Repeater Design for the Newfoundland-Nova Scotia Link

By R. A. BROCKBANK,* D. C. WALKER* and V. G. WELSBY*

(Manuscript received September 15, 1956)

The Newfoundland-Nova Scotia cable required the provision of 16 submerged repeaters each transmitting 60 circuits in the bands 20–260 kc from Newfoundland to Nova Scotia and 312–552 kc in the opposite direction. The paper deals with the design and production of these repeaters. Each repeater has a gain of 60 db at 552 kc, and the amplifier consists of two forward amplifying paths with a common feedback network. Reliability is of paramount importance, and production was carried out in an air-conditioned building with meticulous attention to cleanliness and to very rigid manufacturing and testing specifications. The electrical unit is contained in a rigid pressure housing 9 feet long and 10 inches in diameter with the sea cables connected to an armor clamp and a cable gland at each end. A submerged equalizer was provided near the middle of the sea crossing.

INTRODUCTION

The British Post Office has engineered many shallow-water submerged-repeater systems,[1] and there has been a progressive improvement in design techniques and in the reliability of components which has been reflected in a growing confidence in the ability to provide long-distance systems having an economic life. The seven-repeater scheme from Scotland to Norway laid in 1954 introduced for the first time repeaters which would withstand the deepest ocean pressure together with an electrical circuit which embodied improved safety and fault-localizing devices. Also, since a repeater is only as reliable as its weakest component, much greater attention and control was directed at this stage to the design, manufacture and inspection of all components, both electrical and mechanical. This repeater design was, in fact, envisaged as a prototype for a future transatlantic project.

* British Post Office.

under all working conditions.[2] Factors involved in assessing these margins and in planning the equalization and level diagram for the system are as follows:

(*a*) *Temperature.* — The final assumed sea-bottom temperature was 2.3°C, with a maximum annual variation of ±3°C. The maximum change in attenuation might therefore be ±4 db at 552 kc. The land section change would be ±3 db at 552 kc due to a possible ±10°C change on a mean of 7.5°C. The effect of these seasonal changes would be reduced by the provision of manually adjusted equalization at Clarenville, Terrenceville and Sydney Mines.

The repeaters show a small change in gain (less than 0.05 db) during the warming-up period after energization, but the effect of ambient-temperature change is negligible.

(*b*) *Repeater spacing.* — The repeater-section cable lengths were to be cut in the cable factory such that the expected attenuation at 552 kc when laid at the presumed mean annual temperature of the location should be 60.0 db. An anticipated decrease in attenuation of 1.42 per cent at 552 kc was assumed when laid. The assumed mean annual temperature of sections of the route varied between 1.7 and 4.0°C. Temperature corrections employed an attenuation coefficient at 552 kc of +0.16 per cent per degree centigrade. It was expected that the total error at 552 kc after laying seven repeaters would not exceed 1.5 db, and this could be largely corrected as explained in (*c*).

(*c*) *Cable Characteristics.* — The cable equalization built into the repeater was based on a cable attenuation characteristic which was later discovered to be appreciably different from the laid characteristic. Cutting the cable as described in (*b*) overcomes this difficulty at 552 kc, where the signal/noise ratio is at a minimum. The new shape of the characteristic, however, indicated that at about 100 kc the error would reach 7 db on the complete route. To reduce this deviation it was decided to introduce a submerged equalizer in the middle of the sea section to correct for half this error and to insert in each of the four-wire paths of the transmit and receive equipments equalization for one-quarter of this error. There is an appreciable signal/noise margin in hand at this frequency, so that the system would not be degraded below noise specification by these equalizer networks.

It was also decided that the splice at the equalizer which would connect the halves of the link together should not be completed until after the laying operation had commenced. An excess length of cable was provided on the equalizer tail, and this could be cut at a position indicated by measurements taken during the laying of the first half-section so that the equalization at the 552-kc point could be largely corrected for laying and temperature-coefficient errors. It is not, in practice, easy to separate these two factors.

(*d*) *Repeater characteristic.* — The repeater was designed to equalize the original cable-attenuation characteristic to ±0.2 db, as this was possible with a reasonable number of components. This variation appeared as a roll in the gain/frequency characteristic, which was expected to be systematic and would therefore lead to a ±3 db roll in the overall response. It was proposed that equalization for this should be provided at the receive terminal. Manufacturing tolerances were expected to be small and random.

(*e*) *Repeater interaction.* — At the lower frequencies where the loss of a repeater section is comparatively small, a roll in the overall frequency response will arise due to changes in the interaction loss between repeaters. The design aimed at providing a loop loss greater than 50 db which would reduce rolls to less than ±0.03 db per repeater section and therefore to about 0.5 db at 20 kc with systematic addition on the whole route.

Planning of Levels

From a critical examination of all these variables it was concluded that the repeater should be designed to have an overload margin of 4 db above the nominal mean annual temperature condition. It was also desirable for the system to be able to operate within its noise allowance if one path of a twin amplifier failed. Tests on a model amplifier gave overload values of +24 dbm and +19 dbm for two- and one-path operation, respectively, so that with a single-tone overload requirement of 18 dbm[4] at a zero-level point, the maximum channel level at the amplifier output would be −3 dbr for a single amplifying path.

Thermal-noise considerations (i.e. resistance plus tube noise) fixed the minimum channel level at the repeater input at −69 dbr in order to meet the allowable system noise limit of +28 dba at a zero-level point. At 552 kc the amplifier gain is 65 db, so that the minimum level at the amplifier output is −4 dbr. A system slope of ±4 db due to temperature variations, corrected by similar networks at the transmit and receive terminal, would, however, degrade the noise by 0.5 db. Intermodulation noise was estimated[5] on an average busy-hour basis, and it was concluded that the increase in noise at 552 kc from this source was negligible — less than 1 db, even with several repeaters in which the amplifier had failed on one path. At lower frequencies the contribution from intermodulation noise is greater, and at 20 kc it exceeds resistance noise.

However, at 20 kc the total noise is some 8 db below the specification limit, and therefore again several amplifiers could fail on one path before the noise exceeded the specification limit. Actually it was discovered that the predominant source of third-order intermodulation on the repeater was in the nickel-iron/ceramic seals on high-voltage capacitors and followed a square law with input levels.

From a more detailed examination of the factors briefly mentioned above it was decided that the initial line-up should be based on a nominal flat −3.5 dbr point at the amplifier output and the final working levels decided upon as the results of tests on the completed link.

With equal loading on the grid of the output tube at all frequencies the worst signal/noise ratio exists at 552 kc; some pre-emphasis of the transmit signal should therefore prove to be beneficial. In fact, after completing the tests on the link it was decided to improve the margin on noise by raising the level at 552 kc by 2 db, thus giving a sloping level response at the amplifier output in the high-frequency band. To maintain the same total power loading, the low-frequency band levels were decreased by 1 db, still retaining a flat response.

Laying

It was proposed to use laying methods with continuous testing similar to those employed successfully on the Anglo-Norwegian project. The complete link with a temporary splice at the equalizer would be assembled and tested on board H.M.T.S. *Monarch* and laying would proceed from Terrenceville to Sydney Mines in the high-frequency direction of transmission. A detailed description of the actual laying operation is given elsewhere.[6] After completion of tests on the submarine section the land section to Clarenville would be connected with appropriate equalization at Terrenceville.

DESIGN OF ELECTRICAL UNIT OF SUBMERGED REPEATER

General

The equipment is contained in a hermetically sealed brass cylinder (filled with dry nitrogen) $7\frac{3}{4}$ inches in diameter and 50 inches long, which is bolted at one end to one of the bulkheads of the housing. A flexible coaxial cable emerges through an 0-ring seal at each end, and these are ultimately jointed to the cable glands. The various units forming the complete electrical unit are mounted within a framework of Perspex (polymethylmethacrylate) bars which forms the main insulation of the

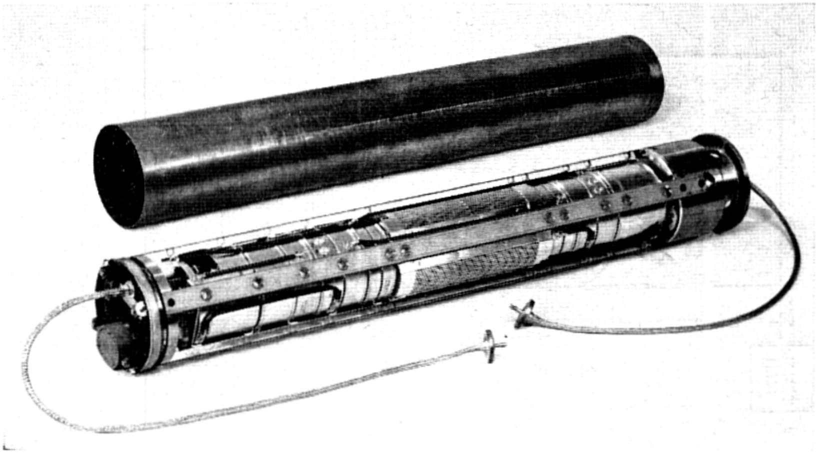

Fig. 1 — Internal unit.

repeater, and these units may operate at 3 kv dc to the grounded brass cylinder. Fig. 1 shows the construction.

A schematic of the electrical circuit is given in Fig. 2. The direct current for energizing the repeater is separated from the carrier transmission signals by the A- and B-end power separating filters, and passes through the amplifier tube heaters and a chain of resistors developing 90-volt high-voltage supply for the amplifier. The carrier-frequency signals pass through the same amplifier via directional filters. Equalization is provided in the amplifier feedback circuit (about 20 db) and in the equalizers and the bridge networks which combine the directional filters. The main purpose of the bridges, however, is to reduce the severe harmonic requirement on the directional filters due to having high- and low-level signals present at the repeater terminals. The whole carrier circuit is designed on a nominal impedance of 55 ohms. Attached to the B-end of the repeater is the loop-gain supervisory unit and also, via a high-voltage fuse, a moisture-detector unit used primarily during the high-pressure test to confirm that the housing is free from leaks. The latter comprises a series-resonant circuit at about 1.3 mc, in which the inductance is varied by the gas pressure on an aneroid capsule mounted in the space between the electrical unit and the housing. The presence of moisture in this cavity increases the gas pressure owing to the release of hydrogen by the reaction of water vapor with metallic calcium held in a special container. At a later stage the fuse is blown to disconnect this circuit.

The circuit design of the repeater introduces multiple shunt paths

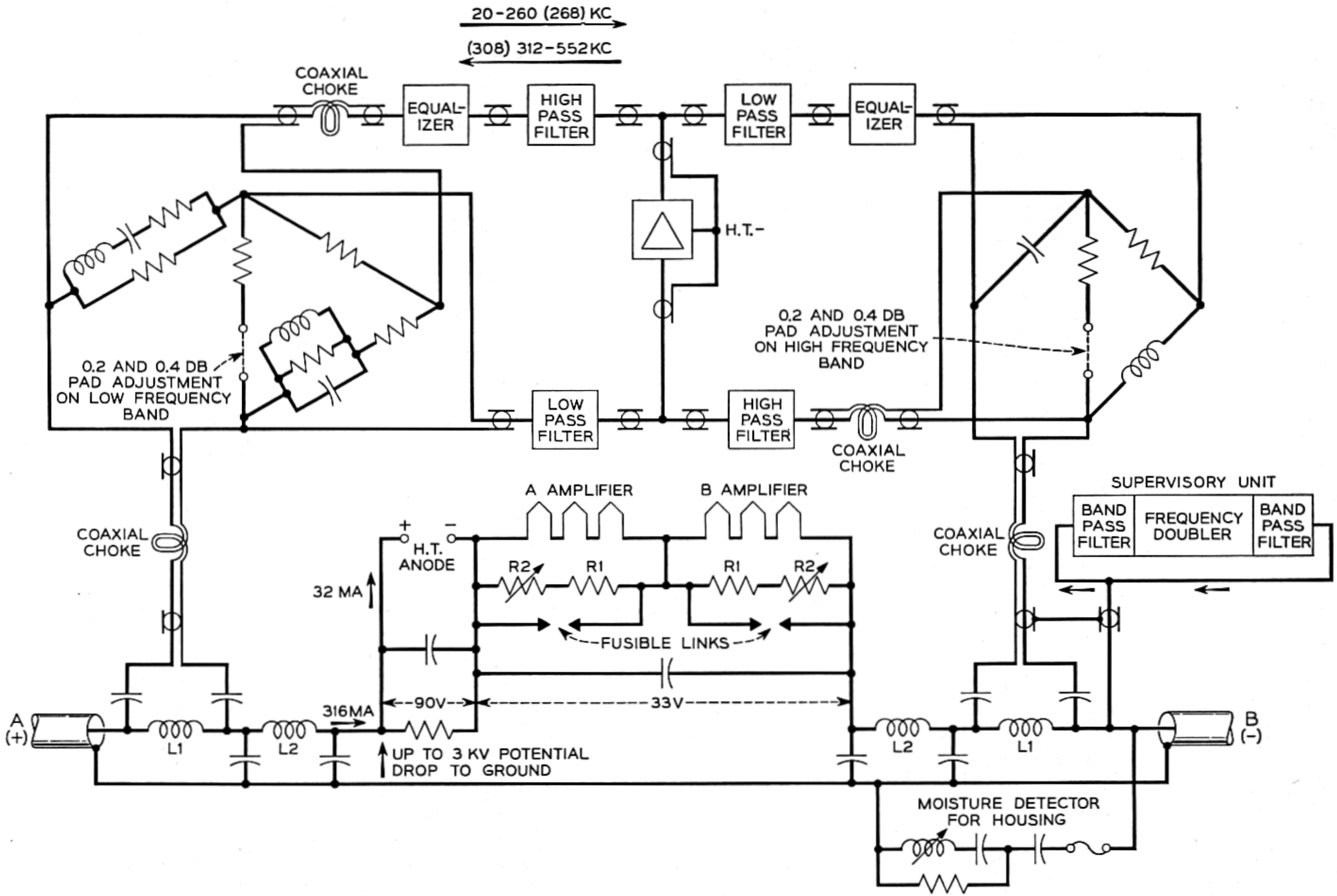

Fig. 2 — Schematic of submerged repeater.

across the amplifier, and care has to be taken to ensure that there is adequate attenuation in each path. In general, the design is such that the combination will give a loop loss of at least 40 db in the working band (to reduce rolls in the gain characteristic) and 20 db at all frequencies (as a guard against instability), even when one repeater terminal is open- or short-circuited to simulate a faulty cable.

Unit Details

Power Filter.

The power filters are, in effect, a series pair of high- and low-pass filters (see Fig. 2). The shunt capacitors may have to withstand 3 kv, and clearances on the input cable and some wiring have to be adequate for this voltage. The inductors have to carry the line current of 316 ma dc, and the intermodulation must be extremely low (see section on inductors below).

Directional Filter.

The directional filters are a conventional Zobel high-pass and low-pass filter pair with a susceptance-annulling network. Silvered-mica capacitors and carbonyl-iron dust-cored inductors are used. The bridges combining the 'go' and 'return' filters reduce the distortion due to the ferromagnetic material to an acceptable level.

Bridge and Equalizer.

A simple non-resonant bridge is used at the B-end of the repeater, but the A-end bridge is a resonant type and provides a substantial degree of equalization (see Fig. 2).

The equalizers are of conventional form. Trimming capacitors (selected on test) were provided for critical capacitances in order to utilize standard tolerances on all capacitors. A pad of 0.2 db and 0.4 db is provided on each equalizer unit so that the repeater low-frequency or high-frequency path can be independently trimmed to give the best match to the target response for the repeater.

The components in the above circuit were small air-cored inductors, silvered-mica capacitors, and wire-wound resistors, except for a few high-resistance ones, which were of the carbon-rod type. Included in this unit are coaxial chokes whose purpose is to separate parts of the circuit to avoid the effect of multiple grounding. They are merely inductors wound with coaxial wire on 2-mil permalloy C tape ring cores.

Supervisory Unit.

The supervisory unit comprises a frequency-selection crystal filter of about 100-cycle bandwidth in the range 260–264 kc fed from the low-frequency output end of the repeater via a series resistor. This filter feeds a full-wave germanium point-contact crystal-rectifier bridge which acts as a frequency doubler. The second harmonic in the band 520–528 kc is filtered out by a coil-capacitor band-pass filter, and fed back through a resistor to the same point in the repeater. The two series resistors minimize the bridging loss of the unit on the repeater and ensure that a faulty supervisory component has negligible effect on the normal working of the repeater.

DC Path.

The dc path includes a resistor providing the 90-volt supply and the heater chain of six electron tubes (see Fig. 2). The voltage drop across the heater chain is not utilized for the amplifier high-voltage supply, as the heaters would then be at a positive potential with respect to the cathodes, thereby increasing the risk of breakdown of heater-cathode insulation. There would also be a complication in maintaining the constant heater current, particularly should the high-voltage supply current fail in one path of the amplifier. The normal amplifier high-voltage supply current is 32 ma.

It is essential to maintain a dc path through the repeater even under fault conditions in order that fault-location methods can be applied. Special care has therefore been taken to provide parallel paths capable of withstanding the full line current. For example, the high-voltage resistor actually consists of a parallel-series combination of ten resistors, and the whole assembly is supported on Sintox (a sintered alumina) blocks which maintain a good insulation at 3 kv dc, even at high temperatures.

Electron tube operation for consistent long life indicates the necessity to maintain a specific constant cathode temperature, and to achieve this, electron tubes are grouped according to heater characteristics into six heater-current groups between 259 and 274 ma and stabilized to ± 1 per cent. The appropriate heater-shunt resistor is applied so that the tube operates correctly with 316-ma line current, but for convenience the shunt is taken across each set of three tubes, all in one heater group, forming one amplifier path. R1 is fixed (300 ohms) and R2 is selected to suit the tubes. R1 is the resistance winding of a special short-circuiting fuse; when energized by the full line current should a heater become open-circuited, it causes a permanent direct short-circuit across the heater chain. The line voltage will be temporarily increased by about 95 volts while the fuse operates (1 min) and will then drop to 12 volts below normal.

Amplifier.

The amplifier circuit is shown in Fig. 3. It consists of two 3-stage amplifiers connected in parallel between common input and output transformers with a single feedback network. This circuit arrangement allows one amplifier path to fail without appreciably affecting the gain of the complete amplifier (less than 0.1 db for all faults except those on the grid of V1 and the anode of V3, but the overload point is reduced by about 5 db and distortion at a given output level is increased (about 12 db for second harmonics). Care has been taken to ensure that the open- or short-circuiting of a component in one amplifier path will not affect the performance, life or stability of the remaining path, and this involves the duplication of certain components.

Mixed feedback is employed to produce the required output impedance; the current feedback is obtained from the resistor feeding the high-voltage supply to the output transformer, and the voltage feedback is developed across a two-turn winding on the output transformer, which also serves as a screen. The output of the feedback network is fed in series with the input signal to the grid of V1. The gain response of the amplifier is chiefly controlled by the series-arm components in the feedback network, which resonate at 600 kc.

The input transformer is built out as a filter and steps up in impedance from 55 ohms to 17,000 ohms. Protective impedances minimize the effect of a short-circuit on the grid of one of the first-stage tubes. The anode load of the first stage resonates at 600 kc, and is roughly the inverse of the feedback network so as to give constant feedback loop gain over the working frequency band. The output tube has about 5.5 db of feedback from its cathode resistor, and the pair of output tubes feed the output transformer, which steps down from 5,000 to 55 ohms.

Specially designed long-life tubes are used.[7] The first two stages are operated at about 40 volts on the screens and anodes; each anode current is 3 ma, giving a mutual conductance of 5.1 ma/v. The output stage is operated at 60 volts on the screen, +15 volts on the suppressor grid to sharpen the knee of the V_a/I_a characteristic, and nearly the full high-voltage supply of 90 volts on the anode; the anode current is 6 ma, giving a mutual conductance of 6.6 ma/v. The tube dynamic impedance is approximately 300,000 ohms. To obtain an anode current nearest to the

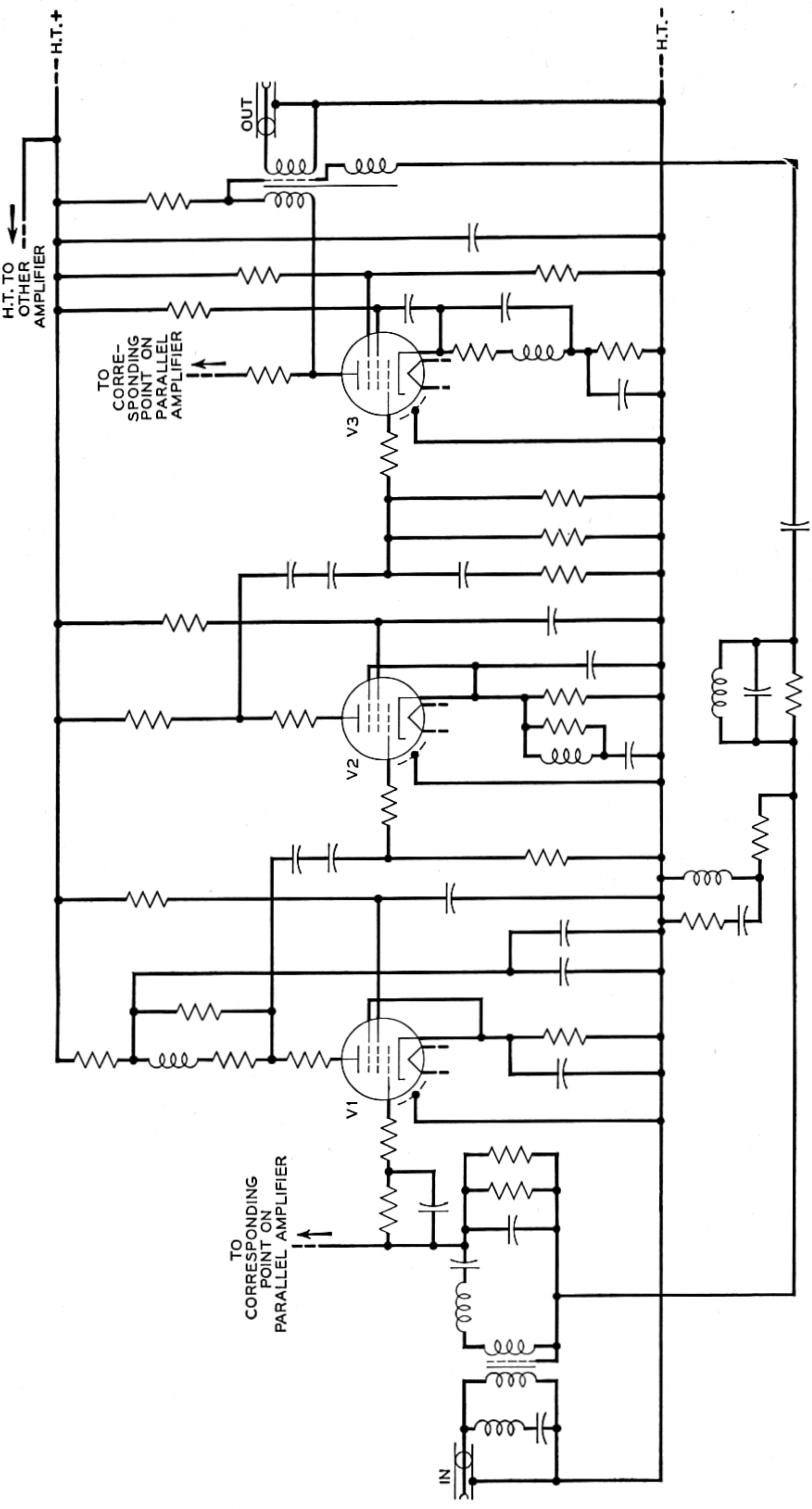

Fig. 3 — Amplifier circuit.

design value (and for which the tubes are aged), one of two values of bias resistance can be selected for V1 and V2, and one of three values of bias resistance for V3.

All capacitors subject to the high-voltage supply voltage are of the oil-filled paper type, and the others are of the silvered-mica type. Inductors are air-cored spools which are multi-sectioned when used in high-impedance circuits. All resistors are of the solid carbon-rod type, except for the input-transformer termination, which consists of two high-stability cracked-carbon resistors, and those in the feedback network, which are wire wound.

The input and output transformers employ 2-mil permalloy C laminations, and the latter core is gapped on account of the polarizing current. A narrow Perspex spool fits the center limb, and conventional layer windings are used; the screen is a sandwich made of copper foil with adhesive polythene tape.

3.3 *Mechanical Design Details*

The arrangement can be seen from Fig. 1. At the A-end is a cast-brass pot containing the resistors providing the amplifier high-voltage supply, and as this is bolted directly on to the housing bulkhead, the heat generated is readily conducted away. The remainder of the units are in cylindrical cans mounted in the insulating framework formed by four Perspex bars. These are sprayed with copper on both faces to guarantee the dc potential on these surfaces and eliminate the risk of ionization at working voltages. The cans are not hermetically sealed but are dried out with the repeater when it is finally sealed and filled with dry nitrogen. Perforated covers on the amplifier allow air circulation to reduce the ambient temperature.

Fig. 4 shows a typical can assembly, and Figs. 5 and 6 the construction of the amplifier. It will be seen that the latter is a double-shelved structure with tubes alternating in direction, and an amplifier path is located on each side of the chassis; the input and output transformers are at opposite ends, and the feedback network is contained in a hermetically sealed can in the center of the unit.

All cans are finished with a gold flash which is inert and gives a clean appearance stimulating a high standard of workmanship. Tin plating was formerly used, but it has been shown that tin tends to grow metallic whiskers.[8] Unfortunately certain capacitor cans had to be tin plated, and extra precautions consisting of wide clearances or protective shields have had to be taken. The risks from growth on soldered surfaces is not

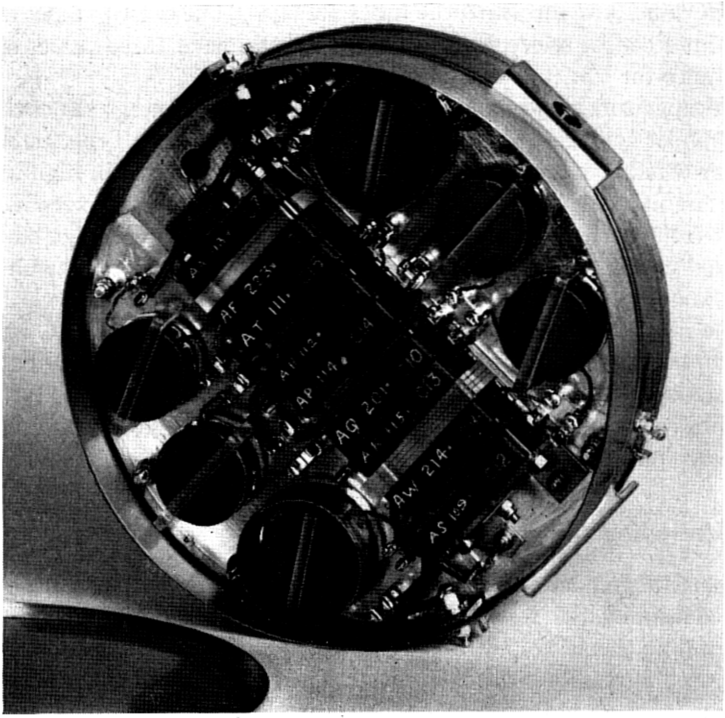

Fig. 4 — Directional filter unit. High-pass filter with low-pass filter can on rear.

thought to be great, as all solders used have less tin content than the eutectic alloy. All connecting wires are gold plated instead of the usual tin plating.

The insulating sub-panels in units are usually made of Perspex, but where the items are subjected to high temperatures (e.g., resistance box), Sintox, a sintered alumina ceramic, or Micalex is used.

Polytetrafluoroethylene (p.t.f.e.) is another insulant used, and p.t.f.e.-covered wire threaded through copper tube forms the coaxial interconnecting leads between the can units.

Careful attention is paid to the mounting of components. Small resistors, etc., are supported by soldering to tags which are the appropriate distances apart, and multi-limb tags are employed to minimize the number of soldered joints. Where it is essential to solder more than one wire per limb on a tag, they must be soldered at the same time.

Larger components are clamped. Electron tubes are mounted in a holder so as to facilitate preliminary testing with 'standard electron tubes,' and they have a sprung nylon retainer; the final electrical connection is made by soldering on to an extension of the wire leading through the pins.

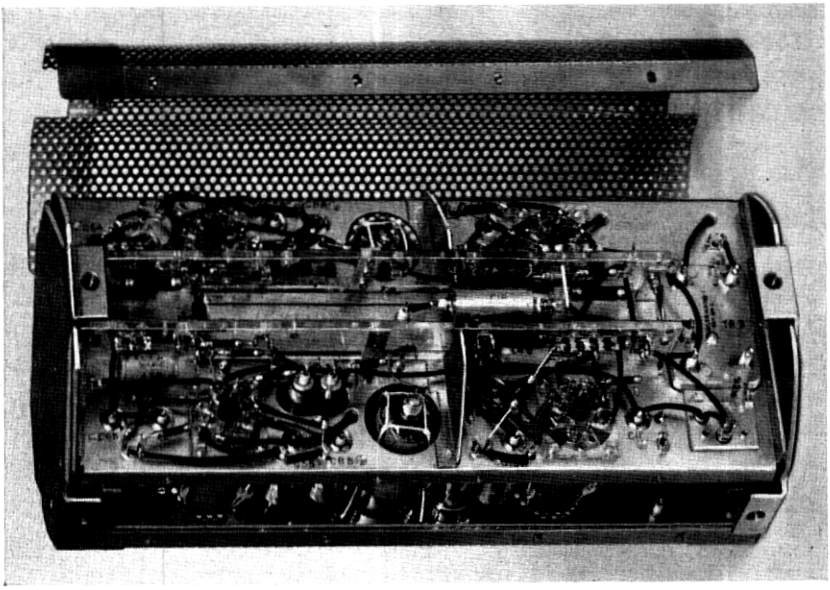

Fig. 5 — Amplifier.

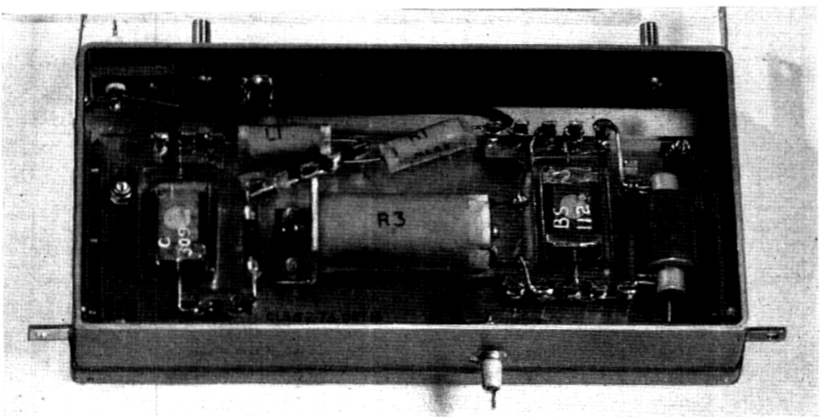

Fig. 6 — Feedback unit of amplifier.

DESIGN OF INTERNAL UNIT OF SUBMERGED EQUALIZER

The submerged equalizer corrects for the difference between the assumed design cable characteristic and the subsequently determined laid characteristic for equal attenuation lengths at 552 kc. It also absorbs the loss of 9 nautical miles of cable and has an attenuation of 26.0 db at 552 kc.

The construction is identical with the submerged repeater except for the replacement of all can assemblies, other than the power filters, by the equalizer cans. Fig. 7 is a schematic of the unit.

ELECTRICAL COMPONENTS

General

The components used in the repeaters were either designed specially for submerged repeaters or were standard items with improvements. There are approximately 300 components in each repeater of which 110 are in the amplifier. Rigorous control of manufacture and meticulous inspection is imperative to ensure a consistent long-life product, and cleanliness is essential at all stages. In some cases 'belt and braces' tech-

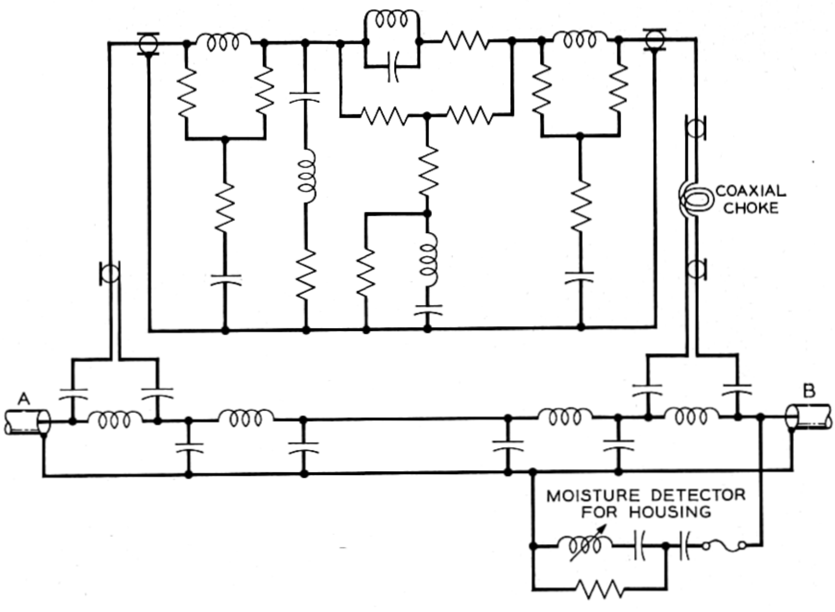

Fig. 7 — Schematic of submerged equalizer.

niques can be effectively employed, e.g., by using double connections. Over 1,500 separate soft-soldered connections are involved in the complete assembly. Much work has been done on components, but only a brief indication can be included here. A range of typical components appears in Figs. 4–6.

Resistors

Resistors fall into the following categories:

(*a*) Power resistors used solely for dc purposes (e.g., resistors providing the amplifier high-voltage supply). These are wire-wound vitreous-enamelled resistors on Sintox ceramic formers. Nichrome terminal leads are used, and all connections are brazed.

(*b*) High-frequency resistors whose tolerance is not close, and often carrying direct current but of low power (e.g., anode load resistances). A modification of a standard carbon-rod resistor is used. The ends of the rod are copper plated and the end caps and terminal leads are soldered on. The tolerance is normally ±5 per cent, and the maximum rating permitted is about one-quarter of the commercial rating.

(*c*) Precise high-frequency resistors of resistance below 1,000 ohms (e.g., feedback components). Here wire-wound spool resistors are suitable, and bifilar or reverse layer windings with Lewmex enamel and silk-covered wire are used.

(*d*) Precise high-frequency resistors of high resistance. For terminating the input transformer a resistance of 17,000 ohms is required. Because it is not possible to make a suitable wire-wound resistor, high-stability cracked-carbon film resistors are used, but to minimize the effect of a disconnection two are used in parallel.

Inductors

The majority of inductors used in the amplifier and equalizer do not require a high Q-factor. They are wound on air-cored ceramic bobbins of four types, and the high-inductance ones are sectionalized. In general solid wire with Lewmex enamel and double-silk covering is used for the amplifier inductors, and stranded wire for the equalizer inductors.

A high Q-factor inductor is essential in the directional filters, and a carbonyl-iron pot core was used; the Q-factor is about 250 at 300 kg, Precise adjustment and stability of inductance was obtained by settins the gap between the halves of the pot core with a cement of Araldite (an epoxy resin) and titanium dioxide. A Perspex former was used.

Special inductors were required in the power filters to take the 316-ma dc line current. A wave-wound air-cored coil was used for the carrier-path filter (L_1 in Fig. 2), and a toroid on an a.f. Permalloy dust-core ring for the low-pass filter (L_2 in Fig. 2). Solid wire, with Lewmex and double-silk covering, was used to keep the dc resistance to a minimum.

5.4 *Capacitors*

Capacitors are divided into three categories:

(*a*) Those subjected to the full line voltage which may operate at up to 3 kv.

(*b*) Those subjected to the amplifier high-voltage supply of 90 volts.

(*c*) Those which have negligible polarization (less than 10 volts), and which are often required to precise values.

Groups (*a*) and (*b*) are of the oil-filled paper type, with, respectively, four layers of 36-micron and three layers of 7-micron Kraft paper. The oil is a mineral type loaded with 18 per cent resin, and the capacitors are filled at 60°C and sealed at room temperature.

Small capacitors and those of precise value as in group (*c*) are silvered-mica capacitors. These are encased in an epoxy resin to give mechanical protection and a seal against moisture. Visual inspection of all mica plates is made before and after silvering, and any with cracks, inclusions, stains or any other abnormality are rejected. Mica is a very variable material and at times the percentage rejects were high, but probably many of the reasons for rejection would not have been significant as far as the life of the capacitor is concerned. However, experience has shown

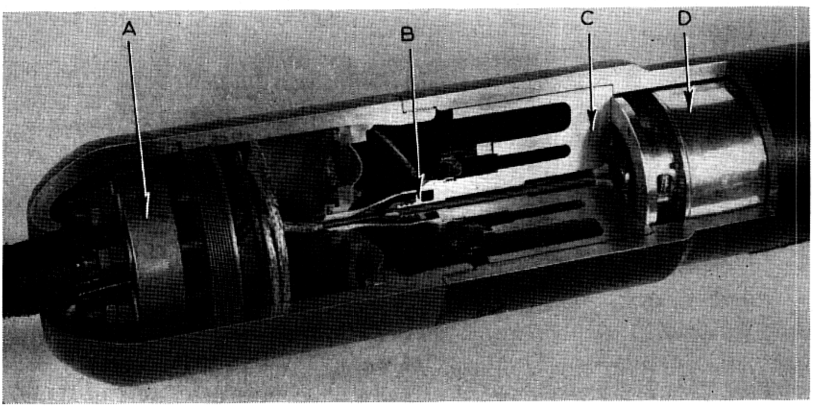

Fig. 8 — Details of housing construction. A. Armour clamp. B. Gland. C. Bulkhead. D. Part of internal unit.

that even with stringent precautions mica is not an entirely satisfactory dielectric material.

Other Components

Electron tubes form the subject of a separate paper.[7] Of the other miscellaneous components used, one of interest is the short-circuiting fuse across the electron tube heaters. It is constructed like a normal wire-wound resistor on a Sintox tube former, but inside are two cupped copper electrodes filled with a low-melting-point eutectic alloy. If the full line current (316 ma) is passed through the winding, owing to a heater disconnection, the heat generated is sufficient to melt the alloy, which then fuses the two electrodes together. The winding is thus short-circuited, and a permanent connection is left between the electrodes.

DESIGN OF HOUSING AND GLAND

General

Although the maximum depth of water in which British rigid-type repeaters were laid did not exceed about 250 fathoms, the housings used for these repeaters were generally of a type designed for use at ocean depths, and when connected into the cable they were amply strong enough to transmit stresses up to the breaking point of any of the cables used.

The part of the housing which is sealed against water pressure consists essentially of a hollow cylinder, machined from hot-drawn steel tube, and closed at both ends by steel bulkheads carrying the cable glands through which the connections are made to the electrical unit (see Fig. 8). The latter is bolted rigidly to the inner face of the A-end bulkhead. The steel blanks used for the main cylinder and the bulkheads are tested with an ultrasonic crack detector, and after machining they are further subjected to magnetic crack-detection tests.

Each gland has a brass cover which completes the coaxial transmission path and contains a weak solid mixture of polythene and polyisobutylene (p.i.b.). Outside the brass cover is a larger chamber closed by a flexible polyvinylchloride (p.v.c.) diaphragm and containing p.i.b. — a viscous liquid — which prevents sea water coming into direct contact with the bulkhead seal and the gland assembly.

Cylindrical extension pieces, screwed on to the main casing, contain the clamps for attaching the repeater housing to the armour wires of the sea cable, and the housing is completed by dome-shaped end covers. Two external annular ridges near the centre of the housing accommodate the special quick-release clamp used for handling the repeater during the laying operation.

Protection against corrosion is provided by shot-blasting the surface and then applying hot-sprayed zinc to a thickness of 0.010 in, followed by two coats of vinyl paint. The A-end of the repeater is finished red. The dimensions of the complete repeater are 8 feet $11\frac{3}{8}$ inches $\times$ $10\frac{1}{2}$ inches diameter, and its weight is 1,150 lb in air

Sealing of Housing

The bulkheads, which register on seatings designed to withstand the axial thrust due to the water pressure, are in the form of discs with extended skirts. A watertight and diffusion-proof seal is formed between the casing and the outer skirt of each bulkhead by a silver-soldering process, using carefully controlled electromagnetic induction heating to raise the jointing region to the required temperature. The diametral clearance between the cylinder and the locating surface of the bulkhead is 0.003 inch $\pm$ 0.002 inch, the diameter of the bulkhead being reduced by 0.004 inch for an axial distance of 3 inches from the rim of the skirt to provide a recess into which the molten solder can flow.

The solder is applied as eight pre-formed No. 16 s.w.g. wire rings which are fitted into place cold and coated with a paste formed by mixing flux powder with dehydrated ethyl alcohol. The generator used for heating has a nominal output of 50 kw at a frequency of about 350 kc and is capable of raising the temperature of the jointing region to 750°C in 5 min. The temperature, as indicated by four thermocouples inserted in special holes drilled in the ends of the casing, is maintained at 750°C for a period of 45 min to allow ample time for the entrapped gas and flux pockets to float to the surface. Fig. 9 shows the arrangement for soldering in a bulkhead.

The primary object of the outer skirt is to keep the heated region far enough away from the base to prevent the temperature of the latter rising unduly. Temporary water jackets are also clamped over the gland and around the outside of the casing during the sealing operation. A subsidiary skirt on each bulkhead contains a vent hole which serves to allow displaced air to escape as the bulkheads are inserted into the casing. These vents are later used to apply a low-pressure gas-leak test to the bulkhead seals and then to flush the housing with dry nitrogen to remove any trapped moisture. The vents are finally sealed. At this stage the sealed housing is pressure-tested in water at $1\frac{1}{2}$ tons*/square inch for a

* These are long tons. 1 long ton = 2240 lb.

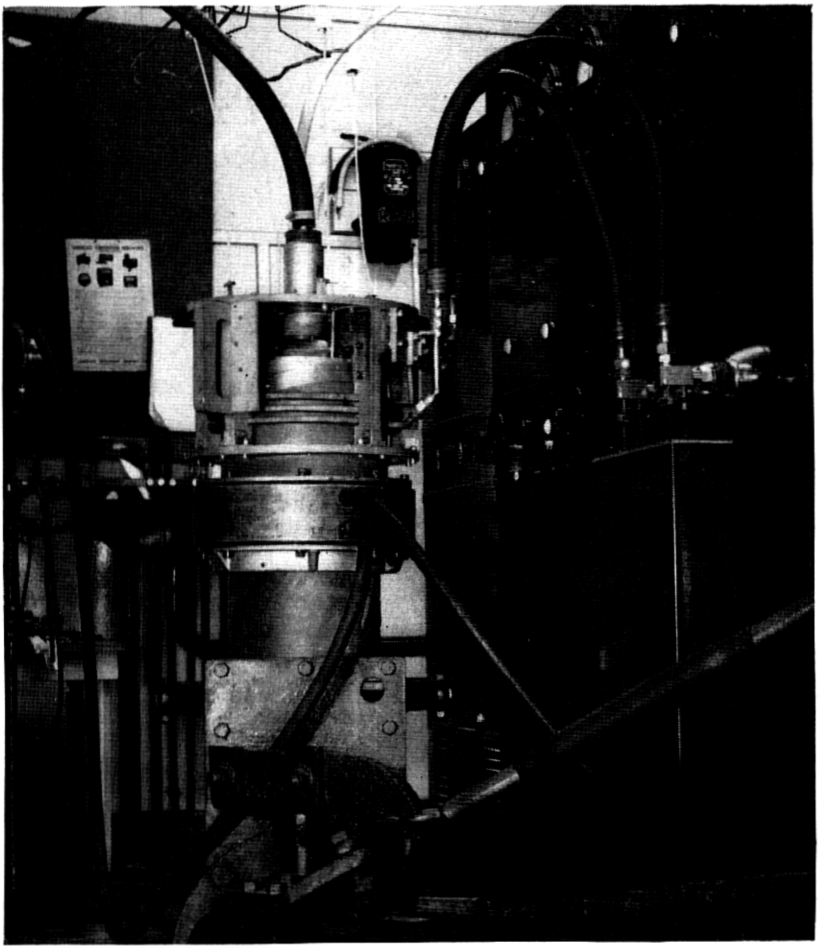

Fig. 9 — Silver-soldering of bulkhead into housing with induction heater.

period of seven days, a moisture detector, mentioned previously, being used to check that no leakage occurs.

Glands

The deep-sea gland was developed from the castellated gland which has been used successfully for a number of years in shallow-water repeaters. The basic principle of this gland is very simple and is shown in Fig. 10; the polythene-insulated cable core passes right through the

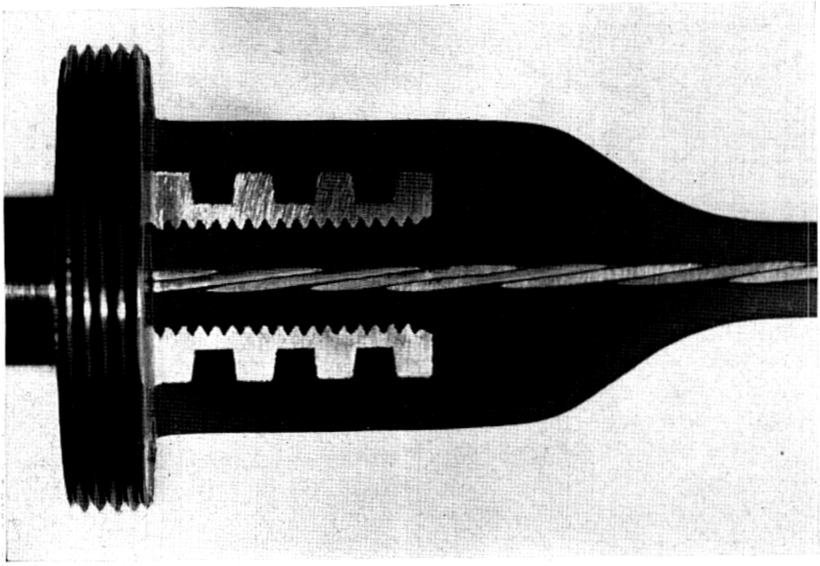

Fig. 10 — Section of high-pressure gland.

bulkhead, and the initial seal is formed by the contraction, during cooling, of polythene moulded on to the core and enclosing a steel stem, having a castellated profile, which forms part of the bulkhead. Each side of the castellation has a taper of about 7°. The application of water pressure increases the contact pressure between the polythene and the stem, thus making the gland inherently self-sealing. As an additional safeguard, the gland stem is first prepared by a lead plating and anodizing process, followed by the application of a thin film of polythene which forms a chemical bond to the plated surface. The injected polythene merges with this film, thus bonding the molded portion to the castellated stem. Tests on sample gands, using a radioactive tracer, have shown no measurable (less than 0.001 mg) water diffusion at a pressure of 5 tons*/square inch over a period of 6 months.

Intrusion of the polythene into the housing, at hydraulic pressures up to at least 6 tons*/square inch, is eliminated by the use of a small-diameter core and by the provision of a screw thread in the hole through which the core passes. During the molding operation a corresponding thread is formed on the polythene core itself. This method of construction distributes the axial force over a sufficiently wide area to prevent any appreciable creep of the polythene.

The completed gland assemblies were all subjected to a minute X-ray examination, followed by a pressure test at 5 tons*/square inch for three months. Whilst under pressure, the glands had to withstand a voltage test of 40 kv dc for 1 minute, to show no ionization effects when a voltage of 3 kv (r.m.s.) at 50 cycles was applied and to have an insulation resistance greater than 20×10^{12} ohms.

MANUFACTURE

General

The manufacture of the electrical units was carried out in accommodation specifically designed for submerged-repeater production. Temperature was controlled at 68°F and the relative humidity was less than 20 per cent in the component shops and 40 per cent in the assembly and test shops. Filtered air forced into the building maintained a slight positive pressure with respect to the outside and eliminated the ingress of dust. With the exception of the tubes and some resistors all components were manufactured in this 'diary' (Fig. 11). Operators are specially selected, and they must change into clean protective clothing in an anteroom before entering the working area, where no smoking or eating is permitted. All operators are particularly encouraged to report or reject any condition which is abnormal or in which they have not complete confidence. Rigorous inspection and testing were carried out by the contractor at all stages, and a Post Office team collaborated with 'floor' inspection and the examination and approval of test results.

The Electrical Unit

The components, after the most careful examination and testing, which in some cases included an aging test, were assembled into their cans and then subjected to a shock test before undergoing detailed electrical characteristics tests. Initial tests on the amplifier were done with a set of 'standard' electron tubes, which were later replaced by the final tubes for the complete tests. The cans were then assembled in a repeater chassis and the electrical tests required before sealing performed — this included a gain response to determine the best settings for the trimmer pads in each transmission band. After fitting and sealing the outer brass case, dry nitrogen was blown through the unit for 24 hours and the gas holes then sealed. The overall electrical characteristics were then taken, the repeater was energized for a two weeks' 'confidence trial' and the characteristics were rechecked. During the 'confidence trial' the gain was

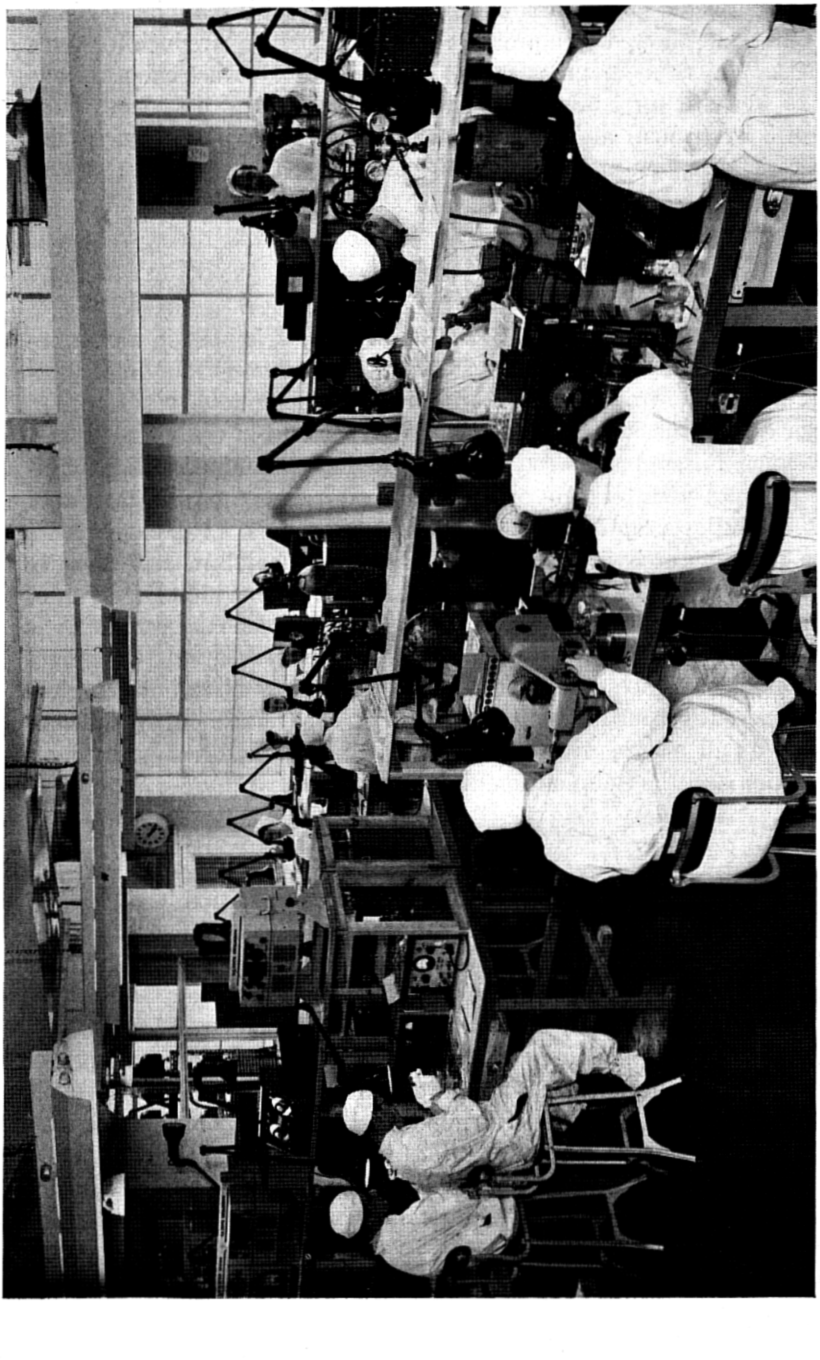

Fig. 11 — Coil production in the 'dairy'.

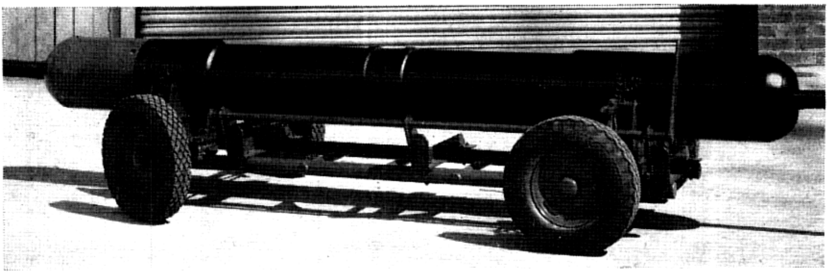

Fig. 12 — Completed repeater.

continuously monitored on a recorder (duplicated to distinguish between test equipment and repeater variations) on which changes in gain of 0.01 db were clearly indicated. On satisfactory completion of these tests the unit was ready for housing.

Assembly of Electrical Unit in Housing

The first step was to complete the molded joint between the tail cables from the A-end of the electrical unit and the low-pressure side of the appropriate bulkhead. This joint was X-rayed and proof tested at 20 kv dc for 1 minute. The electrical unit was then bolted to the bulkhead, the slack tail cable being correctly coiled into the recess provided, and the whole assembly was lowered into the housing for the first silver-soldering operation. Following this sealing the tail cable joint was made to the B-end bulkhead, which was then lowered into the housing and sealed.

A leak test was then made by applying an internal air pressure of 5 lb/square inch (gauge) and observing the surface when wetted with a solution of a suitable detergent in water. After flushing with dry nitrogen the vents were sealed and the housing was pressure tested. Finally the brass gland covers were fitted and filled with compound, the extension pieces were screwed on, the flexible diaphragms were fitted and the internal space was filled with polyisobutylene. The housing was then ready for further electrical testing.

Tests on Complete Repeater

After housing, the repeaters were submerged in a tank of water for a three-month electrical 'confidence trial.' Before and after the trial the complete characteristics were checked and the noise was monitored on both terminals; during the first and last few weeks of the trial the gain

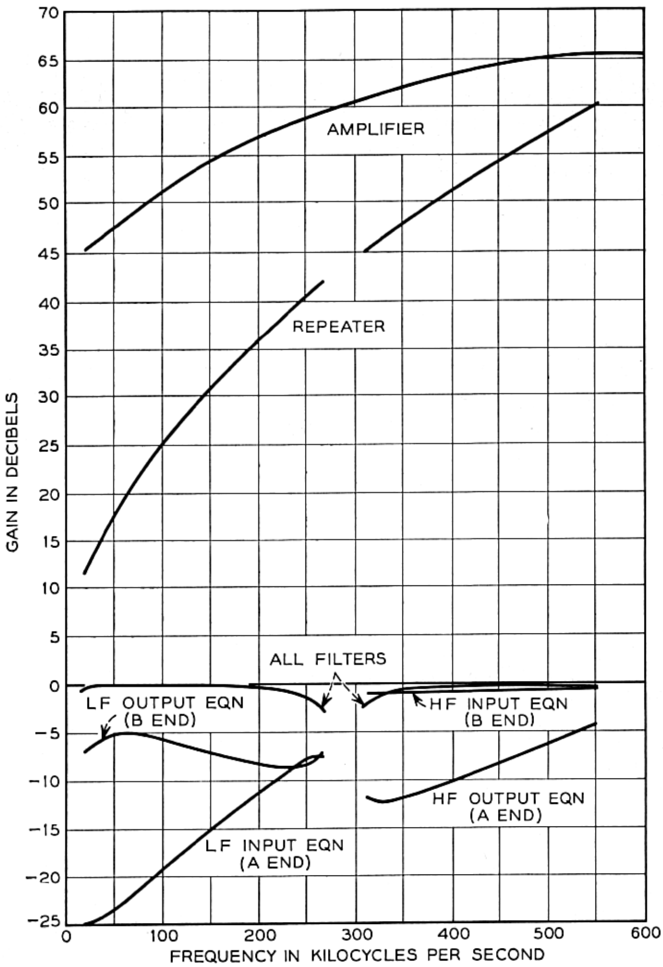

Fig. 13 — Repeater gains and losses.

was monitored on recorders in both directions. Owing to the insertion and withdrawal of repeaters in the power circuit from time to time, the repeaters were subjected to several power-switching operations and temperature cycles.

Stability of electrical characteristics, particularly gain, between the pre-housing tests and the completion of the 'confidence trial' some four months later was regarded as an important criterion of the reliability of a repeater. Unfortunately test conditions and differences between, and

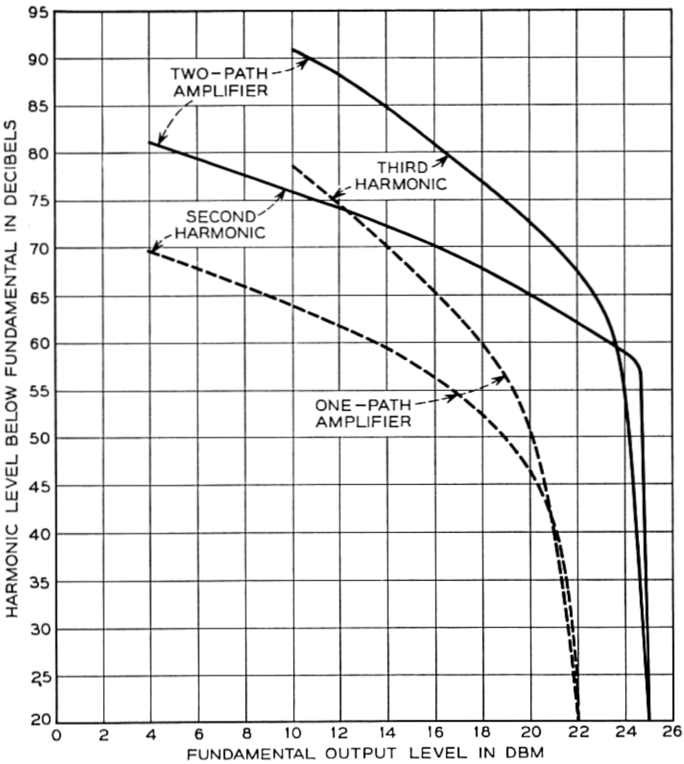

Fig. 14 — Amplifier distortion.

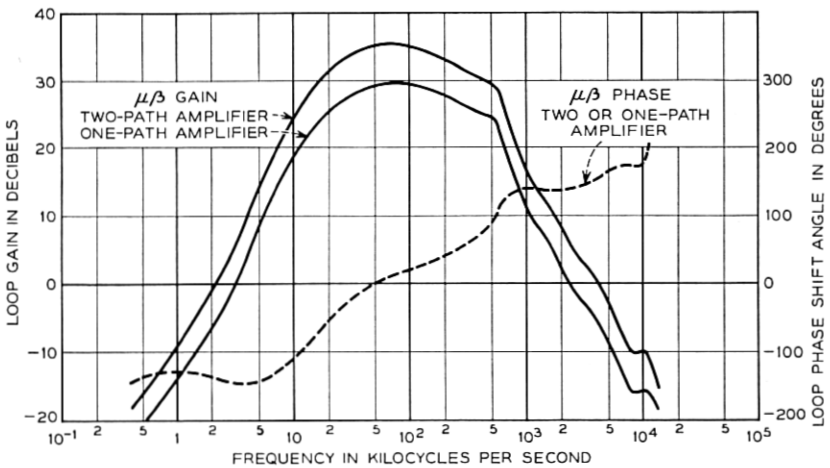

Fig. 15 — Amplifier $\mu\beta$ characteristic.

stability of, the testing equipments reduced the accuracy originally expected, but even so, changes of over 0.1 db were regarded as significant.

Connection of Repeaters to Cable

On board the cable ship the cable ends were prepared by making tapered molded joints to 0.310-inch tail cable, sliding the domed ends of the repeater up the cable and forming the armor wires round the armor clamps. The tapered joint included a castellated ferrule on the center conductor, which, operating on the principle of the main gland, acts as a barrier against the possible passage of water down the center conductor into the repeater. The final assembly operation consists of jointing the tail cables, bolting the armor clamps to the repeater housing and screwing on the domed ends. Fig. 12 shows a completed repeater connected to a cable.

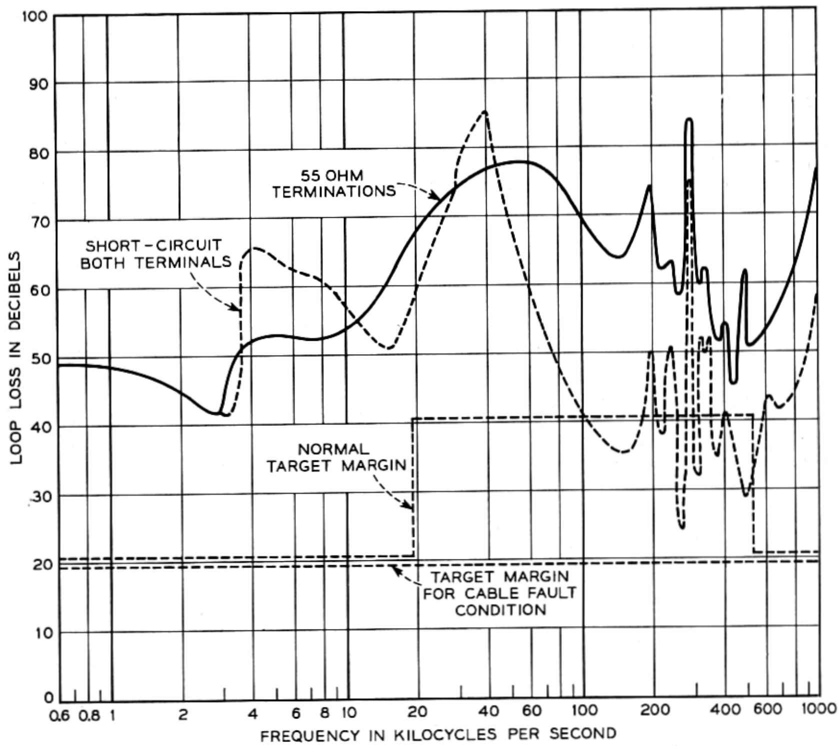

Fig. 16 — Repeater loop loss measured at amplifier input.

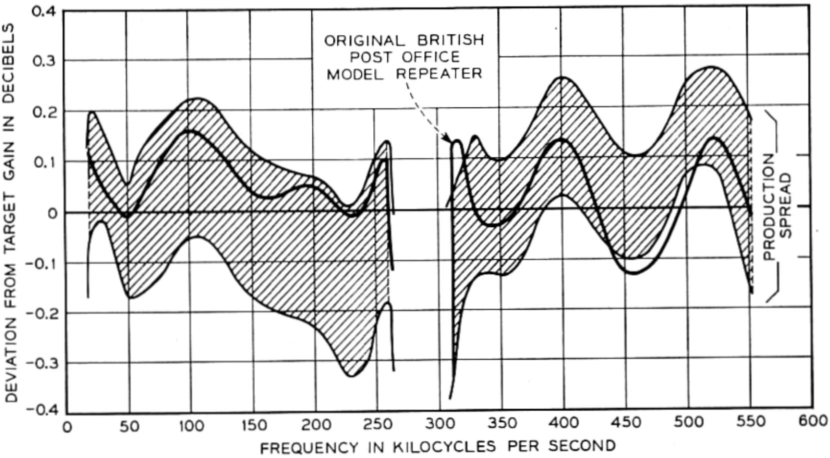

Fig. 17 — Repeater-gain response.

PERFORMANCE

The gains and losses of various sections of the repeater are shown in Fig. 13. Figs. 14 and 15 show, respectively, the harmonic distortion and the stability characteristics of the amplifier with one and two paths operating. The total shunt loss across the amplifier is shown in Fig. 16 as a margin above the amplifier gain. The curves show the result with 55-ohm terminations on the repeater and with a short-circuit on each terminal. Fig. 17 shows the production spread in gain of the 16 repeaters for the system as a deviation from the target value. The highest standard deviation (at 260 kc) was only 0.11 db. In all respects the production repeaters proved to be very consistent and satisfactory in their performance and differed little from the original laboratory-built model.

Typical electrical characteristics of a repeater and the submerged equalizer are shown in Appendices 1 and 2 respectively.

The characteristics of the completed link are described elsewhere,[9] but it is of interest to note that the overall tests showed that the link behaved as predicted and met the noise requirement and the design margins.

ACKNOWLEDGMENTS

It will be appreciated that the design and manufacture of these repeaters has been an undertaking of teams rather than of individuals. The authors are very grateful to Standard Telephones and Cables, Ltd., and Submarine Cables, Ltd., for their unsparing efforts to ensure the very highest standards in the engineering, production and testing of these repeaters. Numerous firms have also co-operated in specialized fields, and the authors are very appreciative of their help. The authors also wish to acknowledge the enthusiastic assistance of their many colleagues in the Research Branch of the Post Office in the design and in the supervisory inspection during manufacture. Finally a grateful acknowledgment is made to the Engineer-in-Chief of the British Post Office for permission to publish the paper.

Appendices

1 PERFORMANCE OF TYPICAL SUBMERGED REPEATER

(*a*) Insulation resistance.................... 8000 megohms (cold).
(*b*) DC resistance at 20°C.

Current, ma	DC resistance, ohms
5	343.0
20	343.2
50	344.2
100	347.9

(*c*) Voltage drop at 316 ma............................ 124 volts
(*d*) Carrier gain (55 ohms) without moisture detector.

Frequency, kc	Gain, db	Frequency, kc	Gain db
20	11.54	308	44.52
30	13.82	312	44.87
50	17.47	320	45.56
100	25.06	330	46.29
150	30.86	350	47.75
200	35.81	400	51.19
230	38.40	450	54.20
260	40.96	500	57.31
264	41.13	552	60.01
268	40.83		

(*e*) Noise level.
A terminal (312–552 kc)........................ −59.8 dbm
B terminal (20–260 kc)......................... −70.3 dbm
(*f*) Harmonic level.
170 kc fundamental level at B terminal.............. +10 dbm
340 kc second harmonic level at A terminal........... −60 dbm
510 kc third harmonic level at A terminal............. −58 dbm

(*g*) Supervisory — 260.800 kc (nominal).

Fundamental level at B terminal, dbm	Second harmonic level at A terminal, dbm
−12	−26
−2	−13.8
+8	−3.6

(*h*) Moisture detector.
Resonant frequency with 30-ft cable tail................ 1,237 kc

(*i*) Impedance.

Return loss against 55 ohms

Frequency, kc	A-terminal return loss, db	B-terminal return loss, db
20	17	8
50	17	13
100	16	15
200	16	4
260	16	4
312	13	21
350	14	14
500	18	16
552	16	25

2 PERFORMANCE OF SUBMERGED EQUALIZER

(*a*) Insulation resistance.......................... 8,000 megohms
(*b*) DC resistance at 20°C............................ 9.2 ohms
(*c*) Voltage drop at 316 ma........................... 3.0 volts
(*d*) Carrier loss (55 ohms) — without moisture detector.

Frequency, kc	Loss, db	Frequency, kc	Loss, db
20	4.28	260	15.90
30	4.23	312	18.26
50	4.87	350	19.96
100	7.47	400	21.75
150	10.35	450	23.16
200	13.04	500	24.55
230	14.52	552	25.97

(*e*) Moisture detector.
Resonant frequency with 5-ft cable tail................. 1,387 kc

(*f*) Impedance
Return loss against 55 ohms

Frequency, kc	A-terminal return loss, db	B-terminal return loss, db
20	35	31
50	19	19
100	25	25
260	34	27
552	30	23

REFERENCES

1. R. J. Halsey and F. C. Wright, Submerged Tilybene Repeaters for Shallow Water, Proc. I.E.E., **101,** Part I, p. 167, Feb., 1954.
A. H. Roche and F. O. Roe, The Netherlands-Demark Submerged Repeater System, Proc. I.E.E., **101,** Part I, p. 180, Feb., 1954.
D. C. Walker and J. F. P. Thomas, The British Post Office Standard Submerged Repeater System for Shallow Water Cables (with special mention of the England-Netherlands System), Proc. I.E.E., **101,** Part I, p. 190, Feb., 1954.
2. M. J. Kelly, Sir Gordon Radley, G. W. Gilman and R. J. Halsey, A Transatlantic Telephone Cable, Proc. I.E.E., **102B,** p. 117, Sept., 1954, and Communication and Electronics, **17,** pp. 124–136, March, 1955.
3. J. F. P. Thomas and R. Kelly, Power-Feed System for the Newfoundland-Novia Scotia Link. See page 277 of this issue.
4. B. D. Holbrook and J. T. Dixon, Load Rating Theory for Multi-Channel Amplifiers, B.S.T.J., **18,** p. 624, 1939.
5. R. A. Brockbank and C. A. A. Wass, Non-Linear Distortion in Transmission Systems, Jl.I.E.E., **92,** Part III, p. 45, 1945.
6. J. S. Jack, Capt. W. H. Leech and H. A. Lewis, Route Selection and Cable Laying for the Transatlantic Cable System. See page 293 of this issue.
7. J. O. McNally, G. H. Metson, E. A. Veazie and M. F. Holmes, Electron Tubes for the Transatlantic Cable System. See page 163 of this issue.
8. S. N. Arnold, Metal Whiskers — A Factor in Design, Proc. 1954 Elec. Comp. Symp., pp. 38–44, May, 1954, and Bell System Monograph 2338.
9. R. J. Halsey and J. F. Bampton, System Design for the Newfoundland-Nova Scotia Link. See page 217 of this issue.