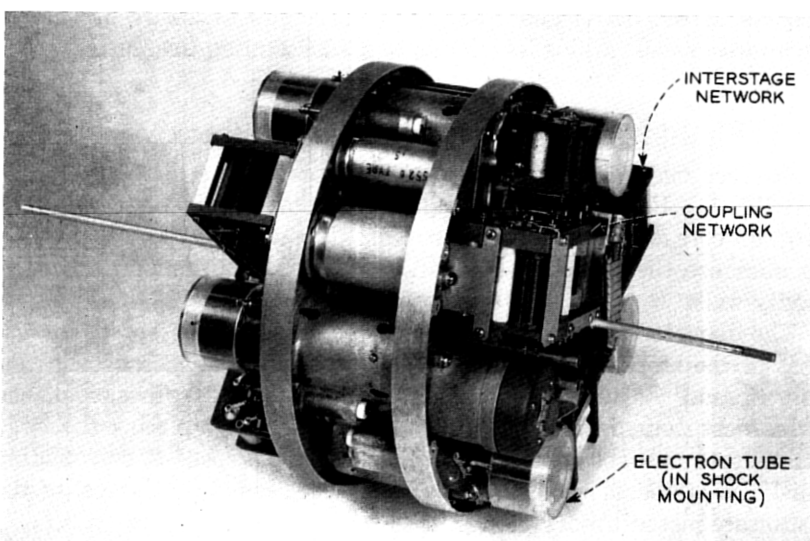


Fig. 13 — Assembled amplifier.

that they also provide a means for mounting the network on the chassis. The ruggedness of this network assembly has been amply demonstrated by punishing vibration tests at 50 g over a frequency range of 20–100 cps.

Maximum ruggedness and design flexibility in the amplifier chassis are obtained through the use of castings. The two chassis are similar but not identical. There are some differences in the layout of coupling networks, and only one chassis is equipped with the fault location crystal. The electron tubes are supplied with individual housings equipped with rubber shock mountings. To accommodate these, turrets are provided in the chassis casting. These serve a dual purpose, as they are also used as spacing bars between the two chassis, affording a large area of support.

A copper grounding plate superimposed on the chassis is used to realize reliable ground connections to the aluminum chassis. The grounding plate also serves as a convenient means for tying down the power wiring, which does not require rigid control.

The final twin chassis assembly is very rugged, as attested to by no failures in wiring or assembly when subjected to the same rigorous vibration tests as individual networks.

The complete amplifier assembly is mounted into a cast "barrel." Special means are used to mount the unit with inside fastenings. It is necessary to maintain a smooth exterior on the over-all repeater unit assembly, and the fully occupied amplifier chassis left no room for internal bosses in the barrel. Consequently, "butterflies" are set in internal grooves in the barrel and equipped with screws to assure a tight fit regardless of the varying length due to manufacturing tolerances.

6.8 *Directional Filter*

Another major subassembly of the repeater is the directional filter (see Fig. 14). Each unit consists of a high- and a low-pass filter. The very large air core inductors must be surrounded by as much space as possible to minimize the reduction of Q due to the eddy current losses in the cavity walls.

The diameter of the directional filter containers must exactly match that of the amplifier. There are ten filter sections in each of the containers, and the ultimate configuration chosen was a division of the cylindrical shape into the ten cylindrical sectors. By placing the large inductor toward the base of the sector, maximum space to surrounding shields is provided, while the capacitors which make up the rest of the sector are placed toward the apex.

All ten sections are mounted on a base plate equipped with grooves

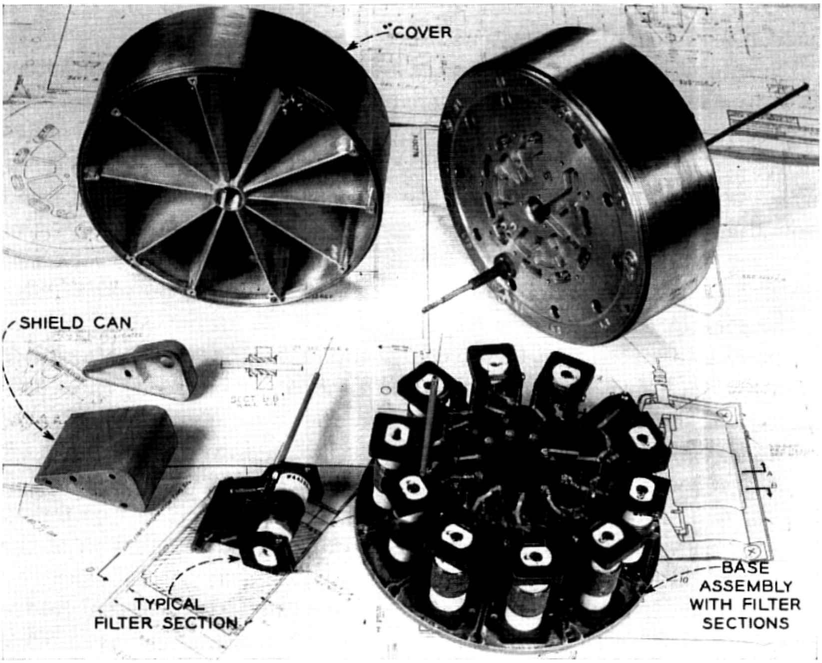


Fig. 14 — Directional filter.

between adjacent sections. The separating ribs in the deep cover match the grooves of the base. This tongue and groove arrangement, supplemented by a woven wire mesh insert, provides shielding between sections.

In the circular design the input low-pass filter section is adjacent to the input high-pass filter section. Crosstalk requirements are severe and are not met with the container shields alone. Additional copper shielding is therefore provided for both of these sections.

A unique feature is the arrangement of the interconnecting wiring. In normal filter designs, sections which must be tuned individually are tuned in equivalent cavities and then transferred to the final assembly. In this design terminals are carried through the housing and are not connected until after each section is individually tuned. Thus the effects of shifts in position with respect to cavity walls are avoided.

6.9 *Power Separation Filter*

The third major subassembly required for the repeater unit is the power separation filter. Because of large size and irregular shape, these components were not amenable to the "cordwood" type of construction. Instead, components are fastened directly to the casting.

The circuit layout for the repeater unit is arranged so that high potentials appear only in the power separation filter. The components are physically arranged to provide a minimum of exposed high voltage wiring.

The power separation filter is the unit into which transmission and grounding leads are fed. Since the repeater unit forms a second barrier to water vapor, it is necessary to provide helium-tight seals for these leads. This seal consists merely of a center conductor, bulged slightly in the middle, and a copper beryllium shell with an outward bulge in the middle to match that of the center conductor for uniform thickness of insulation. Polyethylene is molded into the cavity between center conductor and shell.

The five major subassemblies are assembled into a repeater unit. Since it is necessary to keep the exterior of the unit smooth, all fastenings must be internal, except for those fastenings which can be put in from the end. The major problem in assembly is the attachment of the directional filters to the amplifier assembly. This is accomplished by providing an expansible stainless steel ring mounted in an internal groove in the barrel. This ring, which is inserted after the amplifier is in place in the barrel, is equipped with welded-on bosses, substituting for the bosses which could not be cast in place. The ring is kept in the expanded position by a double wedge, driven and locked in place. Three rods are threaded into the bosses and carried through the directional filter, which is held fast by nuts on the far end of the rods.

The two directional filters are cross connected by shielded coaxials which are carried through the amplifier. Careful coordination of the two designs was necessary to effect a straight line path for these rigid pipes. The shields (copper tubes) are mounted in the amplifier section and serve as assembly guides for the coaxials themselves, which are necessarily appendages to the directional filter. Since the expanded mounting band may be oriented as required, it can be positioned to the requirements of any individual assembly, avoiding the difficulties resulting from manufacturing tolerances. Other coaxials from the amplifier (input and output) are merely carried through a center hole in the directional filter, as are the power leads. These input and output coaxials must be kept straight during assembly, but must be bent to make connections on the cover side of the directional filter. To preserve the integrity of the solid return on these leads, an electroformed bellows is interposed between two rigid tubes, permitting bending to assembly requirements. The amplifier, assembled to both directional filters, is a major subassembly of the repeater unit.

6.10 *Repeater Unit Assembly*

Inasmuch as the over-all repeater unit is an assembly of five major units and two end caps, there are six joints between castings which must be sealed. O rings are used to effect these seals. Here the O ring is not used in a normal application but is used as a gasket confined in an open dovetail groove (see Fig. 15). The design permits sufficient rubber flow to assure adequate electrical contact between units and sufficient gasket pressure to assure sealing under either internal or external pressure loads.

The sealed unit is dried and tested for leaks, but since the plastic materials will continue to outgas even after the drying operation, precautions are taken to insure low humidity for the entire life of the unit. The possibility of condensation as a consequence of a temperature drop when the power is removed makes such a precaution important. A glass-sealed desiccator mounted directly below the tubulation in the power separation filter provides the required control.

The final seal-off of the tubulation is done while the unit is pressurized with nitrogen (see Fig. 16). A cup-like aluminum plug inserted into the tubulation hole is used for this purpose. A tapered steel pin is forced into the cup to expand the walls. The hollow seal-off plug design includes a pin at the forward end. This pin is arranged to pierce the glass seal, thus activating the desiccant simultaneously with seal-off.

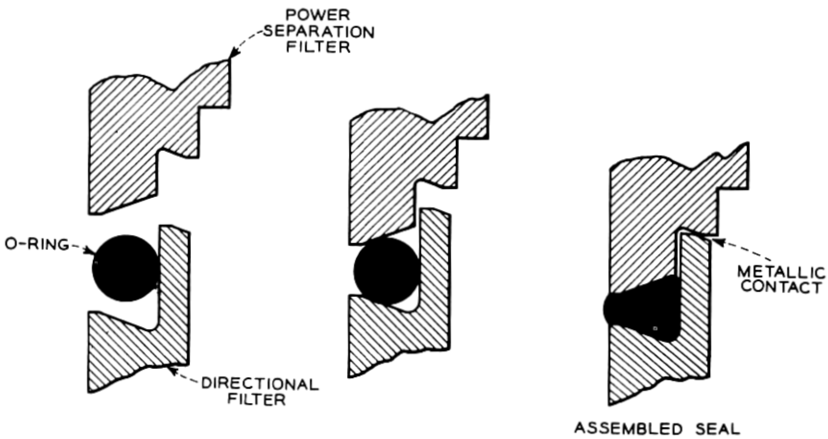


Fig. 15 — O-ring assembly.

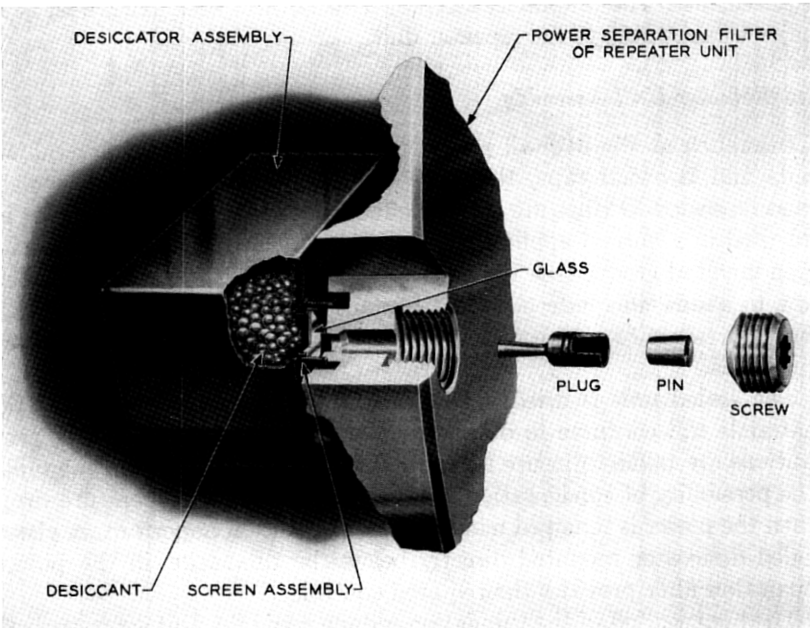


Fig. 16 — Final sealing of tubulations.

To provide electrical insulation, the entire repeater unit is covered by a wall of epoxy 0.140 inch thick, cast in place. The epoxy is mica-filled and the mixture is adjusted to have a coefficient of expansion approximately equal to that of aluminum. A flexibilizer is added to prevent damage to the coating as a result of temperature cycling during manufacture and subsequent handling. The exothermic heat generated during the epoxy curing is not sufficient to raise the temperature of components within the repeater unit beyond safe limits.

The over-all dimensions of the completed repeater unit are:

length	23.30 inches
diameter	9.54 inches
weight	65 lbs.

6.11 *Shock Mounting*

It is not desirable that a heavy repeater such as this require handling with more than ordinary caution. Therefore, the repeater unit is spring mounted within the pressure housing for shock absorption.

There are twelve single-leaf springs running the entire length of the repeater housing. Each spring is curved in section and placed between pressure housing and repeater unit with the edges toward the pressure housing. The springs are made of 5-ply epoxy-bonded fiber glass, cured to the required curved shape. The diameter of the circle tangent to the inserted springs is 0.05 inch less than the diameter of the repeater unit, so there is a preloaded condition when the repeater unit is inserted.

Endwise shocks are absorbed by flat multi-ply epoxy-bonded fiber glass springs mounted in the high pressure cover. These are positioned so that when the covers are in position against the shoulders in the high pressure cylinder, they also are preloaded.

With the repeater unit inserted into the spring assembly, the leads from the high- and low-pressure seals are joined by welding the conductor and patch molding the polyethylene insulation. The completed lead assembly is covered by a copper braid and is helically formed to allow freedom of motion to the repeater unit against the springs during shock conditions.

6.12 *Complete Repeater*

After the high-pressure covers are set and welded the repeater is complete. Two small polyethylene-insulated flexible ground leads are then spot welded to the high-pressure cover. Insulated leads are used in lieu of a copper shield braid which might be attacked by corrosion. These leads are ultimately run directly alongside the center conductor lead and approximate the performance of a coaxial structure.

Completed repeaters are shipped from the factory in a special package designed for protection against severe shock. The repeater body is carried in two end sockets made of rigid foam and mounted on a palette. The density of the foam is controlled so that under shock conditions greater than 25 g the foam will deform, limiting the shock to the repeater. Any shocks to the repeater in transit from factory to shipboard are recorded on an impactograph mounted at one end of the repeater.

The permissible temperature range of the repeater is limited by the oil-filled high-voltage capacitors. It is therefore necessary to specify the range of temperature exposure during transit or storage. To assure that the allowable range has not been exceeded, a test tube indicating thermometer has been developed and mounted in the other end of the repeater. This test tube thermometer will burst from freezing below 0°F or from expansion above 150°F. A delay time is built in so that short exposures at either extreme will not cause breakage.

The foam-blocked repeater on its palette is covered by a conventional package of sufficient strength to permit stacking.

6.13 *Cable Connection*

In order for the repeater to become part of a system it is necessary that it be mechanically and electrically joined to the cable. The bulk and weight make handling in normal cable loading lines difficult, and the design therefore permits the loading of repeaters as cargo separate from the cable. Thus a termination applied at the cable factory may be joined to the repeater on board ship to provide an orderly and systematic arrangement for subsequent overboarding.

Since most of the cable is not armored, the design of the termination or coupling is primarily directed at this type of cable. The coupling design for armored cable is similar with few changes in parts (see Fig. 17).

The center strength member of the cable is a strand comprising 41 high-strength steel wires. In order to effect a satisfactory mechanical cable termination, it is first required that this strand be gripped to its ultimate strength without slip. A sleeve of AISI 1141 steel, $4\frac{13}{16}$ inches long by $\frac{3}{4}$ inch OD, 0.333 inch ID, has been developed for this purpose. This sleeve is pressed over the strand into a hexagonal exterior shape 0.658 inch across the flats. Press force is in the order of 500 tons. An epoxy coating over all of the wires prevents slip before ultimate strength is developed. The assembly develops a strength of 17,000 pounds ultimate.

The copper overlay of the steel strand is stripped back for most of the sleeve length. The internal diameter of the sleeve is contoured at the cable end to provide a good grip to this copper without crushing or tearing. The opposite end of the sleeve is threaded for further assembly into the coupling anchor.

The terminated steel strand is the center conductor of the cable and as such must be insulated. The polyethylene used as cable insulation is desirable to avoid discontinuities. Polyethylene, however, is a soft material without much shear or tensile strength. It will also readily cold flow. Therefore the strand termination has been arranged to compressively load the insulation and encapsulate it so as to restrict cold flow. A large disk or anchor, is threaded onto the pressed sleeve. The anchor is premolded in polyethylene and ultimately closely confined in a copper beryllium housing which forms the return conductor of the coaxial structure. A flexible polyethylene-insulated lead is attached to the repeater end of the premolded anchor assembly for later attachment to the repeater.

The greatest cable tensions, which could cause cold flow of the polyethylene, are applied only for short periods during laying and recovery. There are, however, ocean-bottom conditions which could result in con-

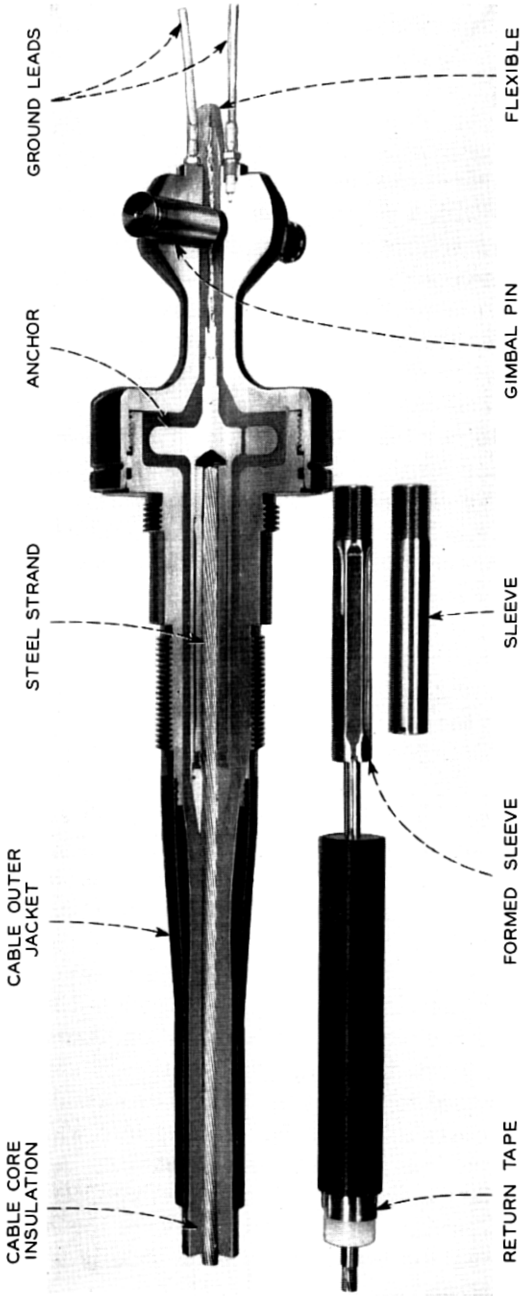


Fig. 17 — Repeater-cable coupling.

stant cable tensions regardless of the care with which the cable is laid. Should a repeater with a specific gravity of about 4.0 be laid in silt, the lighter cable (sp. gr. 1.1) would float while the repeater would sink, resulting in tensions up to an estimated 1,500 pounds. The method used to confine the polyethylene has been found to be effective against cold flow under this value of tension.

Armorless cable with a polyethylene outer jacket and rather delicate copper tape return conductor is subject to damage from any severe bending. To best accommodate normal shipboard operations, flexibility has been added by the provision of a gimbal ring as a coupling between repeater and cable. The gimbal ring has been designed to provide 45 degrees of free motion in any direction from the axis of the repeater. Thus the cable is maintained in a straight line when the repeater-cable assembly is bent to any diameter of 8 feet or larger.

Further protection for the cable against damage is afforded by a bell-mouthed gland nut and a rubber boot which provides a tapered stiffness type of support. Tests have shown that this assembly combination may be satisfactorily run over sheaves with pitch diameters as little as 7 feet under laying or recovery tensions.

The gimbal ring is mounted in a copper beryllium casting provided with a bolt circle matching that furnished in the repeater end attachments. The gimbal ring assembly is protected from the incursion of large stones or shells by the addition of a surrounding rubber bellows. This arrangement assures freedom of operation in any later recovery operation.

Couplings are assembled to precut cable lengths at the cable factories. Two polyethylene patch molding operations resembling cable splicing molds are required. In the first, the cable core insulation is patched to the insulation around the anchor, providing continuous polyethylene center conductor insulation from cable to flexible pigtail.

Subsequent to the core patch mold, the return tape of the cable is joined to the anchor housing by a brazing operation. Finally, the outer jacket is restored in the second molding operation. The anchor housing is directly exposed to sea water, and termination of the restored cable jacket must be designed to protect the cable return conductor from corrosion. Annular grooves in the anchor housing into which the molded material flows and shrinks provide this protection.

The armored cable required for shallow water applications moves the strength member from the center to the outside of the cable. The basic coupling design used for armorless cable is readily adapted to this difference in cable structure by a few part changes.

Sufficient resistance against bending is provided by the stiffness of the armor wires, and both gland nut and rubber boot are eliminated. A slotted ring threaded onto the anchor housing is substituted for both parts. A single armor wire, terminated in a crimped sleeve, is laid in each slot, providing a termination equal in strength to that of the armored cable.

Inasmuch as the armor wires are wound helically on the cable, and the center conductor is solid copper, tension in the cable will result in a longitudinal displacement of the core and center conductor with respect to the armoring. There will also be relative twist. This condition requires another departure from the basic concept used in the armorless coupling. The anchor is eliminated and the cable is terminated in a molded assembly including a center conductor and two ground leads. The assembly can slide freely in the neck of the housing. The two ground leads are run in a spiral in the anchor cavity. The spiral configuration accommodates any relative twist, while the ability to slide accommodates longitudinal displacement.

Terminated cable lengths of either armored or armorless type are ultimately connected to repeaters in a like manner on shipboard, to complete the system.

VII. CONCLUSION

The first SD submarine cable system was put in service between Florida City, Florida and Jamaica in February 1963.

Several other systems have since been laid. By early April, 1964, 502 repeaters and equalizers were operating at sea bottom; at that time 640 units had been manufactured.

All repeaters and equalizers are performing as predicted and, as indicated by measurements on several installed systems, system requirements were met.[2]

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