Repeater and Equalizer Design

By R. G. BUUS, J. J. KASSIG and P. A. YEISLEY

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Long-distance submarine cable transmission systems require precise, highly reliable repeaters for amplification, and adjustable equalizers for reducing accumulated transmission deviations. This article describes the problems and solutions in designing suitable repeaters and equalizers for the high capacity SF System. This system uses a repeater with transistors to provide a capacity of 800-message circuits.

I. INTRODUCTION

The undersea portion of the SF System includes repeaters spaced at 18.52 kilometer ($\simeq$10 nautical mile) intervals along the undersea cable to compensate signal loss in the cable across the two nominal transmission bands of 564 to 2788 kHz and 3660 to 5884 kHz. This allocation permits 720* three-kilohertz two-way message channels. Since it is not possible to make the repeater gain characteristic exactly match the cable loss, an equalizer corrects the error accumulated after every 20 repeaters.

Physically both repeater and equalizer units are sealed, encapsulated, and shock mounted within a sealed beryllium copper pressure hull.

The repeaters of the SF System use transistor and semiconductor diode circuitry. The advantages gained include small size, improved power efficiency, and low aging. It should be noted that total repeater size and weight are little altered by the use of transistors, since most other repeater components are not scaled down in size. However, the smaller physical size of the transistors shortens the feedback loop and thus contributes to the wider bandwidth.

Careful attention to design detail, lengthy testing programs, and proven electrical and mechanical concepts refined to meet system re-

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* The basic SF design objective was 720 channels. On the 1300-nautical mile system between Florida and the Virgin Islands, out of band misalignments are small enough to permit possible use of as many as 820 channels. The recently completed TAT-5 System is able to meet objective for over 820 channels.

quirements, were the guideposts in producing a satisfactory design. Specially devised digital computer techniques played a prominent role in circuit design and transistor characterization.

II. REPEATER REQUIREMENTS AND CHARACTERISTICS

The SF System requirements are discussed in a companion article.[1] Briefly, the SF System is an equivalent 4-wire (single cable) design with rigid repeaters. It uses armorless coaxial cable[2] as the transmission medium. The basic band of the SF System provides 720 three-kilohertz message circuits over routes up to 4000 nautical miles. It carries both regular telephone service and special services such as data.

2.1 *Repeater Requirements*

2.1.1 *Electrical Performance*

Important repeater electrical performance characteristics appear in Table I.

The nominal insertion gain of the repeater compensates the loss of 18.52 kilometers of 3.8 cm ($1\frac{1}{2}$ inch) diameter coaxial ocean cable for the two SF System frequency bands 564-2788 and 3660-5884 kHz. In the low-frequency band repeater gain exceeds cable loss by a small amount to provide additional loss range for the ocean block equalizer networks. The resultant repeater gain objectives are tabulated in Table II.

The allowable gain deviation from nominal has two parts—systematic and random deviations. The average repeater must match the objective of Table II to within $\pm 0.025(6/f)^{\frac{1}{2}}$ dB, with f the frequency in megahertz. The random deviation from this objective cannot exceed $\pm 0.1(6/f)^{\frac{1}{2}}$ dB on a 20-repeater block basis. Equalizers must remove the bulk of the residual deviations.

TABLE I—SF REPEATER NOMINAL PERFORMANCE PARAMETERS

At 5.884 MHz:	
Input/Output return loss (minimum)	28.0 dB
Noise Figure	7.6 dB
Power Output	20.0 dBm
Third Order Modulation Coefficient, M_{3R}	−95.0 dB
At 564. kHz:	
Input/Output return loss (minimum)	32.0 dB
Noise Figure	12.0 dB
Power Output	17.0 dBm
Second Order Modulation Coefficient, M_{2R}	−65.0 dB

TABLE II—REPEATER GAIN OBJECTIVE—dB

F(kHz)	Cable	Boost	Objective
500	11.339	0.200	11.539
600	12.449	0.192	12.641
700	13.463	0.184	13.647
800	14.403	0.176	14.579
1000	16.114	0.160	16.274
1200	17.662	0.144	17.806
1400	19.090	0.128	19.218
1500	19.767	0.120	19.887
1600	20.423	0.112	20.535
1800	21.679	0.096	21.775
2000	22.870	0.080	22.950
2200	24.005	0.064	24.069
2400	25.093	0.048	25.141
2500	25.621	0.040	25.661
2600	26.138	0.032	26.170
2650	26.394	0.028	26.422
2700	26.647	0.024	26.671
2750	26.898	0.020	26.918
2800	27.146	0.016	27.162
2850	27.393	0.012	27.405
3600	30.875	0	30.875
3650	31.092	0	31.092
3700	31.312	0	31.312
3750	31.529	0	31.529
3800	31.744	0	31.744
4000	32.593	0	32.593
4200	33.422	0	33.422
4400	34.233	0	34.233
4500	34.633	0	34.633
4600	35.028	0	35.028
4800	35.807	0	35.807
5000	36.571	0	36.571
5200	37.321	0	37.321
5400	38.058	0	38.058
5500	38.422	0	38.422
5600	38.783	0	38.783
5800	39.496	0	39.496
6000	40.199	0	40.199

Repeater gain deviations cannot include any sharp shapes or any which have many zero crossings, even if they fall within the above formula requirements. These kinds of mismatch cannot be equalized by available networks.

The repeater ports must match the cable impedance of 59.4 ohms to prevent the formation of undesirable ripples in the overall transmission characteristic. At the top of the band the repeater's return loss at both ports is better than 28 dB, as shown in Table I, while at lower frequencies it must be somewhat higher, due to reduction of cable loss. For this reason minimum realized return loss at 0.5 MHz is 32.0 dB at both ports.

The repeater noise figure is slightly under 8 dB and nearly flat except for a slight degradation at the low end due to $1/f$ noise. The maximum output power of the repeater is 20.0 dBm. It also is nearly constant with frequency.

A direct current of 136.0 mA from the shore terminals powers the repeaters. The voltage drop is 13.1 volts per repeater. Including cable drop, a maximum length system comprising 400 repeaters requires shore terminal voltages of ±3500 volts (plus an allowance of ±1000 volts for peaks of earth potential). In order that most repeater components and devices be operated at low voltages, ground separation filters transfer the high voltage through the repeater and around sensitive circuitry.

With 4500 volts dc applied, the corona impulse noise generated by the high voltage components at each end of a fully assembled repeater must not exceed an average of 4 "pops" per 24 hours. A "pop" is any impulse larger than 31 microvolts in a 48 kHz band. This corresponds to a discharge of 10.8 picocoulombs into the repeater input circuit.

Directional filters give the repeater its two-way capability by splitting the band into two parts. An oscillator in each repeater injects a unique frequency onto the cable which can be monitored at the shore terminals to identify the repeater for fault location purposes and to check misalignment. Major electrical and mechanical parts of the repeater appear in the repeater cutaway of Fig. 1.

2.1.2 *Mechanical Performance*

The maximum permissible leak rate of the repeater under helium pressure test is 1×10^{-7} standard cc/sec at 844 kg/cm^2 (12,000 psi). This corresponds to a depth of 8,050 meters (26,400 ft.). Under this same test, individual seals and other components are allowed a maximum leak of 10^{-8} or 5×10^{-8} cc/sec., as required.

The temperature limits are from −18°C to 57°C (0°F–135°F) for sustained exposure in storage. Operating temperature limits are in the range from 0°C to 30°C (32°F–86°F) for a continuous period of 20 years.

Repeaters must remain undamaged after being subjected to 5 shocks to 60 g peak acceleration and 6 millisecond duration between half amplitude points along each of the three principal axes. Vibration limits are 1.27 cm sinusoidal peak-to-peak displacement from 5 to 11 Hz and sinusoidal vibration at 3 g maximum from 11 to 500 Hz.

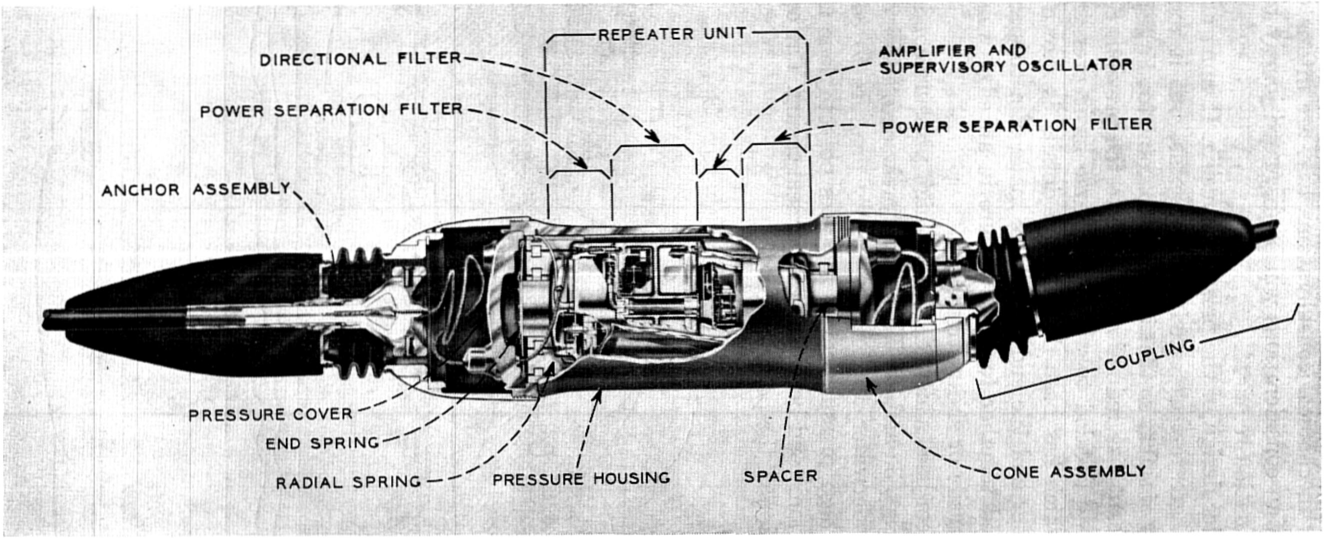

Fig. 1—SF repeater.

Several other mechanical considerations that are intimately related to electrical design considerations will be discussed jointly to illustrate the close coordination required.

Let us consider design of the pressure housing. It must not be overstressed at the greatest expected ocean depths, but it must have a minimum factor of safety so that it will not become too large and heavy. With no significant size reduction relative to the previous SD electron tube repeater, we decided to utilize the same basic pressure housing. This housing which has been described in detail,[3] is shown in Fig. 2. Both the cylinder and the end covers are made of a copper beryllium alloy and welded together for final closure in an edge weld virtually free of either tensile or shear stresses.

The SF System uses a new design for high pressure conductor seals (Type 3). See Figs. 3a and 3b. This seal, a preloaded "Bridgman" type, designed for underwater application at any pressure to 844 kg/cm^2, mounts in the high pressure cover and uses polyethylene as a gasket between the ceramic and beryllium copper seal casing. The ceramic disc prevents extrusion of the polyethylene.

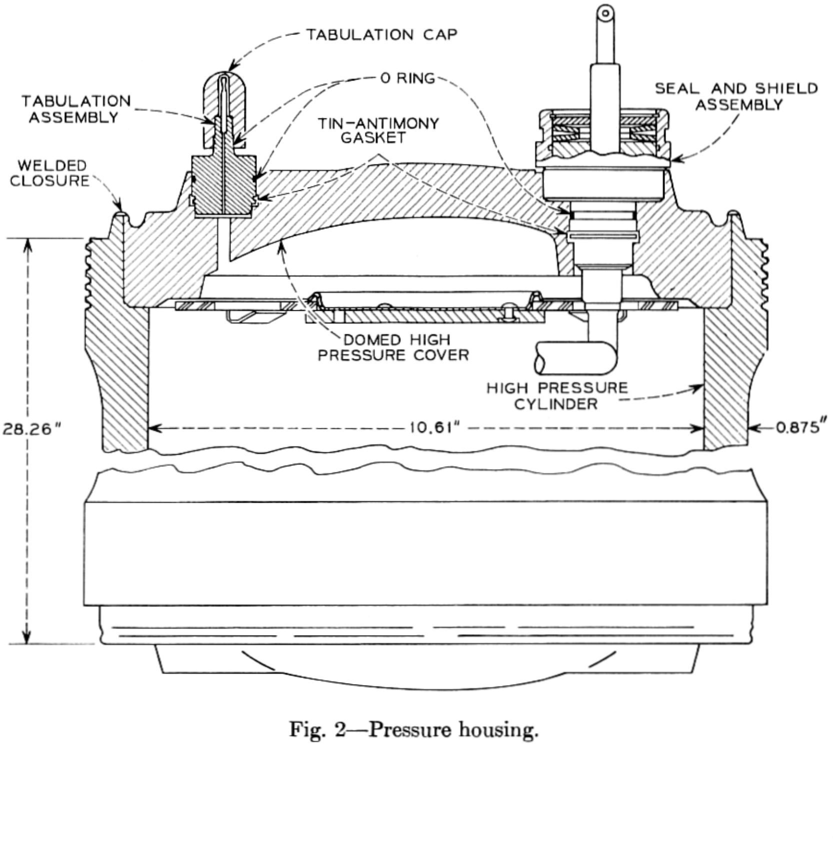

Fig. 2—Pressure housing.

The seal is exposed to the high voltage dc and must satisfy a requirement of no more than one "pop" per 24 hours at a test voltage of 7000 volts dc. This provides a substantial margin at 4500-volt operation.

2.2 *Troubles with 3A Seals and Pigtail Splices*

During the installation and early operation of the Flordia-St. Thomas II System, two types of failures were encountered. The first involved improper seating of five seals in their seal casings. In each case, pressure on the type 3A (Fig. 3a) seal caused the outer sleeve to deform inward. This limited the plunger motion in the casing and prevented proper seating. A new seal, type 3C (Fig. 3b), is now being used for the SF System. It is a modified version of the 3A which provides a heavier cylinder plus a spring-actuated preload to establish and maintain proper seating of the plunger. Sixteen type 3C seals are operating satisfactorily in the Flordia-St. Thomas II System. In addition, laboratory testing has confirmed the reliability of the 3C seal. All seals of the TAT-5 System are of the 3C design; no difficulty has been encountered with any of these.

The second failure mode involved four of the final repeater splices ("pigtail" splices) made on board ship. These faults occurred at the Jacksonville side of the Flordia-St. Thomas II System at relatively low voltages within a short time of laying. The cause of these failures appears to have been a reduction in the prescribed mold block temperatures which occurred with a field modification of the temperature sensing device. Since that experience, we require periodic requalification of molds by molding a test sample instrumented with a thermocouple.

As a result of the pigtail problems, two further improvements were made in mold design and procedure:

(*i*) elimination of a polyethylene preform which had been used as a filler, and
(*ii*) provision of bleeder ports near the mold interfaces.

These two improvements provide more uniform heating and more complete mixing of the polyethylene materials, particularly at the critical interfaces. Severe over voltage tests have confirmed the large performance margin provided by this improved molding technique.

III. THE REPEATER UNIT, MECHANICAL

Certain repeater requirements, such as shock, vibration, 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 apparatus. This complete inner housing, with the repeater circuitry,

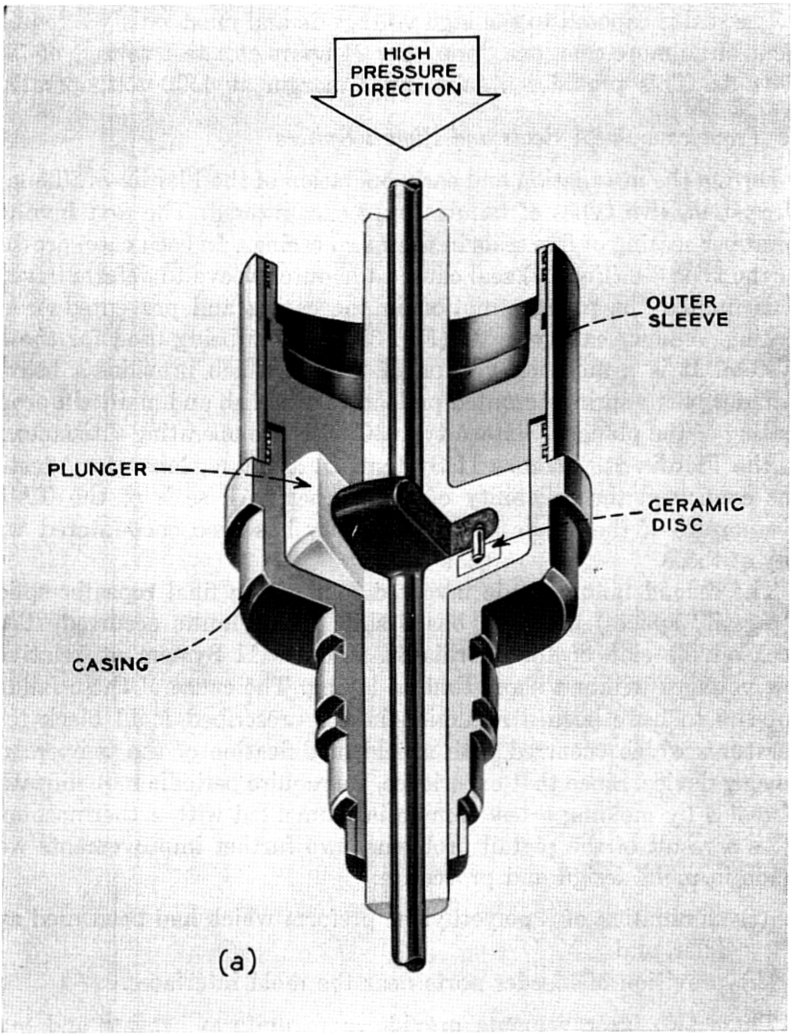

Fig. 3a—Type 3A seal.

is called the repeater unit to distinguish it from the complete repeater with pressure container.

The repeater unit housing is made of several aluminum plaster mold castings in a manner similar to that used for the SD repeater unit.[3]

The electrical connections to the circuitry within the repeater unit must be conveyed through the sealed walls of the repeater unit. This requires low pressure seals. These seals are subjected to about 3.5 kg/cm^2 or 50 psi. Because we did not use a coaxial low pressure seal, the coaxial path is interrupted in coming through the repeater unit wall. Two separate seals are used and the path made coaxial outside the unit. Corona noise requirements argue against a double coaxial seal, and

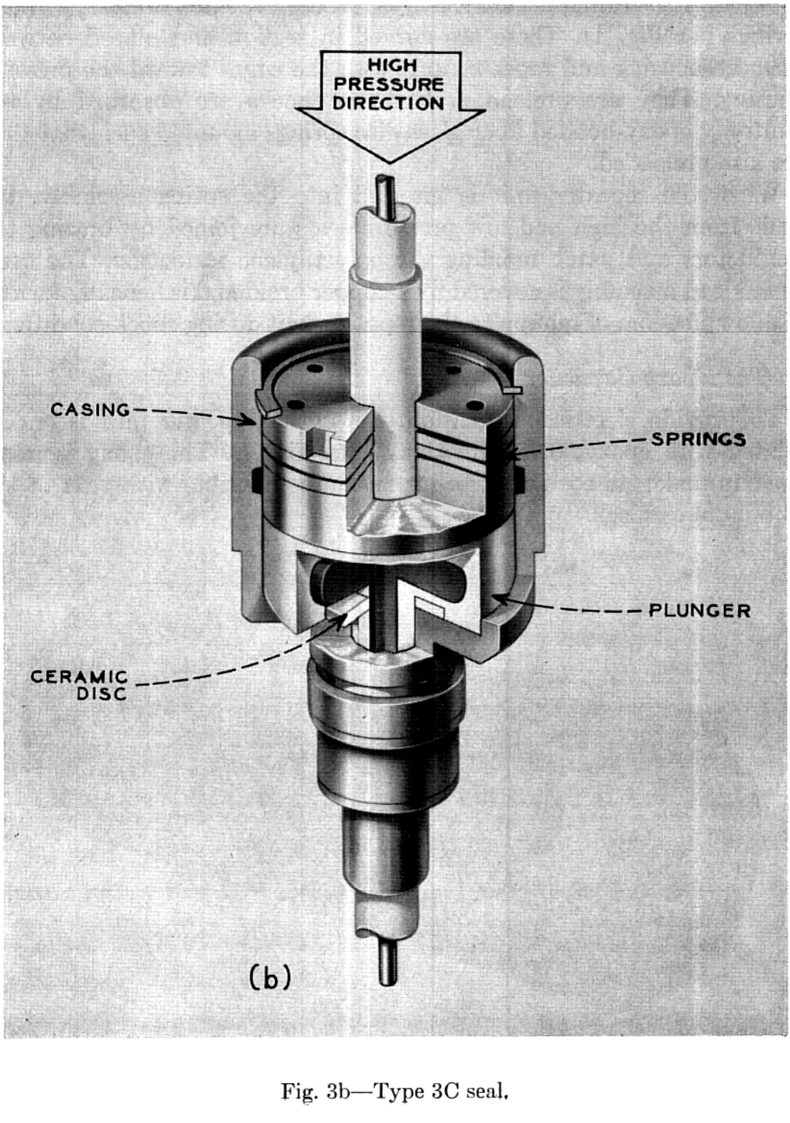

Fig. 3b—Type 3C seal.

impedance continuity is not a controlling argument in favor of such a seal.

3.1 *Shock Mounting*

To protect shock-sensitive elements in the repeater unit, the unit is spring mounted within the pressure housing. Twelve fiber glass and epoxy springs run the entire length of the repeater housing (Radial springs per Fig. 1). These are curved in section and placed between pressure housing and repeater unit with the edges toward the pressure housing. They are preloaded. Endwise shocks are absorbed by flat multi-ply epoxy-bonded fiber glass disc springs mounted such that they are also preloaded.

When the repeater unit is inserted into the spring assembly, the leads from the high and low pressure seals are joined by brazing the conductors 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 during shock conditions.

3.2 *The Epoxy Capacitor*

To provide electrical insulation, the entire repeater unit is encapsulated with epoxy, 0.356 cm thick (See Fig. 4). The epoxy is mica-filled to make its coefficient of expansion compatible with that of the aluminum castings.

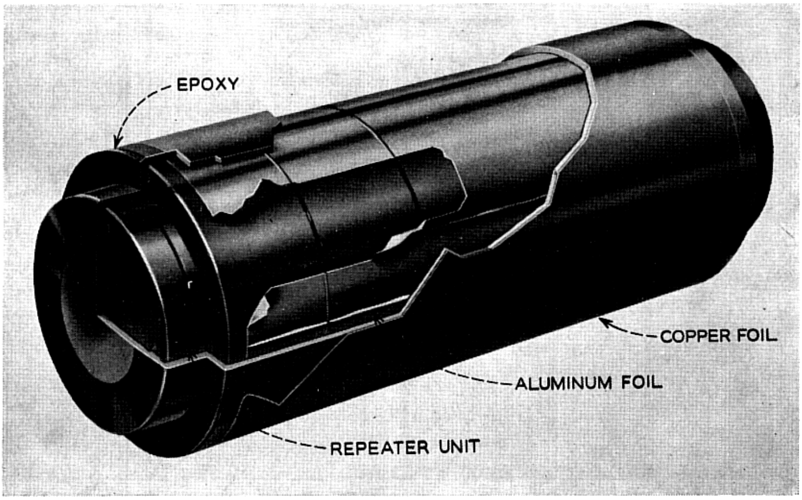

Fig. 4—Repeater unit.

To meet certain electrical requirements described in Section 4.3, it is necessary to provide a large-value capacitor between the repeater unit housing and the sea ground (Fig. 4). This capacitor must be free from corona inpulse noise to an extent compatible with the assembled repeater objective of an average of no more than 4 "pops" per 24 hours at 4500 volts dc. Because of the surface discontinuities at the "O" ring between the cylindrical subassemblies, it is necessary to wrap the repeater unit with aluminum foil (0.05 mm thick) prior to epoxy coating to prevent voids and hence corona noise. This foil is stretched over the unit and rolled smooth. After epoxy encapsulation, the surface is machined smooth and an adhesive backed copper foil is wrapped over the machined epoxy surface. The foil is, in turn, electrically connected to the pressure housing through a foil wrapping over three of the fiber glass springs placed 120° apart. The net effect is that the epoxy coating provides over 3000 pF of capacitance between the repeater unit and the pressure housing. The high-frequency ground separation filter design relies on the fact that this capacitance has negligible parasitic series inductance.

IV. REPEATER CIRCUIT

The repeater block diagram, Fig. 5, shows the basic electrical sections of the repeater or repeater unit. After passing through ground separation filters, the transmission path is frequency split by the directional filters. The low-pass directional filters also serve to separate the dc power from the signal. This scheme uses a single common amplifier for both frequency bands.

4.1 *Amplifier*

4.1.1 *Configuration*

The amplifier is the heart of the repeater. Much of the design effort was spent on it. The extreme gain stability and linearity requirements dictate a feedback amplifier. As shown in the schematic of Fig. 6, the basic configuration consists of three common emitter connected transistors with the feedback network paralleling them. The transistors are germanium diffused-base mesa types having f_T's in the 700 to 1000 MHz range. They were designed and fabricated solely for submarine cable application.[4] No redundancy is provided. The output transistor, coded as the 38C, dissipates one watt. The remaining amplifier transistors, plus the one contained in the supervisory oscillator are coded separately as 38A, B, and D and biased in the 25 to 75 milliwatt range.

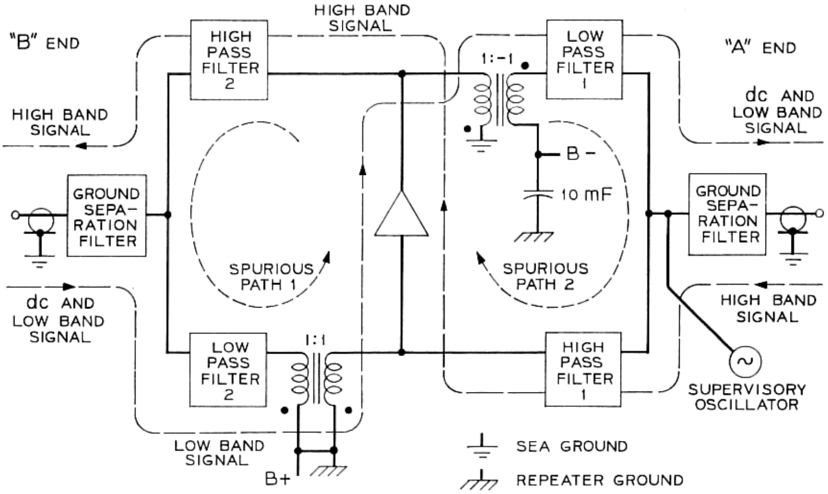

Fig. 5—SF repeater block diagram.

The repeater's signal carrying capacity depends on the power capability of the 38C, whose f_T of 900 MHz made it a state of the art device at the time the design was adopted. Noise figure requirements on the amplifier's input transistor led to operating this stage at 5.0 mA. To operate at this current and achieve high gain a separate transistor design was used. The same device is used for the middle transistor but operated at 15.0 mA, where its f_T and low frequency current gain are maximum, and its modulation properties preclude any significant degradation of amplifier linearity.

The shunt feedback connection produces very low active impedances at the amplifier's input and output ports. Thus we terminate these ports by means of simple series resistors. The resultant impedance of about 120 Ω externally facing the input and output transistors is near the value needed for best noise figure and linearity.

4.1.2 *Transmission Gain*

All the gain shaping is accomplished in the amplifier's Beta network, which is a *T*-structure containing 16 components. A digital computer program using an iterative least-squares procedure adjusted the magnitude of the Beta network's transadmittance to achieve a theoretical repeater insertion gain match of better than ±0.002 dB at all transmission band frequencies. In addition to compensating 10 miles of cable loss, the Beta network also provides for losses in the repeater's direc-

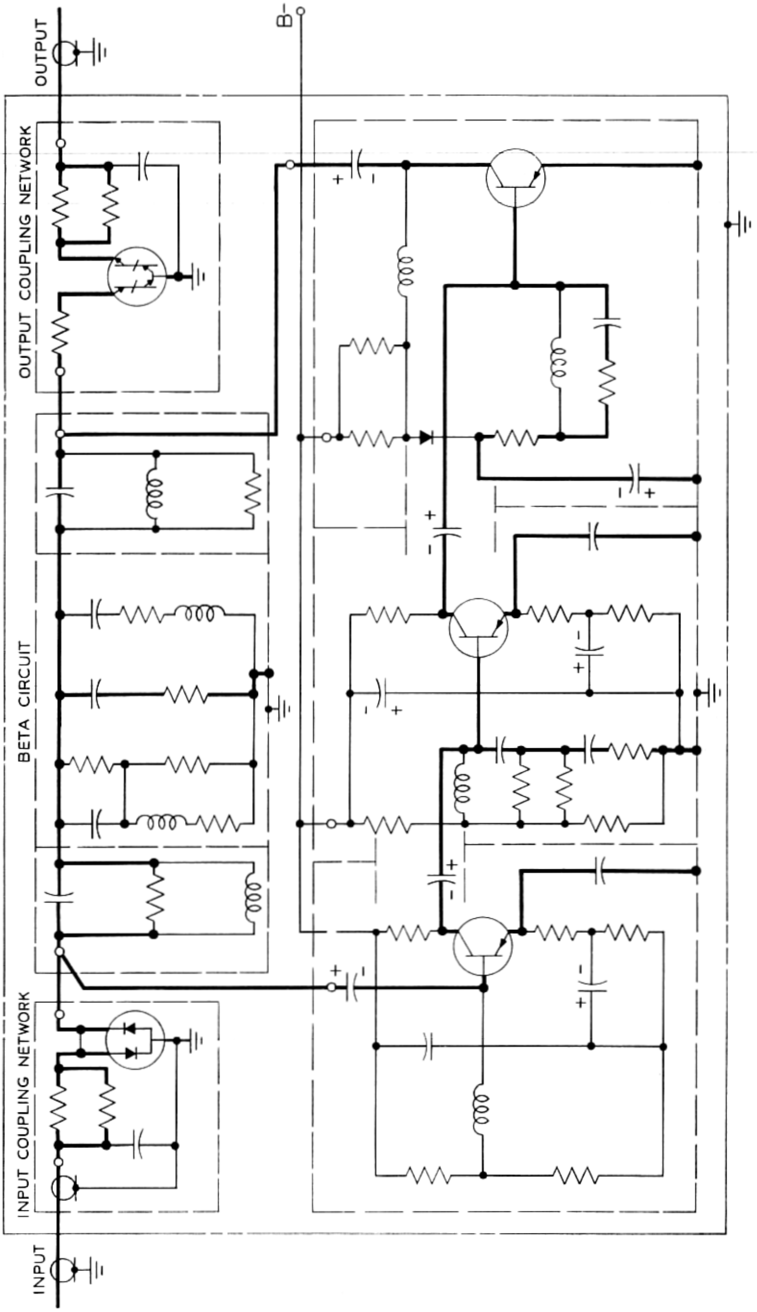

Fig. 6—SF amplifier schematic.

tional and ground separation filters, the amplifier's $\mu\beta$ effect, and a slight gain boost at low frequencies to provide additional flat loss for the ocean block equalizer.

Practical realization involved characterizing each component to an elaborate degree, extremely tight component tolerances, and precise adjustment of a slug-tuned inductor. A fixed inductor having the ±0.05 percent tolerance required was not practical, but the same effective tolerance was obtained by adjusting it after its assembly as part of a low Q resonant circuit. This adjustment, made prior to amplifier assembly itself, is the sole trimming operation involved in the course of manufacture, and is instrumental in restricting amplifier gain deviations caused by Beta circuit component tolerances to about ±0.03 dB.

The other major contributor to repeater transmission deviations is transistor variability. This effect, unlike Beta circuit variations, is suppressed by feedback. Besides referring to the differences in small signal characteristics that exist among transistors of the same code when biased identically, variability also involves the degree of accuracy with which the nominal transistor characteristics are known since any error here also translates into amplifier deviations.

To define the transistor's small signal characteristics, we adopted a device parameter equivalent circuit, following consultation with the device designers, experimental work on the transistors, and review of the equivalent circuit models used by others.[5] We computer-fit the equivalent circuit model to two-port circuit parameters measured in the frequency range 0.5–250.0 MHz. The fitting operation validated the model shown in Fig. 7 within the accuracy of the test equipment (better than ±0.2 dB and ±2.0°). Although the device manufacturer's small signal measurements were not as comprehensive as those used to validate the equivalent model, they were designed to have sufficient scope to

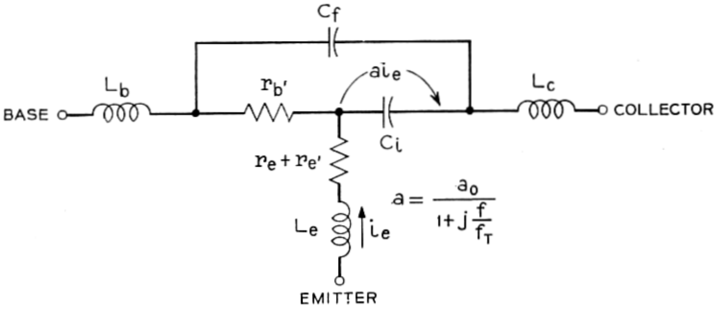

Fig. 7—Diffused base transistor equivalent circuit.

extract the element values of the model for each transistor destined for underseas use.

This procedure effectively yielded wide band characterization data necessary for establishing nominal or design center values, evaluating variability effects, and setting specifications. Development work indicated that random placement of transistors in amplifiers would produce transmission deviations in excess of 0.2 dB at the top frequency. This was unacceptable. Hence, a transistor grouping technique was used to sort transistors into amplifier sets on the basis of the manufacturer's small signal measurements.

The result of these efforts to control transmission deviations is summarized by the curves in Fig. 8, which indicate for the repeaters manufactured for the Florida-St. Thomas II Cable:

(*i*) the closeness of match of average repeater gain to cable loss; and
(*ii*) the degree of variability that exists among repeaters.

The ease and precision with which the Florida-St. Thomas II Cable was equalized are the best indications of how well these requirements were met.[1] The same transistor grouping was used in the TAT-5 SF System.

Although no significant changes in the system's transmission characteristic are expected from component and transistor aging effects, this fact was not known at the time basic circuit design decisions were made. As insurance, we decided to retain the phase-controlled feedback characteristic employed in the SD amplifier to suppress electron tube g_m aging effects.[3] This covers transistor Beta aging, the only aging phenomenon which had been considered physically significant. The latest data available from the long-term tests described elsewhere[4] verify that aging is restricted to Beta changes only, but these changes are so small that the resultant changes in system transmission are insignificant over a 20-year period (<1.0 dB). However, maintaining the $\mu\beta$ characteristic close to 90° as is done between 2.0 and 6.0 MHz, where feedback is low, is instrumental in restricting transmission deviations due to Beta variability among transistors. Calculations indicate that the phase-controlled design suppresses the gain change due to Beta variability as much as an additional 8.0 dB of feedback.

An important added result of the transistor characterization program is that it confirms the absence of any unsuspected small signal behavior in the transistor. The Tee equivalent circuit used proves to be sufficient and complete in the sense that additional elements could not have been identified uniquely on the basis of the comprehensive two-port measure-

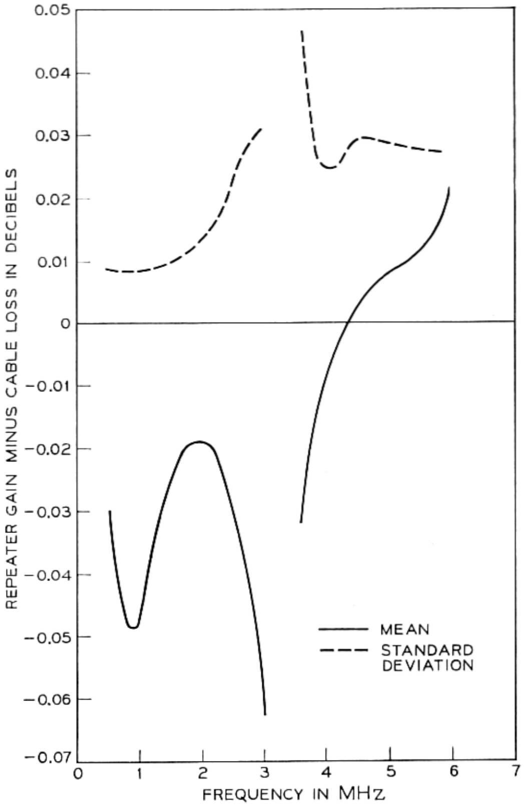

Fig. 8—Repeater gain characterization. Data applies to 112 production units.

ments in the frequency range of interest. (The word "elements" includes lumped components, frequency parameters, excess phase factors.)

The gain of this amplifier compresses slightly under signal load. The effect is measurable by loading all channels except for a narrow slot with gaussian noise and measuring the amplifier gain by application of a small amplitude sinusoid in the quiet slot. The result of such a measurement in the middle of the high band on a typical amplifier is shown in Fig. 9. Note that the gain with the full design load of −9.6 dBm0 per channel is 0.011 dB less than under light load conditions. For a transatlantic system, this could amount to over 4 dB of gain change with applied load and must be considered in the system layout.[1,6]

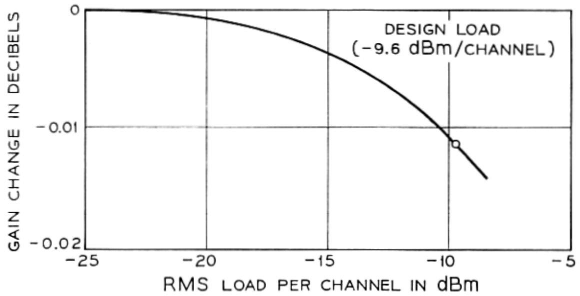

Fig. 9—Compression of SF amplifier at 4.715 MHz under noise load.

4.1.3 *Feedback*

Stability considerations limit the achievable feedback. The nominal feedback characteristic displayed in Fig. 10 shows that in-band feedback varies from 41.0 dB at 500.0 kHz, to 22.0 dB at 6.0 MHz. The major factors determining available feedback are high-frequency transistor response, length of the feedback loop, circuit parasites, and the margins established to guarantee stable operation. Except for the phase control exercised in-band, the $\mu\beta$ characteristic follows conventional lines. There are three major frequency regions to consider. To

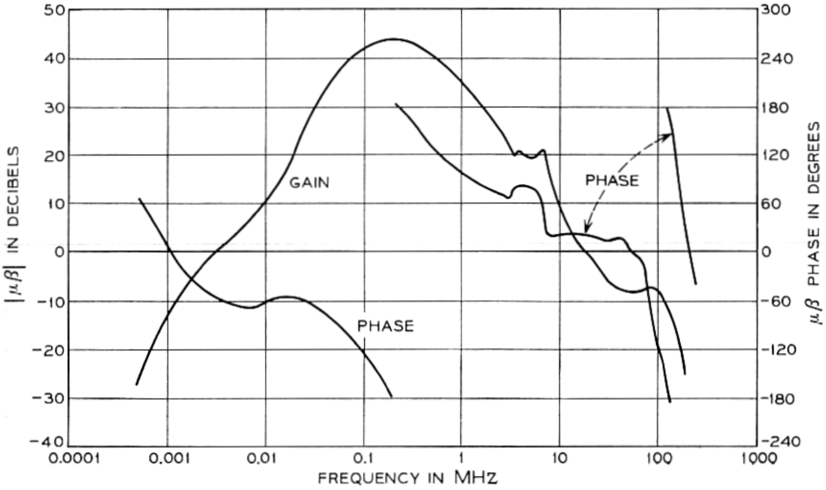

Fig. 10—SF amplifier $\mu\beta$ characteristic.

minimize deviations from the nominal in the high-frequency gain and phase margins, we pair the amplifier transistors with the input and output surge protector diodes; thus, variability in transistor high-frequency characteristics balances capacitance deviations of the diodes. This ensures that worst case margins are better than 4.0 dB and 15°. At the low-frequency cutoff, worst case margins are better than 10.0 dB and 30°. At the second high-frequency phase crossover ($\simeq$200.0 MHz) parasitic effects are stronger, and extra margin has been supplied there. Temperature effects in the operating range of interest (0° to 30°C.) are not significant.

As a means of verifying that measured margins were accurate, barely stable and unstable loops were constructed with the open loop measurements correctly forecasting the stability transition. Further checks proved the stability of the feedback loop under overload, and for the case in which an equalizer (whose return losses are very poor at high- and low-outband frequencies) terminates a repeater port. Pertinent computer-based calculations substantiated measurements, assessed variability effects, and evaluated parasites.

Two-terminal shunt interstage networks are the principal $\mu\beta$ shaping mechanisms. A special $\mu\beta$ computer program trimmed these networks and certain Beta circuit elements effective at high frequencies to achieve the desired feedback loop characteristic.

Amplifier construction uses "cordwood" configuration for network components and a compartmentalized cast aluminum framework for shielding individual amplifier stages and Beta circuit branches. The combination of three transistors, coupling, and Beta circuit bypass capacitors, plus inspectable soldered connections, produce a feedback loop length of about 36 cm (14″). The resultant inductive and capacitive parasites, plus transit time effects, are substantial contributors to the phase shift in the high-frequency asymptote. Although these parasites are relatively large for a high-frequency design, we keep them within narrow limits by close tolerances in fittings, piece parts and wiring strips, and by the extreme care taken in assembly.

To minimize the chance of unpleasant surprises in manufacture, we wanted to understand thoroughly the circuit design. To achieve such understanding, we characterized carefully each component and device, each network, the amplifier, filters, and finally the repeater. When we could accurately predict from computations how variations in components, devices, and parasites would affect pertinent response characteristics, we felt we had achieved the necessary confidence in the design.

4.1.4 *Components*[4]

A summary of the types of passive components used in the repeater is given in Fig. 11. All resistors are metal film types on sapphire substrates. Resistance tolerances range from a few tenths of a percent to 0.05 percent.

Open silvered mica capacitors serve for capacitances up to 6500 pF. The emitter bypass capacitors, in the tenth of a microfarad range, are paper capacitors, meeting tight requirements on low values of L and R at high frequencies. Solid tantalum capacitors in the 1 to 10 μF range serve as coupling capacitors.

The inductors are all air core, with values below 100 μH being single layer solenoids, and over 100 μH duolateral-wound solenoids. Tolerance and stability requirements are particularly tight for beta network values.

4.1.5 *dc Design*

The bias point of the output stage is maintained by a unique method.[7] Because power for the entire system must be supplied from the shore ends, it is highly desirable to bias the transistor stages as efficiently as

RESISTORS

Type	*Values* (Ω)	*Min Tol*	*Remarks*
Metal Film	5–500	0.05%	Minimum L&C

CAPACITORS

Type	*Values* (μ*F*)	*Min Tol*	*Max V*	*Remarks*
Mica	20–6500 p*F*	0.3%	15	Low L silvered
LV Paper	0.1–0.22	5%	15	Low L&R at high freq
Tantalum	1–10	7%	15	Low L&R at high freq
HV Paper	0.18	5%	3500	Low L

INDUCTORS

Type	*Values* (μ*H*)	*Min Tol*	*Q*	*Remarks*
Air Core	0.087–15	5%	10–50	
Air Core	0.2–65	0.5%	10–50	High stability, small size, 1 type adjustable
Air Core	220–450	2%	10–50	Duolateral winding
Air Core	2–100	Adjustable±2%	150	High stability

TRANSFORMERS

Type	*Remarks*
Coaxial	4 turns/winding of 50 ohm coaxial cable
Phase Turnover	59.4Ω 1:1 and 1:-1, ±2° phase match, electrostatic shield. For a 0.4 vrms, 1 MHz fundamental into 30 ohms $2f/f < -104$ dB and $3f/f < -131$ dB

Fig. 11—SF repeater passive components.

possible. For uniformity of performance, it is also desirable to maintain the bias points rather accurately over a wide range of transistor dc characteristics and component tolerances. This latter point suggests some form of dc feedback. Emitter feedback and base bleeder networks provide stable bias in the first two stages. This scheme is inefficient of power; hence, for the output stage another approach was created. This method places a zener diode between collector and base to establish a constant collector-to-base voltage. Since the emitter-base voltage is very low and reproducible, this scheme also establishes a near constant collector-to-emitter voltage. The current regulation of this stage occurs in the shore terminals and utilizes the fact that most of the dc cable current flows through the output emitter. At dc, the output stage serves as an efficient voltage regulator for the bias voltage of the previous stages. Under constant voltage conditions these earlier stages draw a constant current and thus leave a constant current for the output stage emitter.

4.1.6 *Equipment Design*

The physical design considers inspectability of completed assemblies, chemical and physical stability of all materials, and uniform thermal behavior under all conditions.

The circuit components are mounted in cavities in molded plastic end plates. Wiring strips spaced 0.2 cm away from the plates are used to interconnect the components. This spacing affords visibility for the inspection of both sides of the soldered joints. Amplifier networks are then mounted into individual cavities of a casting as shown in Fig. 12. Adding a cover casting completes the shielding of the amplifier.

Consistent thermal behavior is maintained by uniform heat conducting geometry. Realization of maximum reliability of the output transistor required that the device junction temperature be minimized while maintaining electrical isolation to ground. This is accomplished using a beryllium oxide mount for electrical insulation and thermal conductivity.

4.2 *Directional Filter*

The directional filter is a constant-impedance four-port network with two low-pass and two high-pass filters (See Fig. 5). Special high-Q, adjustable air core inductors meet the critical requirements of this filter. In-band tranmission ripples are held to less than a thousandth of a dB.

The directional filter creates two spurious feedback paths around the

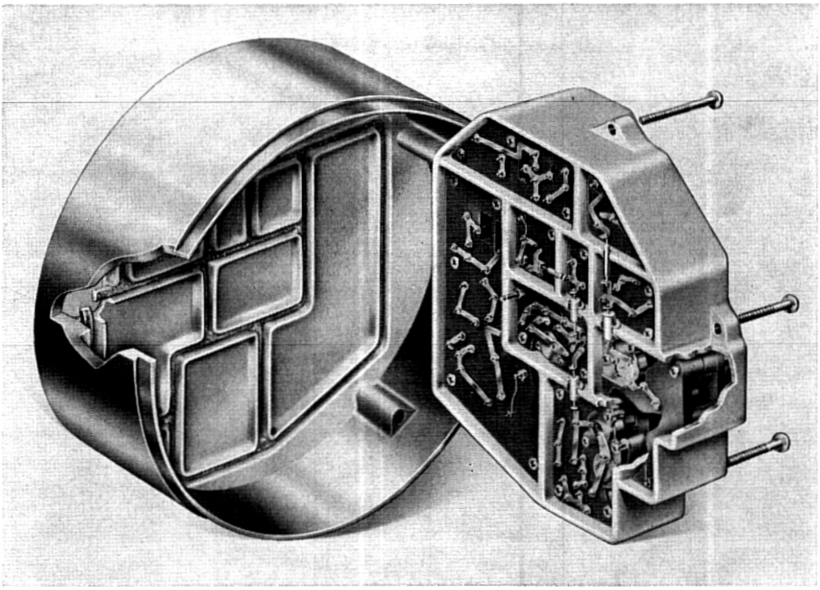

Fig. 12—SF repeater amplifier unit.

amplifier that could affect the overall gain characteristic if the loop losses were inadequate. These two spurious paths are symmetrical except for the presence of a 1 : 1 transformer in one path and a 1 : -1 transformer in the other. The two unwanted signals substantially cancel at the amplifier input port if an adequate balance is maintained. To aid in realizing this balance, return loss at each directional filter port must be maintained above 27 dB.

Referring to Fig. 5, the ground separation filters and the two low-pass filters conduct dc cable current to amplifier supply points marked $B+$ and $B-$. Since the $B-$ point must be at ac ground, it is bypassed with a 10 μF capacitor. Close control must be maintained on the series resistance of this capacitor since it directly affects the loss of the low-pass filters and hence the low-band repeater gain.

We avoid serious interactions among the filter sections of the directional filter by shielding each section separately.

Each section contains a large, high-Q, air core inductor which is surrounded by as much space as possible to minimize the loss of Q due to eddy currents in the shield walls. The design to meet these objectives is shown in Fig. 13 where ten sectors appear on each side of the filter. With the large inductor placed toward the base of the sector we realized

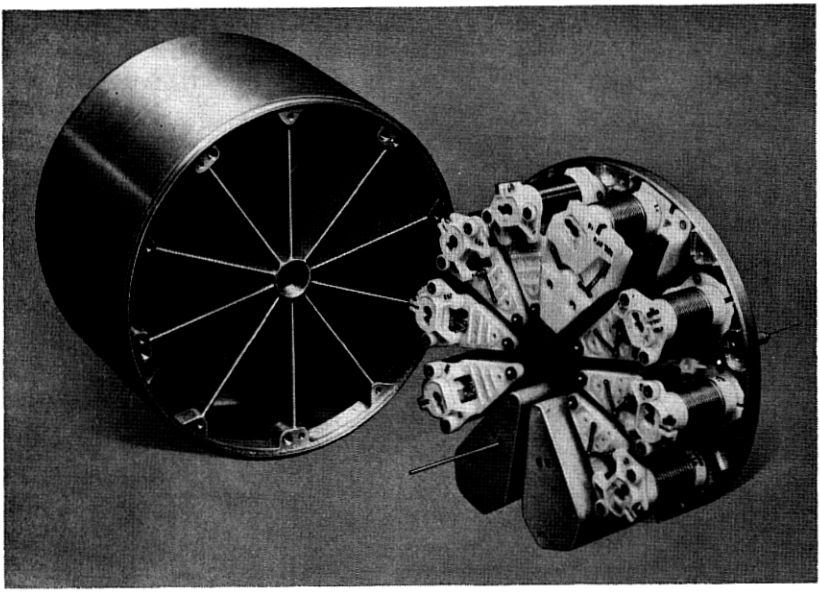

Fig. 13—Directional filter assembly.

maximum space to surrounding shields. The capacitors which make up the rest of the sector are placed toward the apex.

In the circular design the input low-pass filter section is adjacent to the output high-pass filter section, and vice versa. Crosstalk requirements are severe and are met through the use of additional copper shielding to double-shield each of the four critical sections.

Since the various filter sections used the same component codes, we modularized the filter construction. This modularization used three mounting plate designs instead of 28. With the quantities achieved thus, we exploited injection molding to reduce the cost. Tooling costs are considerably lower because of fewer designs. Material costs are reduced by using "celcon" (acetal plastic). This material also facilitates assembly by introducing controlled flexibility.

4.3 *Ground Separation Filter*

As illustrated by Fig. 14, the ground separation filters' function is simply to isolate at dc the cable's sea ground potential from the repeater ground's high potential, while coupling signals between the two. To achieve the dc isolation, capacitors with a voltage rating equal to the highest voltage on the system (4500 volts in this case) couple the two grounds at each cable port. Unfortunately, any signal frequency impedance in this ground coupling path at one repeater port will cause a voltage drop which will appear across the opposite repeater port and this will affect the repeater gain. Thus, we must maintain the ground coupling impedance as low as possible. At the low end of the transmission band, this requires a large capacitance (0.18 μF) for the coupling capacitor. At the high end of the band, the impedance is determined by the inductance in the ground coupling path. We would like to minimize this inductance by keeping the ground coupling path as short as possible. However, the coupling path passes through a separate seal in the repeater unit. Also, the high-voltage capacitor is physically large. Hence, the inductance in the coupling path is large. The effects of this high coupling impedance at high frequencies are alleviated by the use of coaxial chokes at the input and output ports of the repeater. The chokes consist simply of 4 turns of coaxial cable wound around a ferrite core. This choke tends to force the current to be equal in the center conductor and the return sheath. As a consequence, additional isolation is achieved between repeater input and output. At still higher frequencies (60 MHz), such measures are still inadequate to assure adequate ground separation filter loop loss for repeater stability. At these frequencies, we use the capacitance between the repeater unit and the pressure housing. Fortunately, this capacitance has negligible series inductance. As previously mentioned, this capacitance is increased to 3000 pF by applying a metal electrode (connected to sea ground) around the epoxy coated repeater unit.

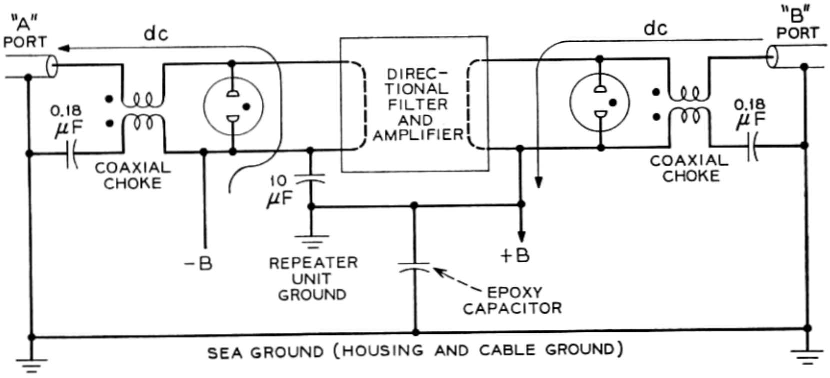

Fig. 14—Ground separation filter schematic.

4.4 *Surge Protection*

The high voltage present on the cable can produce a severe transient if the cable is accidentally shorted. The energy in the resulting transient is sufficient to damage a large number of repeaters in a system. To avoid such a catastrophe, we include surge protection circuitry in the repeater. We place gas tubes across the input and output ports of the repeater to dissipate much of the energy that could otherwise damage the capacitors in the directional filters. These gas tubes, of the same design as those used in the SD System, break down very rapidly when the voltage exceeds 75 volts. The gas tubes' protection is not adequate for the transistors in the amplifier but the tubes do reduce the subsequent surge appearing on these devices.

Upon passing through the directional filter, the components of the surge take different paths. A low-frequency component appears in the power path as a current transient having a peak value of as much as 60 amperes and a tail lasting for over 1 second. A zener diode across the amplifier power terminals protects the transistors from this surge component. This diode has a breakdown voltage of 15 volts, a few volts higher than the normal bias voltage.

High-frequency components of a surge which are not shunted by the gas diodes are passed by the directional filter to the amplifier input and output ports. The input port is protected by being shunted with a pair of oppositely poled silicon diodes. Signal levels at the point of application are sufficiently low so that intermodulation due to diode nonlinearity is negligible. The normal signal level at the amplifier output is much higher, making this type of diode unsuitable at this point. Instead, the output port is protected by the shunt connection of a pair of oppositely poled silicon pnpn diodes. These devices break down at a peak voltage of about 18 volts and exhibit a negative resistance characteristic. It was found by experiment that these devices give adequate protection to the transistors used, without degrading modulation performance.

4.5 *Supervisor Oscillator*

Each repeater contains a single-transistor, crystal-controlled oscillator which injects a supervisory tone at each repeater. Half of the repeaters have tones falling just below the bottom edge of the low-frequency transmission band and the remainder of the repeaters have tones falling just above the top edge of the high-frequency transmission band. High-and low-band tones are assigned to alternate repeaters. These tones can be monitored at the shore terminals to detect system misalignments and changes in repeater performance. In the event of a repeater failure which does not interfere with system powering, the received supervisory tones identify the failed repeater.

The oscillators have unique assigned frequencies spaced 100 Hz apart. To meet the lifetime stability requirement of ±40 Hz the oscillators use quartz crystals.

Because the injection level of the supervisory tone is very low (-50 dBm in the high band and -60 dBm in the low band at the repeater output), we mount the oscillator in a shielded compartment and decouple the oscillator bias from the amplifier bias supply. This biasing isolation also assures repeater operation despite any type of fault in the oscillator circuit.

The low-frequency oscillator has stringent requirements on any harmonics that may fall in the transmission band. These requirements are met by filtering the oscillator output through a low-pass filter.

To assure accurate system performance monitoring, the injected signal level of each supervisory oscillator should not vary from its initial value by more than ±0.5 dB at any operating temperature over the expected system lifetime. The initial value of this level is factory adjusted to ±0.3 dB. To achieve the required level stability requires: (*i*) a diode amplitude limiter, and (*ii*) further temperature compensation. A thermistor is used in the oscillator output for this further compensation.

V. EQUALIZER

5.1 *General Description*

The function of the equalizer is to compensate most of the accumulated misalignment in an ocean block consisting of 20 repeaters and 356 kilometers (192 nautical miles) of cable. This misalignment arises from design and manufacturing deviations in both repeaters and cable, and also from the unpredicted effects produced on cable attenuation as the cable is layed (laying effect).

Each of the different causes of misalignment has a distinctive deviation shape versus frequency. At the end of any ocean block, the overall accumulated misalignment will consist of the sum of many such shapes. Equalization is accomplished by connecting several equalizer sections in tandem. Each section is designed to compensate a particular type of deviation shape. In this respect, the SF equalizer is similar to the one used in the earlier SD System.[3]

The SF equalizer differs, however, in that the low and high transmission bands are equalized separately by using directional filters and separate sets of equalizer sections. A block diagram of the equalizer is shown in Fig. 15.

Each equalizer section contains passive constant-resistance, bridged-tee networks. The following basic types are furnished:

(*i*) Buildout Equalizer,
(*ii*) Repeater Direction Filter Q Equalizer,
(*iii*) Mop-up Equalizer,
(*iv*) Cable Manufacturing Equalizer (common to low and high bands),
(*v*) Switchable Equalizer.

In addition to the coaxial input and output connections to the cable, the equalizer also has a transmission test lead and a switching control lead. These connect through high-pressure seals to test connectors on the exterior of the pressure housing. The transmission test lead goes directly to the signal path at the inboard end of the equalizer. Thus test room personnel may measure transmission between the cable ship and the shore terminal as the cable is being laid. These measurements show the amount of misalignment up to the equalizer.

Just before an equalizer overboards, the personnel switch it to a network combination which best compensates the measured deviation. This is done via the switching control lead on the outboard end of the equalizer, which sets 14 magnetically latched relays.

5.2 *Mechanical Considerations*

The equalizer unit design follows the pattern already described for the repeater unit. There are a few differences. The epoxy coating of the equalizer unit does not require any foil wrap since an external capacitor is not required. Internally there are differences in the mounting of components of the individual networks. A standard module or cavity serves much of the equalizer. This was especially attractive for this application because the many different shaping networks used in the equalizer are comparable in complexity. Thus, the space required for the most complex network can also be efficiently used for the somewhat simpler networks.

The cylindrical shape of the equalizer and the expected size of the networks dictated "pies" subtending 40° and thus allowing nine sections to a complete layer. Adoption of a standard module for the equalizer allows the use of "universal" end plates which can mount a wide variety of component types.

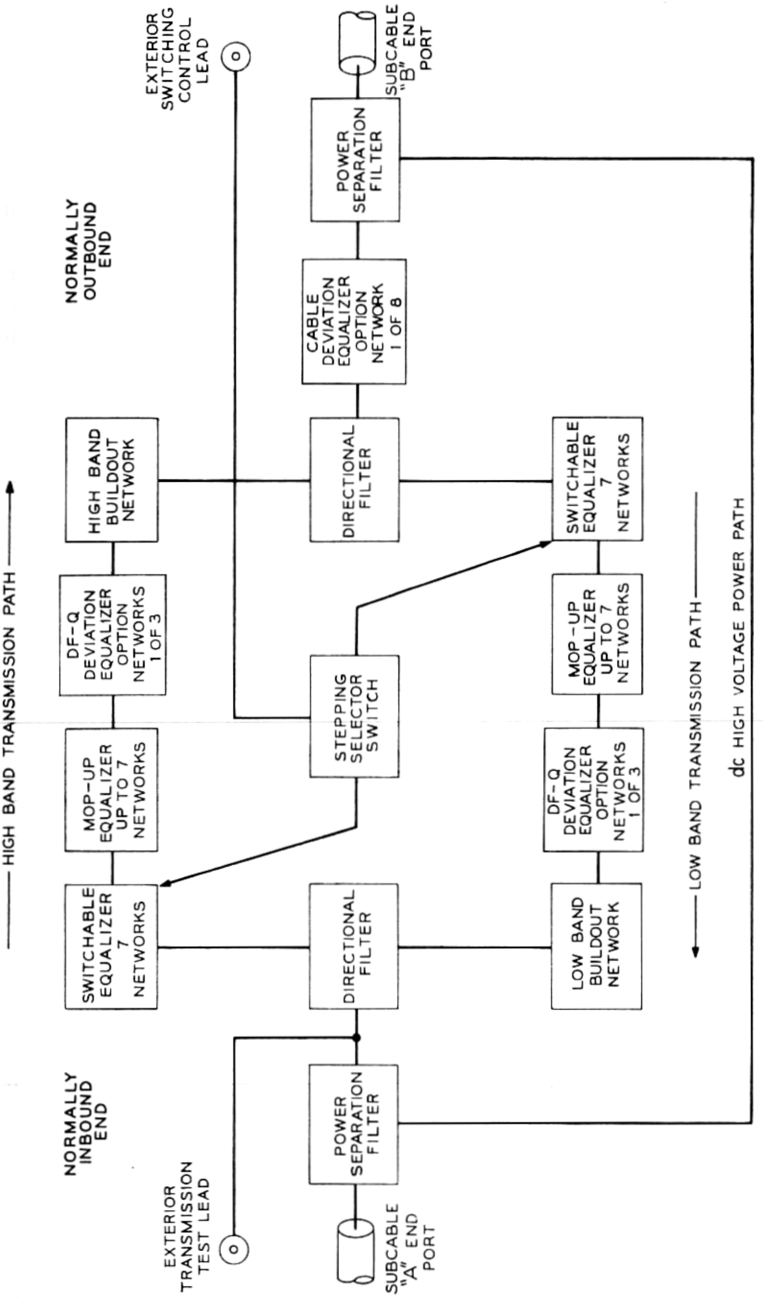

Fig. 15—Equalizer block diagram.

5.3 *Equalizer Networks*

5.3.1 *Switchable Networks*

Upon separation of the two directions of transmission by the directional filter, each band goes into a switchable equalizer network. The shapes provided by the switchable network are shown in Table III. The shapes were designed to compensate laying effects on cable attenuation and residual manufacturing deviations of repeaters and cable.

Seven bridged tee networks for each transmission band give the desired shape combinations. Each network contains a relay having two sets of transfer contacts. A positive pulse latches the contacts in one position, and bypasses the network. A negative pulse latches the contacts in the opposite position and inserts the network. Two states for each

TABLE III—SWITCHED NETWORKS—INSERTION LOSS FUNCTION

Band	Sequence Number	Approximate Insertion Loss Function	
Low	1	$8\sqrt{f/6}$	f in MHz.
	2	$4\sqrt{f/6}$	
	3	$2\sqrt{f/6}$	
	4	$1\sqrt{f/6}$	
	5	$10\sqrt{f/3} - 3f$	
	6	$5\sqrt{f/3} - 1.5f$	
	7	$5f\left(1 - \frac{\log(1 + f/3)}{\log 3}\right) - 2.38\sqrt{f}$	
High	8	$8\sqrt{f/6}$	
	9	$4\sqrt{f/6}$	
	10	$2\sqrt{f/6}$	
	11	$1\sqrt{f/6}$	
	12	$13.5\sqrt{f/6} - 2f$	
	13	$6.8\sqrt{f/6} - f$	
	14	1.2 dB bump $+ 2\sqrt{f/6}$	

of seven tandem networks yield a total of $2^7 = 128$ transmission shapes per band. The magnetically latched relays are energized sequentially via a stepping selector switch.

5.3.2 *Mop-Up Networks*

As blocked out in Fig. 15, in each transmission band the optional mop-up networks follow the switchable network. These mop-up networks are a special series of simple bump, slope, and flat networks which provide a highly flexible and accurate means for equalizing repeater design deviations.

From one to seven mop-up networks per band can be designed and assembled from a factory stockpile of piece parts and predetermined component values. Transmission measurements performed at the manufacturing locations on specific repeaters and cable sections of an ocean block determine the mop-up network designs. To achieve this flexible mop-up capability we have 8 dB of flat loss available in the low band, and 12 dB in the high band.

Fig. 16 shows the loss shapes of the four high band mop-up networks used in one ocean block equalizer of the Flordia-St. Thomas II System.

5.3.3 *Directional Filter Q Network*

In each transmission band we follow the mop-up networks with a directional filter Q network. This factory option equalizes manufacturing Q variations of the repeater directional filter inductors. This deviation has a predictable shape whose amplitude depends on the average Q of directional filter inductors in the ocean block. The options available in each band allow either +1 dB, −1 dB, or 0 dB compensation at the cut-apart region band edge.

After all available flat loss, filter loss, and switched networks bias loss has been accounted for, buildout networks in each band add the loss shape required to make the total nominal equalizer loss match the loss of 8 nautical miles of cable. The low-band buildout also includes an overload limiting circuit. This circuit consists of a transformer and a pair of oppositely-poled diodes which clip abnormally high signal peaks. This limiter prevents buildup of a system overload singing condition which could develop as repeaters modulate highlevel noise components between low and high bands (See Ref. 8).

5.3.4 *Cable Manufacturing Equalizer*

Finally, we again combine the two bands passing through the equalizer via the other half of the directional filter. Here we have a cable manu-

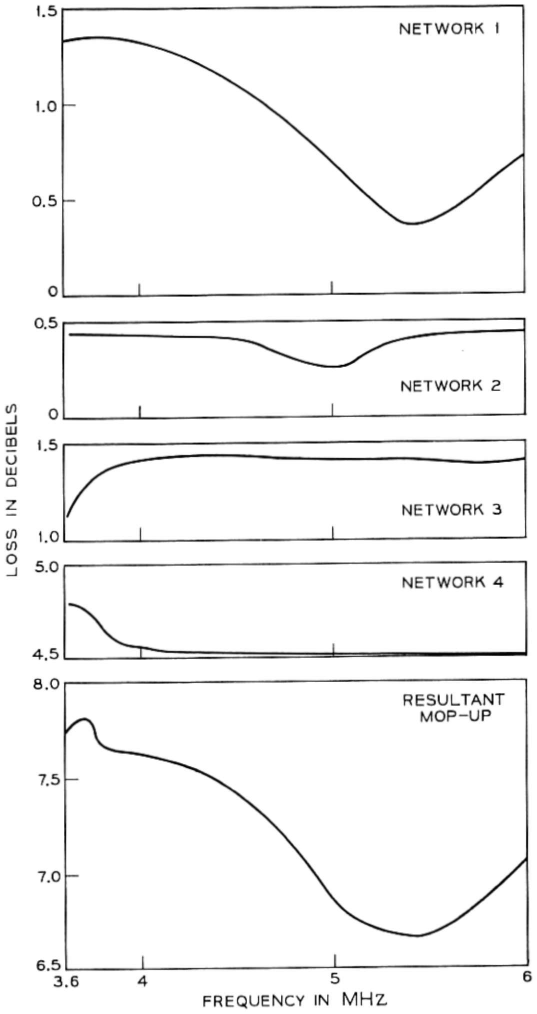

Fig. 16—Mop-up network shapes used in typical equalizer.

facturing equalizer which is common to both transmission bands. This cable equalizer is chosen during equalizer manufacture. It compensates for that part of block deviation caused by cable batches having more or less than nominal dielectric conductance loss. Any one of eight possible networks or none at all may comprise the cable manufacturing equalizer. The general loss function for all shapes is $\alpha_n[(f/6)^{\frac{1}{2}} - f/6] + \beta_n$. The eight possible sets of values for α_n and β_n appear in Table IV.

TABLE IV—CABLE MANUFACTURING EQUALIZER OPTIONS

n	α_n	β_n
1	1.95	0.52
2	3.95	1.01
3	5.96	1.01
4	−1.91	1.13
5	−3.89	1.56
6	−6.13	2.13
7	−8.15	2.63
8	−10.36	3.17

VI. CONCLUSION

The first SF Submarine Cable System went into service between Jacksonville, Florida, and St. Thomas, Virgin Islands, in August 1968. TAT-5, a second installation, is now in service between Green Hill, Rhode Island, and Conil, Spain. Equalization of both systems is outstanding due to the accurate gain match achieved in the repeaters and the high degree of flexibility provided in the underseas equalizers. With a nominal design capacity of 720 channels, these systems actually meet equalization and signal to noise objectives for over 820 channels.

The SF repeaters and equalizers form an effective partnership in transmitting high-quality telephone conversations over the SF Cable. Their success is due in no small measure to a coordinated effort among members of several Bell Laboratories groups and their Western Electric colleagues to realize extreme reliability, precision, and ruggedness in each undersea unit.

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