THE BELL SYSTEM

# Technical Journal

DEVOTED TO THE SCIENTIFIC AND ENGINEERING ASPECTS OF ELECTRICAL COMMUNICATION

VOLUME XLIII JULY 1964 NUMBER 4, PART 1

## SD SUBMARINE CABLE SYSTEM

# THE BELL SYSTEM TECHNICAL JOURNAL




THE BELL SYSTEM TECHNICAL JOURNAL is published six times a year by the American Telephone and Telegraph Company, E. J. McNeely, President, C. E. Wampler, Vice President and Secretary, J. J. Scanlon, Vice President and Treasurer, 195 Broadway, New York, N. Y. 10007. Subscriptions are accepted at $5.00 per year. Single copies $1.25 each. Foreign postage is $1.08 per year or 18 cents per copy. Printed in U.S.A.

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TECHNICAL JOURNAL

VOLUME XLIII | JULY 1964 | NUMBER 4, PART 1



# The SD Submarine Cable System

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(Manuscript received April 3, 1964)

*Submarine cable systems of a new design have recently been installed between Florida and Panama, between New Jersey and Cornwall, England, and between Hawaii and Japan. Using a single lightweight armorless cable for most of the route, with electron tube amplifiers encased in rigid containers at 20-mile intervals, this type of system will carry 128 channels in each direction.*

*More detailed discussion of cable, repeaters, and power equipment will be found in companion articles. This article outlines the system development objectives, gives an over-all system description, and describes the equalization plan and terminal equipment.*

## I. INTRODUCTION

In 1954, before the installation of the first transatlantic telephone cable, growth studies had shown that submarine cable systems carrying many more channels than the systems then under development would be required to carry future traffic. The development of these wider-band systems was therefore initiated before the development of the SB submarine cable system[1] was complete. Exploratory studies indicated that a new approach to cable and repeater design would be required. The SB system used armored coaxial cables, one for each direction of transmission. The repeaters were long and flexible so they could be handled on shipboard without major modifications to the cable machinery, which had been developed to lay submarine telegraph systems. While these long, flexible repeaters have proven to be sound in concept and reliable in performance, the form factor is such as to introduce large parasitic inductance and capacitance in the interconnections between the stages of the repeater and in the feedback path from input to output. In consequence, it is not possible to design a wideband repeater using this mechanical approach. For the new broader-band systems, therefore, the repeater circuit was placed in a rigid cylindrical container.

The cable concept was changed, and the strength was placed in the center of the cable rather than in the armor wires on the outside. Such construction makes possible a cable with a very stable transmission characteristic and eliminates the tendency of the cable to untwist under tension. This latter feature makes it easier to lay the large, heavy repeaters in deep water.

The decision to use a new cable and rigid repeaters made it necessary to consider the impact of these new components on the cable laying process. This resulted in the development of new cable laying machinery and techniques, which were combined to produce a new cable laying ship — the C.S. *Long Lines.*

The SD submarine cable system is the result of this development approach. It will transmit 128 channels of 3-kc bandwidth in each direction over a single cable, and experience with initial installations in the Caribbean from Florida to Panama via Jamaica, in the North Atlantic from New Jersey to Cornwall, England, and in the Pacific from California to Japan indicates that system objectives will be met.

## II. SYSTEM OBJECTIVES

The basic objective in the development of the SD system was to make available a highly reliable transoceanic facility which would be comparable in quality to the land plant of the continents to be connected, at a cost per channel-mile substantially lower than the earlier relatively narrow-band systems. Consistent with the trend to establish more stringent noise requirements on long continental circuits, noise of 41 dbrn at the zero level transmission point over the life of a 4000-statute mile system was taken as a design objective. This is about 3 db quieter than the transmission noise objective used for many years for continental circuits within the United States.

The system was also designed to carry a greater magnitude of signal per kc of transmitted bandwidth than usual in AM telephone systems. This was necessary for several reasons. In the first place, transatlantic callers have tended to speak at higher volumes than customers do on local calls within the United States or Europe. Secondly, because transoceanic spectrum is more expensive than land plant, it is worthwhile to make more efficient use of it by stacking channels more closely together. This loads the system more heavily. In addition, the probable application of TASI[2] makes it necessary to engineer for a talker activity about three times as great as that normally assumed in engineering land systems. The SD system has therefore been engineered to meet the 41-dbrn noise objective while carrying a signal load about six db higher than the CCITT recommendation for an equivalent eight-group land system, as indicated by Table I.

Many other objectives governed the design and layout of the system. Paramount, of course, was the reliability and stability of all the undersea equipment employed. Convenience of maintenance of the shore terminal stations and a high degree of reliability for the equipment employed at these terminals were also considered important objectives.

## III. SYSTEM LAYOUT

As shown by the block diagram of the system in Fig. 1, the length of cable between repeaters is approximately 20 nautical miles (nm). An ocean-block equalizer to correct misalignment is located in the section following every tenth repeater in the direction of the cable lay. The length of cable between ocean-block equalizers and adjacent repeaters is 6 nm. The adjustable equalizer loss is thus approximately equivalent to the loss of 8 miles of cable. The repeaters, equalizers and cable are described in companion articles.[3,4] Transmission in one direction is carried in the frequency band of 108 to 504 kc and in the other direction by the band 660 to 1052 kc. These frequency allocations for 128 channels are shown in Fig. 2. After a system is installed it is possible that an additional 10 channels will meet requirements. When these channels are used the frequency bands are expanded to 90 to 516 kc and 630 to 1052 kc. The two directions of transmission are amplified in a common am-

TABLE I—LOAD ASSUMPTIONS

| | SD System | CCITT |
|---|---|---|
| Average talker volume (VU) | −10.8 | −12.0 |
| Standard deviation (db) | 5.8 | 5.0 |
| Activity | 0.75 | 0.25 |
| RMS power/channel (dbm) | −9.6 | −15* |
| RMS power/group (dbm) | +2.4 | −4.2 |
| RMS power/band (dbm) | +11.5 | +4.8 |

* Includes an allowance for power of signaling tones.

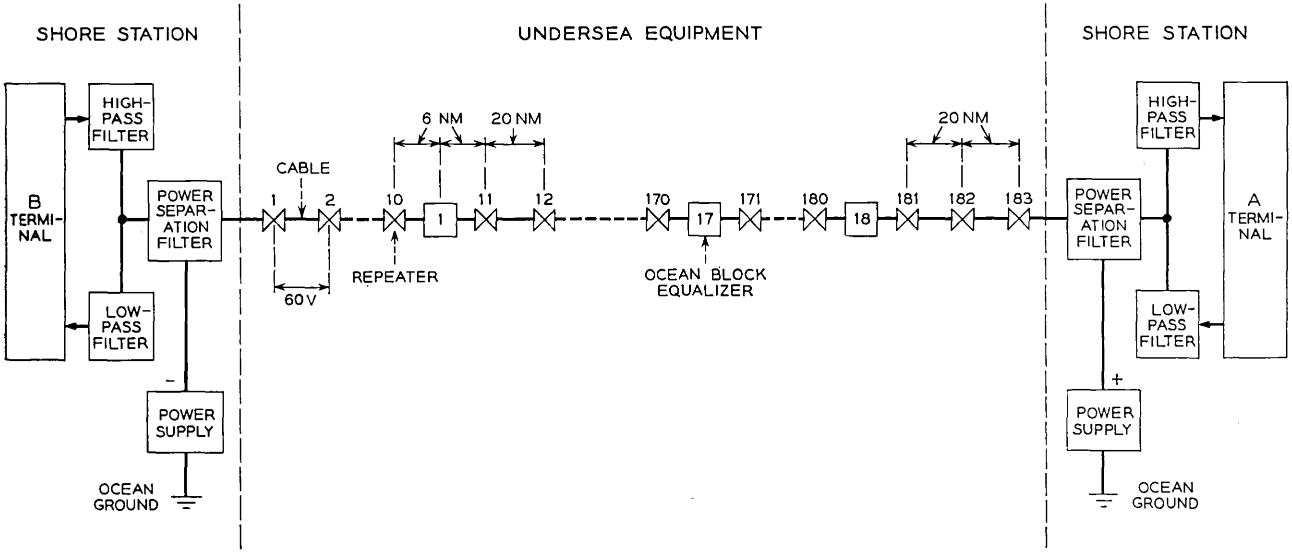



Fig. 1 — Block diagram of system.

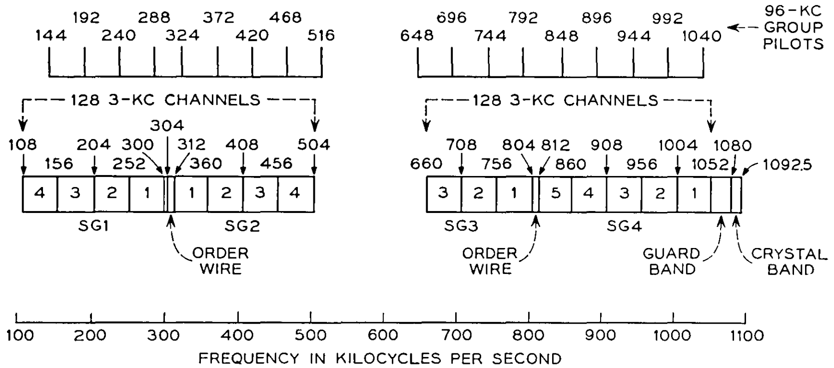



Fig. 2 — Frequency allocations for 128 3-kc message channels.

plifier by the use of directional filters. Parallel amplifiers, each containing three electron tubes, are used to provide protection against tube failure; these amplifiers share a common feedback or beta circuit, as indicated in the block diagram of Fig. 3.

The cable used for the major part of a system has an over-all diameter of $1\frac{1}{4}$ inches and a breaking strength of 18,000 pounds. Armored cable designs are available for use in shallow water to give protection against

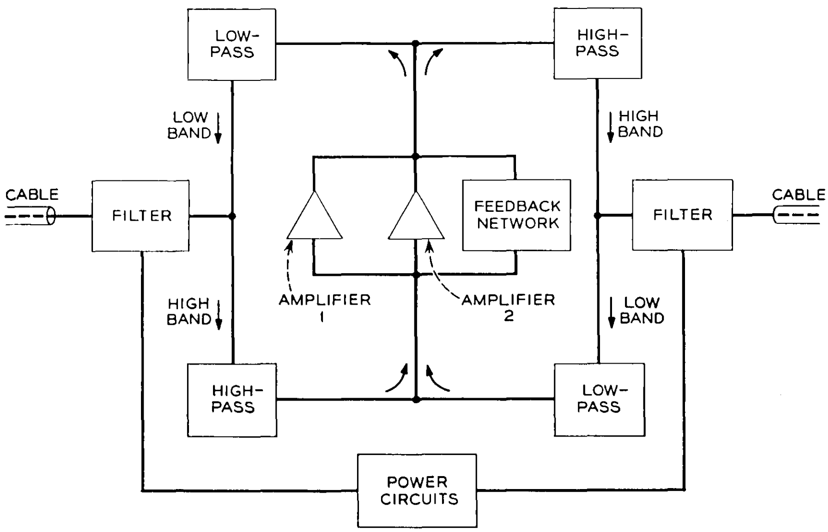



Fig. 3 — Repeater block schematic.

anchor or fishing damage. A shield may also be added to the cable structure at locations where radio or similar electromagnetic interference might be expected. The length of the shore-end section is restricted to the range 5 to 15 nm to minimize noise disturbances.

Power for operating the repeaters is supplied from the shore over the central conductor of the cable. The power system is described in more detail in a companion article.[5] A positive dc voltage is supplied to the cable at the A terminal between the central conductor and ground and a negative potential is supplied at the B terminal. The current path is thus over the central conductor, returning via the ocean. The power supplies provide precise regulation of cable current to a value of 389 ma. The voltage drop in the undersea system is approximately 60 volts per repeater section in armorless cable and 50 volts per repeater section in armored cable. A 3500-nm system will require a nominal supply voltage of 5500 volts at each terminal.

At the shore terminal the signals to be transmitted are frequency multiplexed and pre-emphasized in preparation for transmission through the undersea system. Signals received over the cable are equalized, amplified, demodulated and separated for transmission beyond the shore terminal. Monitoring of performance and trouble location are the other important functions at the shore station.

A description of the shore terminal is given in Section IV, followed by a description of the equalization plan for the complete system in Section V. Facilities for administration and maintenance are covered in Sections VI and VII. The performance characteristics of the first long system between New Jersey and England are given in Section VIII.

## IV. SHORE TERMINAL EQUIPMENT

### 4.1 *Multiplex Equipment*

Multiplex signals to be transmitted over the submarine cable system may be obtained from the land plant on a group connector basis or from channel equipment at the submarine cable terminal. In the latter case, high-efficiency channel banks are normally used. These allocate a 3-kc section of the carrier frequency spectrum to each telephone conversation, instead of the 4 kc common in the land plant. By using two steps of modulation and by imposing more severe requirements on the channel filters, it is possible to obtain a speech bandwidth of approximately 2800 cycles. It is thus possible to transmit 16 channels in the 48-kc carrier frequency spectrum normally allocated to a 12-channel group. The small degradation resulting from this narrowing of the spectrum of each channel is considered tolerable for submarine cable systems in view of the considerable economy obtained. Channel banks of this type, which are described elsewhere in the literature, are manufactured by several foreign manufacturers.[6]

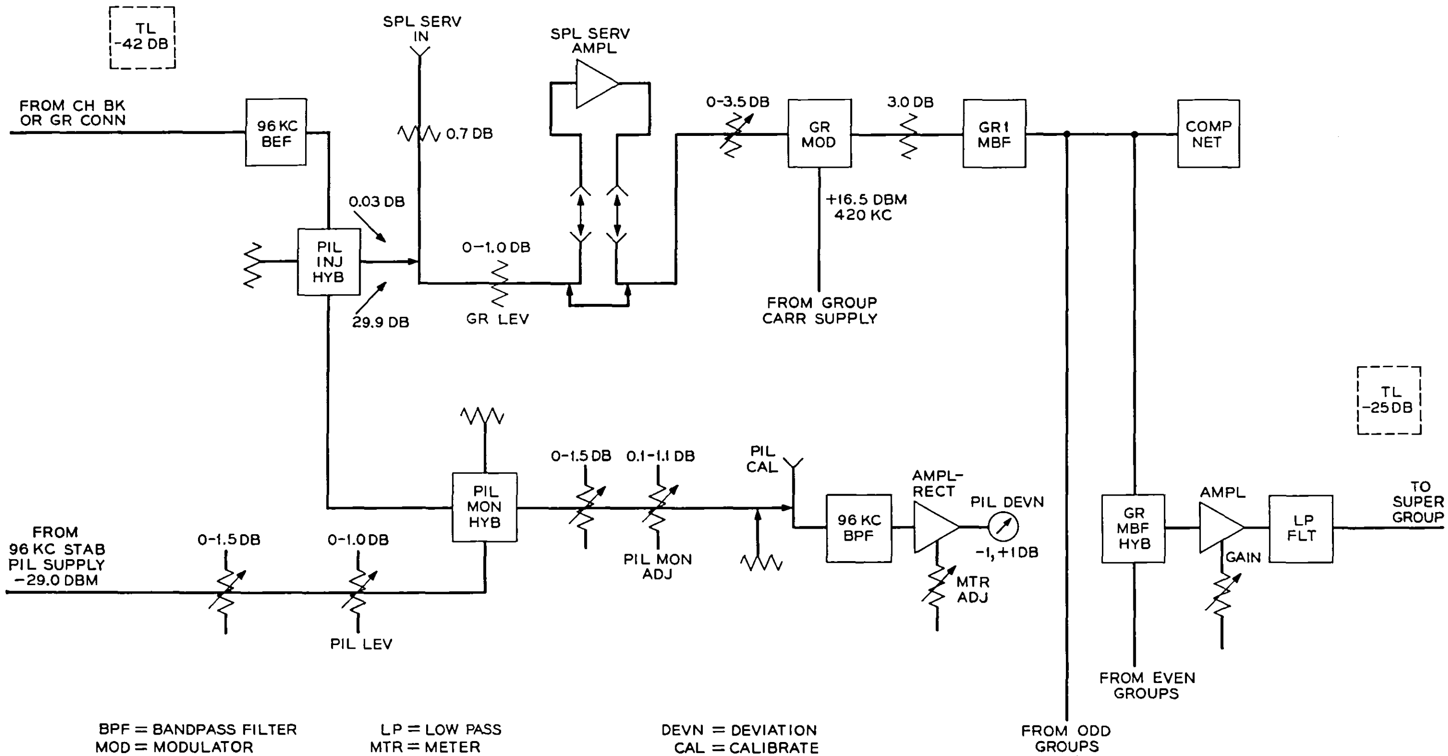
The group and supergroup equipment used is essentially standard L-type carrier multiplex or equivalent equipment supplied by the foreign partner, with minor modifications for pilot insertion and monitoring purposes.

### 4.2 *Pilots*

As in the land plant, a pilot frequency is transmitted in each group to permit monitoring and adjustment of group transmission at the various terminal stations and switching points. A 96-kc pilot is used to be compatible with the frequency allocation of the 3-kc channel banks. The pilot is inserted in each group modulator as shown in Fig. 4. They appear on the high-frequency line at the frequencies indicated in Fig. 2. The nominal power in each pilot is $-20$ dbm at zero level. The pilot in any group may be removed if a special service signal requiring a cleared 48-kc spectrum is to be transmitted.

In order to make possible maintenance without service interruption, much of the terminal equipment must be provided in duplicate. It is therefore convenient and desirable to arrange the terminal equipment as two independent transmission paths, one regular and one alternate, each fed by common channel bank equipment, as shown in Fig. 5. With this arrangement it is possible to use the pilots to initiate automatic protection switching from the working to the standby equipment to prevent loss of service in the event of a failure of the terminal equipment. Switching is inhibited if the standby equipment is nonfunctional.

Pilots are monitored at a number of points in the transmitting and receiving terminal. Fig. 6 is a block schematic of one of the monitoring circuits. At each point a narrow-band crystal filter and a narrow-band amplifier, either at 96-kc for monitoring at group input and group output or at line frequencies for monitoring at the supergroups or in the high-frequency line, are used. Meters of high accuracy for maintenance and adjustment purposes, and lower-accuracy relay-type meters to control alarms — and, in some cases, protection switching — are provided. A departure from normal amplitudes of approximately 1.5 db of any pilot will cause a protection switch from regular to alternate terminal equipment.




BPF = BANDPASS FILTER
MOD = MODULATOR
MON = MONITORING
CONN = CONNECTOR
GR = GROUP
BK = BANK
CH = CHANNEL
COMP NET = COMPENSATING NETWORK

LP = LOW PASS
MTR = METER
ADJ = ADJUST
SERV = SERVICES
STAB = STABILIZED
PIL = PILOT
BEF = BAND ELIMINATION FILTER

DEVN = DEVIATION
CAL = CALIBRATE
AMPL = AMPLIFIER
MBF = MODULATOR BAND FILTER
INJ = INJECTION
HYB = HYBRID
SPL = SPECIAL
TL = TRANSMISSION LEVEL

Fig. 4 — Group pilot insertion.

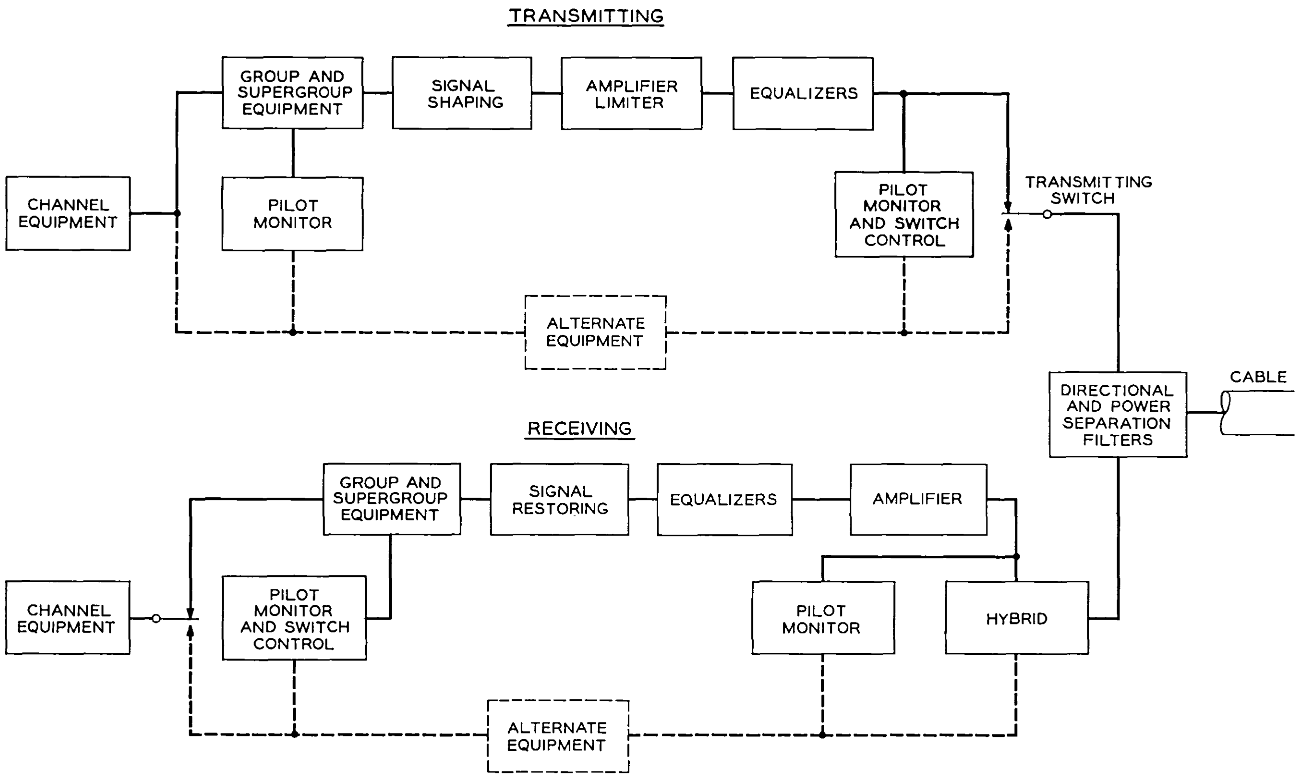



Fig. 5 — Shore terminal block schematic.

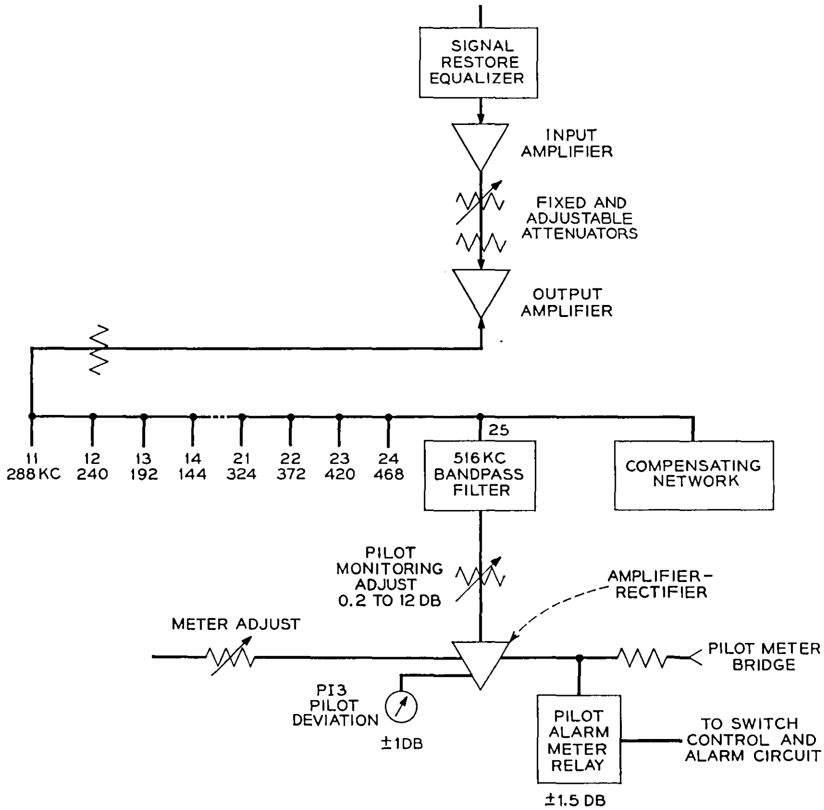



Fig. 6 — Pilot monitoring equipment.

4.3 *High-Frequency Line Equipment*

The final preparation of the signal for transmission over the ocean cable is accomplished in the so-called high-frequency line equipment, which accepts the multichannel load from the supergroup equipment and performs the necessary signal shaping, amplitude limiting and equalization functions.

Fig. 7 shows a block schematic of the transmitting high-frequency line equipment. The output from the supergroups is fed into a hybrid coil which provides for connection of the order wire signal and for pilot monitoring. This is followed by an amplifier and another hybrid that permits maintenance testing on an in-service basis and permits application of test signals for out-of-service adjustment. This is followed by a

**The enclosed illustration was inadvertently omitted from the July, Part 1, B.S.T.J. Please insert between pages 1164 and 1165 of your copy.**

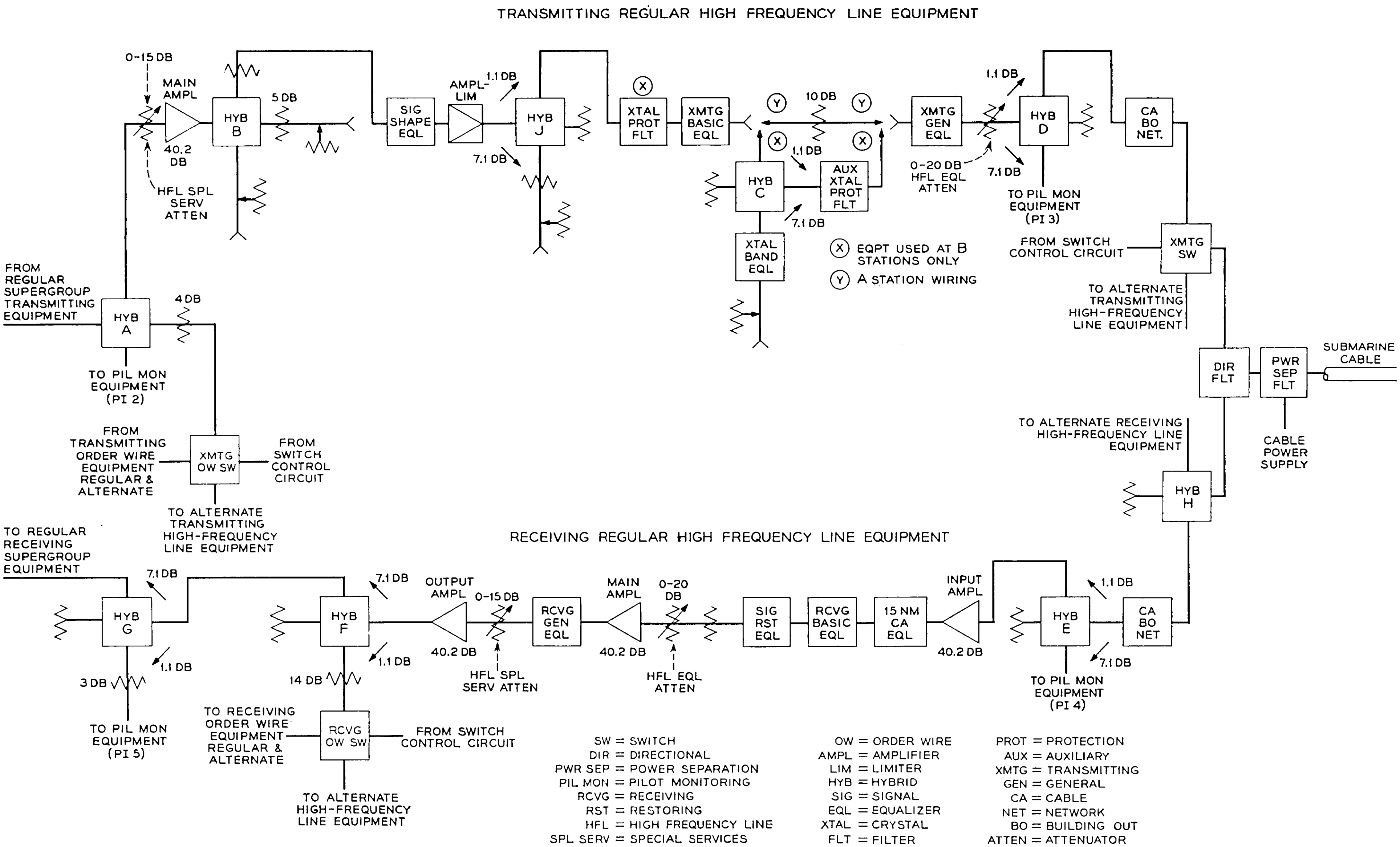



Fig. 7 — High-frequency line equipment.

signal shaping equalizer which predistorts the signal from the multiplex equipment in order to obtain approximately equal noise performance in all channels after transmission over the undersea system. As is commonly the case in cable systems, channels transmitted at high frequencies tend to emerge with a poorer signal-to-noise ratio than those transmitted at lower carrier frequencies unless special provisions — such as predistortion — are made. Such a difference in signal-to-noise performance between various channels is undesirable in any event, since the system performance is limited by the noisier channels. It is particularly undesirable in a system on which TASI may be used, since the customer would notice a sharp difference between noisy and quiet channels as the TASI terminal switched him from one to another. These undesirable effects are eliminated by the signal shaping. The smoothed curves of Fig. 8 indicate the effects of signal shaping on random noise in an SD system. The A curves show the rise in noise with carrier frequency when all channels are transmitted at the same power in the undersea equipment. By lowering the magnitude of all the low-band signals and raising the magnitude of all high-band signals, the noise in the two directions can be made equal (B curves) without increasing the total signal imposed on the system. Finally, the noise for each channel can be made equal by signal shaping (C curves). The characteristics of the signal shaping networks themselves are shown on Fig. 9.

An amplifier limiter which provides 30 db of gain and sharp limiting of the amplitude of the transmitted signal provides protection against overload of the undersea repeaters which might shorten their life. This is followed at B stations by a crystal protection filter to eliminate signals which might fall near the crystal peaks of the undersea repeaters. In this region system gain is so high that additional loss is required to furnish

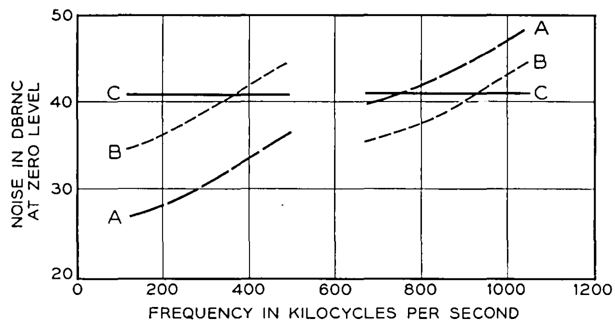



Fig. 8 — Effect of signal shaping on random noise.

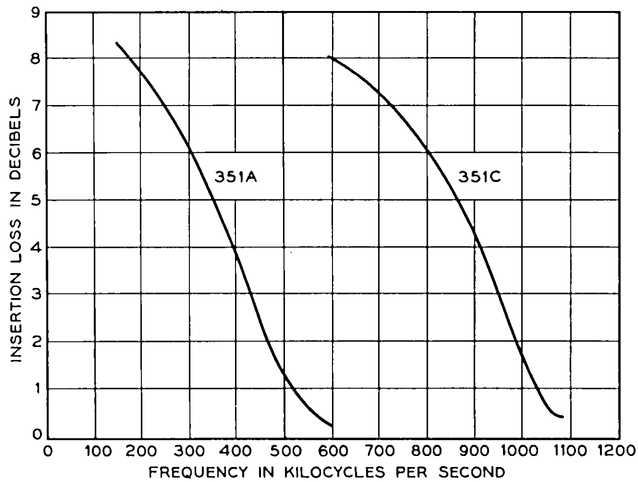



Fig. 9 — Signal shaping networks.

adequate protection. The cable build-out network adjusts for variation in the shore end sections of cable, building out the actual length to an electrical length of fifteen miles plus or minus 0.25 mile. The functions of the directional filter and the power separation filter are similar to those of the corresponding networks in each undersea repeater. Before discussing the various equalizers in the shore terminal equipment, it is appropriate to describe the over-all system equalization plan.

## V. EQUALIZATION PLAN

The total cable transmission loss in a 3500-nm system will approach 9000 db at the highest transmitted frequency. This must be matched by the gain of 180 or more repeaters. Obviously, very small deviations in this match must be corrected at intervals along the system to prevent them from accumulating as large misalignments.

Basic equalization of the cable loss is accomplished by shaping the repeater gain to match the loss of the cable at a temperature of 3°C and a pressure equivalent to a depth of 2000 fathoms. The shaping takes place in the input network, the output network, and the feedback circuit of the amplifier.

The lengths of manufactured sections of cable are trimmed at the factory to obtain the desired loss at the highest transmitted frequency. In this way, it is possible to adjust to a first approximation for known departures from the design temperature and pressure conditions.

The accumulated factory cable deviations, plus those arising from uncertainties in ocean-bottom temperature and depth, temperature and pressure coefficients, and transmission effects introduced by the laying process, are equalized at 200-nm intervals during the cable lay with the adjustable ocean-block equalizers. The available shapes, selected by a stepping switch that can be operated on shipboard, are shown in Fig. 10. The choice of shapes is based on the following rationale. The loss of coaxial cable at high frequencies may be approximated as the sum of two terms, one proportional to the square root of frequency (resistance loss) and the other directly proportional to frequency (conductance loss). Experience so far has shown that providing these two shapes in the ocean-block equalizer permits compensation for any cable changes, regardless of source, and is an effective tool for reducing other misalignments as well.

The ocean-block equalizer also forms a convenient point for introducing a fixed equalizer to compensate for accumulated repeater deviations. Without intermediate equalization of this type along the route, the requirements on the repeater characteristic would be so stringent that undue complexity in the amplifier circuitry would be required. This would increase the probability of a failure of a repeater and would increase repeater cost.

During laying, measurements are made between the shore station and the end of the 200-nm ocean block being laid. As the cable reaches the bottom, its loss, which was high while on shipboard because of its relatively high temperature, begins to approach its ultimate value. Shortly before the equalizer goes overboard, it is adjusted for the desired block transmission as nearly as possible. After adjustment, the measuring equipment is connected to the output of the subsequent block and the process repeated until all the cable has been laid.

The choice of the optimum equalizer network is facilitated by using digital computer programs to carry out a "paper lay" in advance of the actual system installation. These programs utilize factory data on cable, repeaters and equalizers (including transmission characteristic and noise figure), depth and temperature information from route surveys, and apply temperature, pressure and laying effect coefficients obtained from a combination of theory and experience. This makes it possible to evaluate the signal-to-noise ratio obtained for the entire system as a result of various choices made in setting the eighteen or more ocean-block equalizers required in a long system. The foresight thus obtained has proven a valuable guide during the actual lay.

Fig. 11 illustrates the degree to which an ocean-block equalizer decreases misalignment. Two curves are shown — one the misalignment

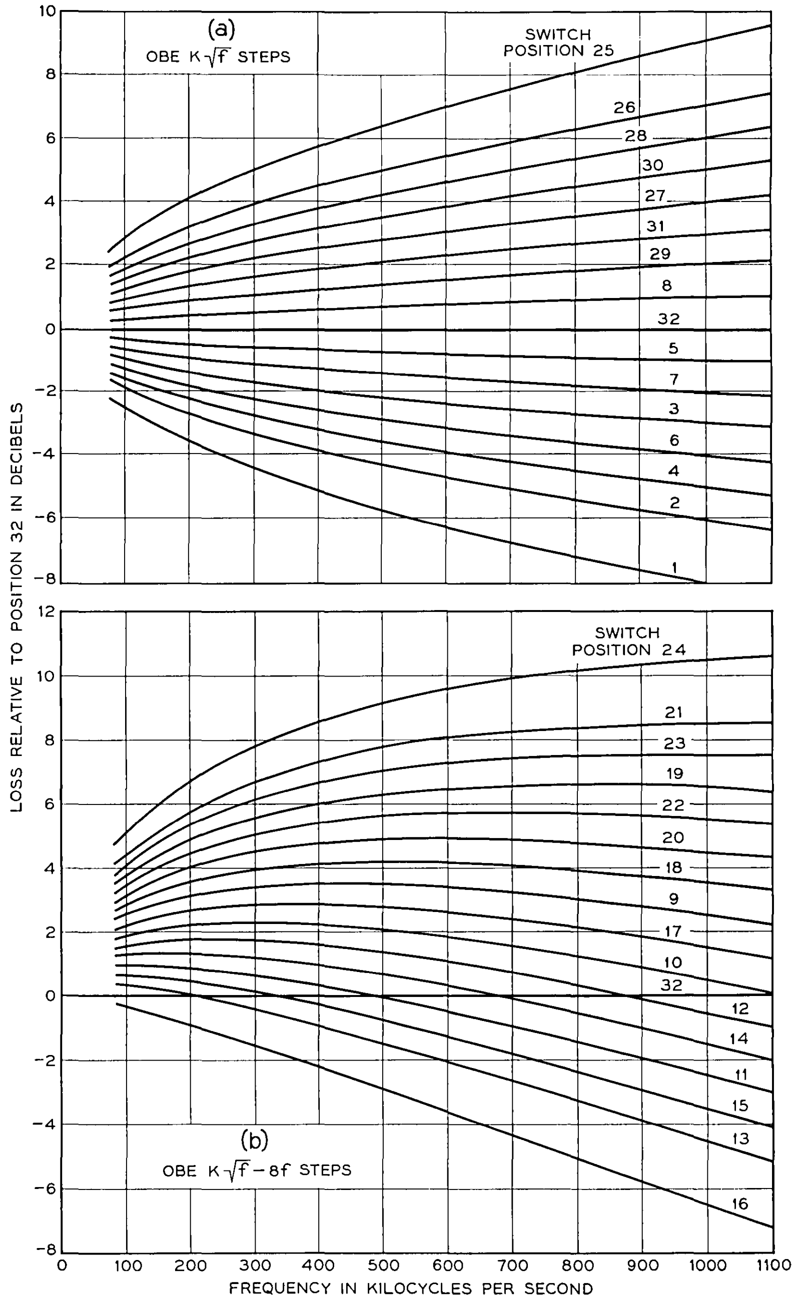



Fig. 10 — Ocean-block equalizer shapes.

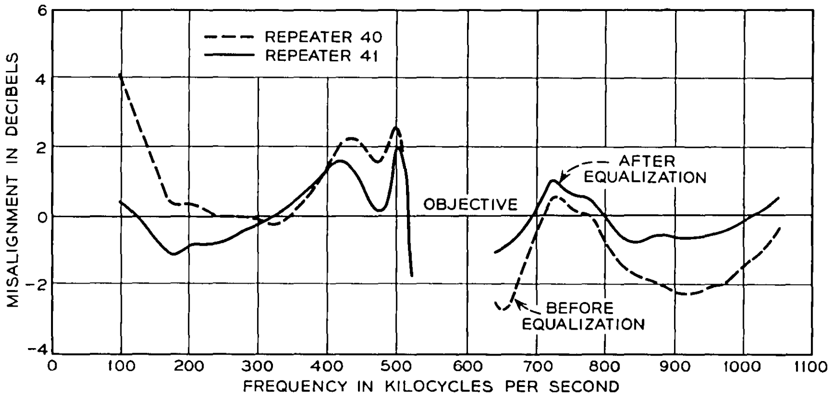



Fig. 11 — Reduction of misalignment by an ocean-block equalizer.

accumulated by the time 40 repeaters had been laid, the other the misalignment at the next (41st) repeater following an ocean-block equalizer. The misalignment has been reduced from a maximum of about 4 db to a maximum of about 2 db. The benefits of repeating such a reduction about eighteen times in a 3500-mile system are obvious.

### 5.1 *Terminal Equalization*

Once the system has been laid, the misalignments in the undersea system are set. From this point on, careful adjustment of signal levels to obtain maximum signal-to-noise ratios without overloading the repeaters is the only method available to optimize system performance. It is the function of the transmitting terminal equalizers to provide this optimization.

A convenient point of reference in describing the terminal equalization problem is the amplifier-limiter in the transmitting terminal. This is assumed to be an ideal limiter, flat with frequency, which will hold the instantaneous waveform to a fixed predetermined maximum value on both positive and negative peaks. Under gross overload, the output of the limiter will therefore have somewhat the appearance of a square wave. The most important function of the limiter is to prevent overloading the undersea repeaters in case of excessive inputs caused by trouble conditions. To obtain the greatest assurance of protection from overload, only passive circuit elements are installed following the limiter.

The question of what constitutes adequate protection needs to be answered. It is convenient to consider the problem initially in a perfectly aligned system. The overload point of the repeater is determined by the start of grid current. This occurs at a value of third-grid voltage (output stage grid voltage) which is essentially constant with frequency. Since the limiter operation is independent of frequency, this implies that the transmission between the limiter output and the third grid should be flat with frequency. The waveform out of the limiter will then be reproduced essentially undistorted at the third grid and will appear as a square wave for severe overloads at the input to the system, neglecting waveform distortion caused by nonlinear phase.

In an equivalent four-wire system, the signal voltage at the third grid will be the sum of the voltages supplied from the two ends of the system. It has been assumed that repeaters must not be overloaded even in the unlikely event that these signals add in phase. The repeaters can be protected against this possibility by inserting an additional 6-db loss at each end or by adding unequal values, e.g., 2.4 db for the high band and 12.4 db for the low band, at the two ends, so that the voltage sum adds up to unity. By using the second procedure a 3.6-db signal-to-noise advantage for the high band is obtained.

Operation with only one of the parallel amplifiers working has been assumed in determining the repeater overload, since this is the most limiting condition. An additional 3-db loss has been included in the terminals to cover uncertainties in the repeater levels and variations in the overload point of individual limiters and repeaters.

When misalignments are considered, the point of concern is the highest-level repeater in the system. This is not necessarily the same repeater at all frequencies. In particular, an equivalent four-wire system may have the highest-level repeater at opposite ends of the system for the two frequency bands transmitted in opposite directions. If misalignment is not uniform, the highest-level repeater at a particular frequency may be at some midway point in the system. Theoretically, some advantage might be taken of the fact that simultaneous overloads from the two ends of the system will not have maximum impact on the same repeater. In practice, however, this would lead to unworkable complexity in the rules for adjusting the terminal equalizers, and the signal-to-noise advantages so obtained would be small. Thus, to recapitulate, the loss in the general equalizer and associated attenuator following the limiter at a B terminal is adjusted so that the maximum signal which can be applied to the undersea system is from 2.4 to 5.4 db below the value which would overload the most vulnerable repeater operating with only a single amplifier. The maximum signal which an A terminal can apply is ten db lower than for the B station.

The transmitting *basic* equalizer shown in Fig. 12 has a fixed loss characteristic. It is intended to provide the optimum overload protection as a function of frequency for a nonmisaligned system. The criterion for its design might be stated as follows: when all transmission components between amplifier-limiter and the third grid of the nearest repeater have their nominal values, the basic equalizer characteristic shall shape the signals so that the relationship between power at limiter output and voltage at repeater grid is independent of frequency.

The transmitting *general* equalizer shown in Fig. 13 is intended to provide the additional loss required when the system misalignments are positive. The equalizer will be adjusted at the time the system is initially lined up and will be readjusted subsequently whenever changes are called for because of system gain changes caused by aging, temperature or repairs. Before adjustment during initial line-up of the system — i.e., with all dials at nominal settings — the loss of the equalizer is flat with frequency. The objective of the line-up procedure is to make the amount of loss change from the flat condition numerically equal to

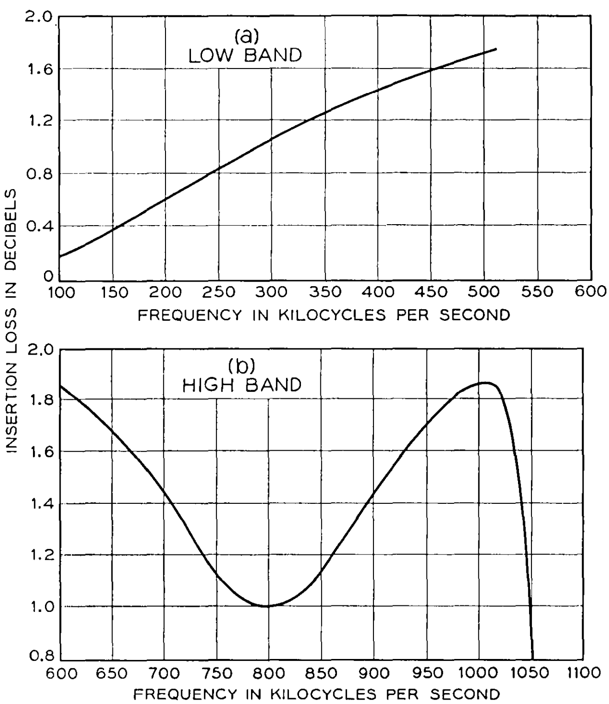



Fig. 12 — Transmitting basic equalizer shape.

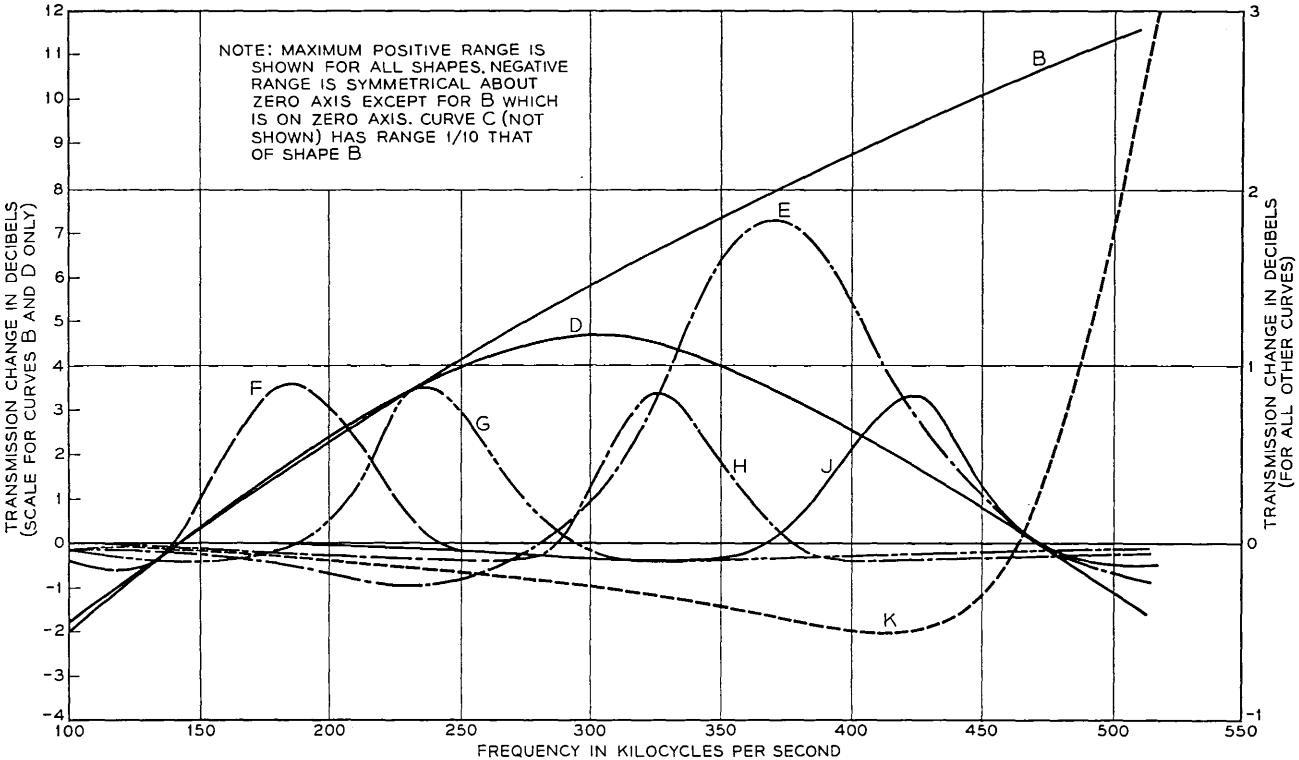



Fig. 13 — Transmitting general equalizer shape.

the maximum positive misalignment at the most vulnerable point in the system.

The function of the receiving terminal equalizers is to provide flat frequency response for the system, end to end. The cable build-out network is intended to bring the electrical length of the shore-end repeater section up to a nominal value of 15 nm. The 15-nm cable equalizer provides a flat transmission characteristic between the output of the last repeater and the input to the receiving basic equalizer. The receiving basic equalizer has a frequency characteristic complementary to the characteristic of the basic equalizer of the transmitting terminal at the other end of the system. The characteristics of the signal-restoring network are complementary to the characteristics of the signal-shaping network in the transmitting terminal.

As mentioned previously, positive misalignments are equalized at the transmitting terminal for overload reasons. Under these conditions, the receiving general equalizer is adjusted to its flat position. For negative misalignments, the total correction is made in the receiving terminal with the transmitting general equalizer set to its flat position. In either case the misalignments in the system will be completely equalized by this process of adjustment.

An exception to these statements occurs when the misalignments are not uniformly positive or negative along the length of the system. In this case the highest-level repeater will, in general, occur at some intermediate point in the system. Where this situation exists, the adjustable transmitting equalizer is used to provide overload protection for this repeater, and the adjustable receiving equalizer is used to compensate for the subsequent misalignment and thus obtain flat transmission for the entire system.

## VI. ORDER WIRE

In order to permit communication over the submarine cable system between the terminal shore stations and between these and the gateway stations of the land plants involved, without preempting commercial circuits for the purpose, so-called "order wire circuits" are provided. To economize on the use of the spectrum of the undersea system, special provisions are made to put these maintenance circuits into the gap which normally exists between supergroups by using modified type ON terminal equipment. Fig. 14 shows in block schematic form the arrangements for this purpose. The ON-type channelizing and group frequency equipment is used to take the voice-frequency signals and form a spectrum lying between 100 and 108 kc for one direction of transmission and from

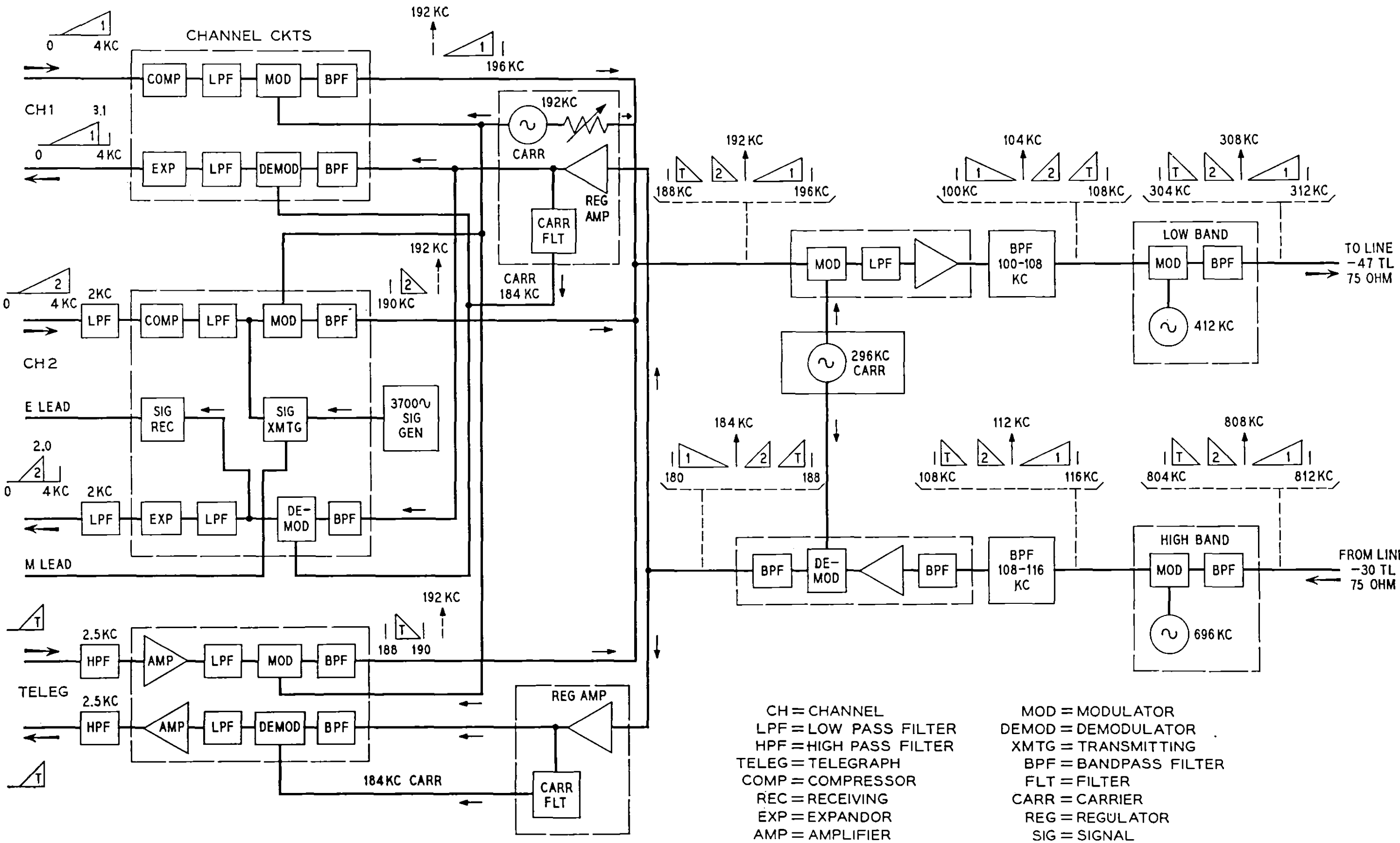



Fig. 14 — Order wire block schematic.

108 to 116 kc for the opposite direction. These signals are further modulated and placed in the 304 to 312 kc deadspace between supergroups 1 and 2, and in the 804 and 812 kc space between supergroups 3 and 4.

The channels thus appear on the line as upper and lower sidebands of 308 and 808 kc. The upper sideband channel is operated at full bandwidth for so-called express order wire service between gateway and land plant cities. The lower sideband channel is operated on a split basis, half of its spectrum being used for voice communication between the submarine cable shore terminal stations and the other half for teletypewriter signals. The use of teletypewriter communications giving a written record is particularly appropriate where language differences exist between the two ends of a system or among the various inland offices administering the circuits.

These signals are introduced into the high-frequency line equipment at a point following the supergroup equipment so that functioning group and supergroup equipment is not required for initial lineup or maintenance of the high-frequency line portion of the system. Switching circuits, interlocked with the automatic switching circuit which protects the multichannel signals, are provided so that the order wire is always connected to the working high-frequency line equipment at the transmitting and receiving ends of the system. Standby order wire equipment is available on a patching basis in the event that the working order wire equipment fails or requires routine maintenance.

Two additional channels are made available as upper and lower sidebands of 300 and 800 kc for use during system installation.

## VII. MAINTENANCE TEST EQUIPMENT

In order to continue to obtain satisfactory performance over the life of the system and properly maintain it, various more or less conventional items of test equipment are required. These in conjunction with the pilot monitoring arrangements discussed above permit periodic adjustment of the transmitting and receiving equalizers to compensate for temperature changes, if necessary, and for long-term aging of the system. The items of test equipment required are sufficiently conventional to call for no further discussion here. Of somewhat more interest, in that they are peculiar to submarine cable systems, are the items of test equipment provided for fault locating. Three different types of test sets are employed for three different types of faults presently envisioned. These are:

(*i*) cable fault locating test sets which, in the event that the cable is broken or shorted, permit balancing the physical cable against an artificial cable to determine with fairly high accuracy the distance from the shore station to the fault;

(*ii*) the crystal band set, which permits measurements of system transmission at the frequencies of the crystals in the undersea repeaters, or measurements of noise peaks originating in these repeaters in the event that transmission from terminal to terminal cannot be obtained;

(*iii*) a repeater low-band fault locating test set which permits identification of a repeater whose transmission of low-band frequencies is faulty although transmission at the crystal frequency is not seriously affected.

### 7.1 *Cable Fault Locating Test Set*

Cable fault locating test sets of the type employed on the SD system have been described in the literature.[7] The basic philosophy is to provide a network which simulates, section by section, the iterative structure of the undersea system. Low-amplitude direct current, pulsed at a low-frequency rate (1, 2, or 4-second pulses of 50 per cent duty cycle), is sent into a bridge circuit of which one arm is the physical cable and one arm the simulating artificial cable. It is necessary to simulate only those system elements — cable, power separation filters, and repeater dc resistance — which are important at very low frequencies. A short or open (or intermediate resistance fault) can then, in essence, be moved along the artificial cable until the low-frequency impedance of the real and the artificial cable are seen to be equal. From a knowledge of where the fault in the artificial cable must be situated to obtain the best balance, the position of the fault in the real cable can be determined.

### 7.2 *Crystal Band Test Set*

The crystal band set is also similar to the measuring equipment described for use on earlier submarine cable systems.[8] Each undersea amplifier in the system is equipped with a crystal of unique frequency across the feedback network. At the resonant frequency the feedback path is shunted and the amplifier gain rises to a value determined by its forward gain. The test set essentially consists of a carefully controlled oscillator capable of supplying a signal at the crystal frequency of the repeater or slightly away from the crystal peak in order to determine the gain peak introduced by each repeater crystal circuit.

Alternatively, the receiving components of the crystal band set can be used to measure the noise peaks originating at the crystal frequencies of each repeater even if no signal is applied in the crystal band. In the event of a failure of transmission not caused by a cable fault and therefore not detectable by the cable fault test set described above, the noise peaks originating in the submarine cable system can be scanned and the results of this roll-call will indicate the location of the faulty repeater in the system.

### 7.3 *Repeater Fault Locating Test Set*

The basic concepts of the repeater fault locating test sets are indicated in Fig. 15. From the A terminal (low-frequency transmit, high-frequency receive) short pulses of 350 kc are transmitted. For any particular system, the repetition rate is set so that there is time for a signal to traverse the entire length of the system and return before the next pulse is launched. An answering pulse of 700 kc, produced by second-order modulation, is evoked in each repeater and propagates back toward the A terminal. At the A terminal, these returned 700-kc pulses, which are separated in time by the round-trip delay of 20 miles of cable, are observed. A marker pulse locked to the basic pulse timing circuits permits ready identification of the signal from a particular repeater. The presence or absence — and magnitude — of the pulses from the various ocean-bottom repeaters constitutes a roll-call of the system, and information about low-frequency transmission, high-frequency transmission, and second-order modulation of the repeaters

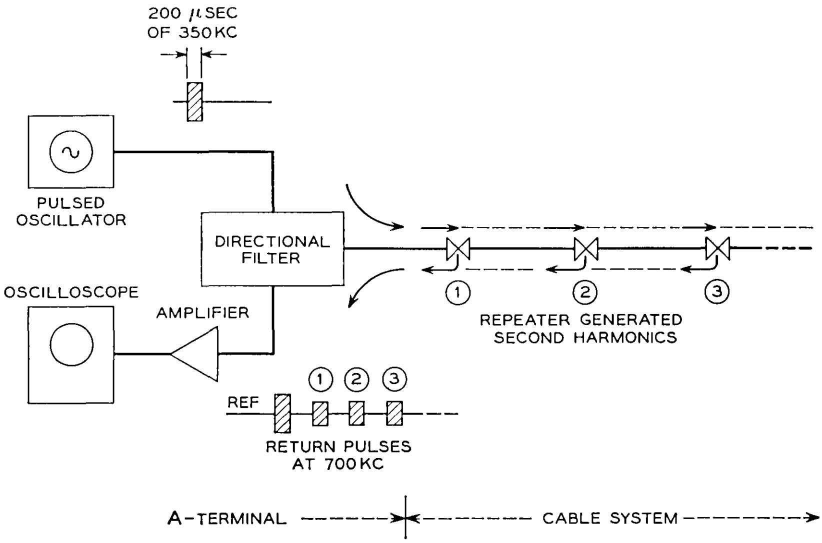



Fig. 15 — Repeater fault locating test set.

which answered the roll-call can be deduced. In a system with relatively little misalignment, the returned pulse trains can be displayed and examined on an oscilloscope. A photograph of a sample display is shown in Fig. 16. Should a system suffer considerable misalignment (6 db or more) the signal-to-noise ratio with respect to the 700-kc pulse would be so poor as to make oscilloscope presentation inadequate. Field experiments have shown that in such a case the presence or absence of a given repeater can be determined, even if the noise (in a 3-kc band) is 30 db greater than the returned pulse, by gating the detector and integrating the return signal over a long period of time — many minutes may be required under the least favorable circumstances.

## VIII. SYSTEM INSTALLATION

At present an SD submarine cable system is in operation between Florida and the Canal Zone with an intermediate terminal at Jamaica, W.I. Another is in operation between Tuckerton, New Jersey and Widemouth, England. Installation of a system between Hawaii and Japan has just been completed. Since the system between the United

(a)

(b)

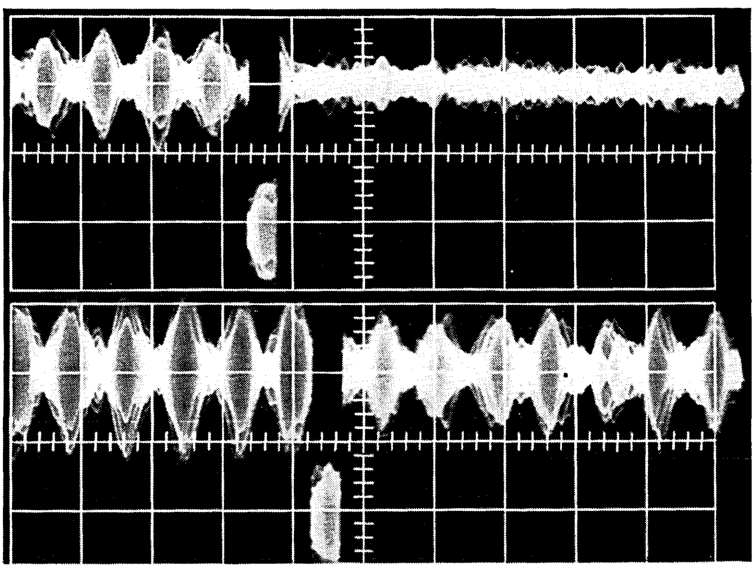


Fig. 16 — Repeater fault locating test set displays: (a) pulse returns from repeaters 178–182 — the pulse from the last repeater in the system (182) has been displaced for identification; (b) returns from repeaters 165–178 — repeater 171 has been displaced for identification.

States and England (commonly called TAT-3) has proved to be typical of long transoceanic systems, its performance will be discussed in some detail.

The length of the TAT-3 cable system is 3511 nm; the system follows a route shown approximately in Fig. 17. Maximum depth is 2800 fathoms. The system uses 182 repeaters and 17 equalizers. Approximately 12 per cent of the total cable is armored.

Laying operations were carried out during the summer of 1963. The British cable ship *Alert* laid the first 612 miles, starting at Tuckerton, New Jersey. Cable Ship *Long Lines* picked up at this point and completed the installation in two operations.

### 8.1 *Measurements During Laying*

Measurements made during the installation are summarized in Fig. 18 for four frequencies. The measurements show good agreement with the levels predicted from cable and repeater data, using ocean-block equalizer settings chosen during the laying operation.

### 8.2 *System Transmission*

The net gain of the undersea system (cable, repeaters and equalizers) is shown in Fig. 19. This was measured in October 1963, shortly after completion of laying, and shows similarly good agreement with computations. The transmission characteristic after equalization at the shore stations is shown in Fig. 20. This figure shows the deviation from flat transmission measured at the points where the multiplex signal is connected.

### 8.3 *Channel Noise*

Random noise measured at channel output with no talker load applied is plotted in Fig. 21. Since cable loss is a function of temperature, the random noise will exhibit a seasonal variation. The measured noise has been corrected to a mean annual temperature for comparison with computed noise under the same temperature conditions. It should be noted that most of the channels meet the 41-dbrn noise objective. Actually, 138 channels are acceptable for service.

### 8.4 *Modulation Performance*

The computed modulation noise produced by the talker load for which the SD system was engineered is shown in Fig. 22. The method of computation, which — like the equalization and random noise programs

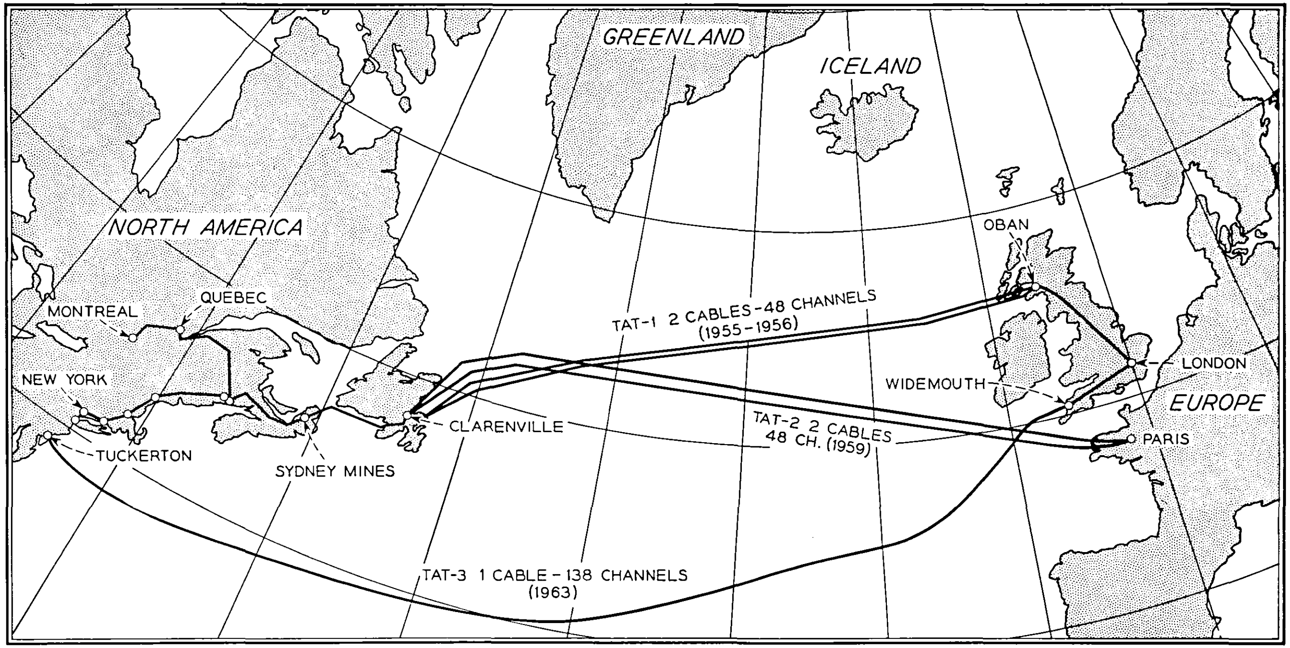



Fig. 17 — Route of TAT-3 system.

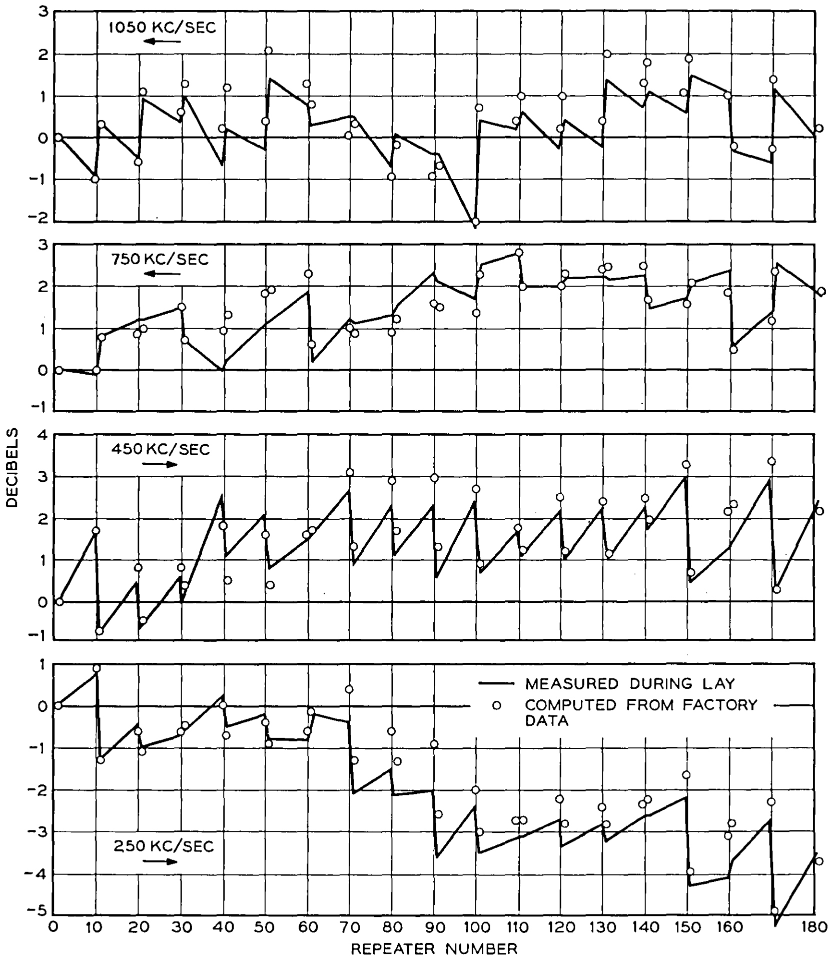



Fig. 18 — TAT-3 level diagrams, showing deviation of repeater output level from nominal.

discussed above — makes use of digital computer techniques, takes into account the effects of directional filter delay distortions on the addition of modulation product contributions from the various ocean-bottom repeaters. Two- and three-frequency intermodulation product measurements made on the undersea portions of the system give results which are consistent with the modulation noise values plotted versus frequency in Fig. 22.

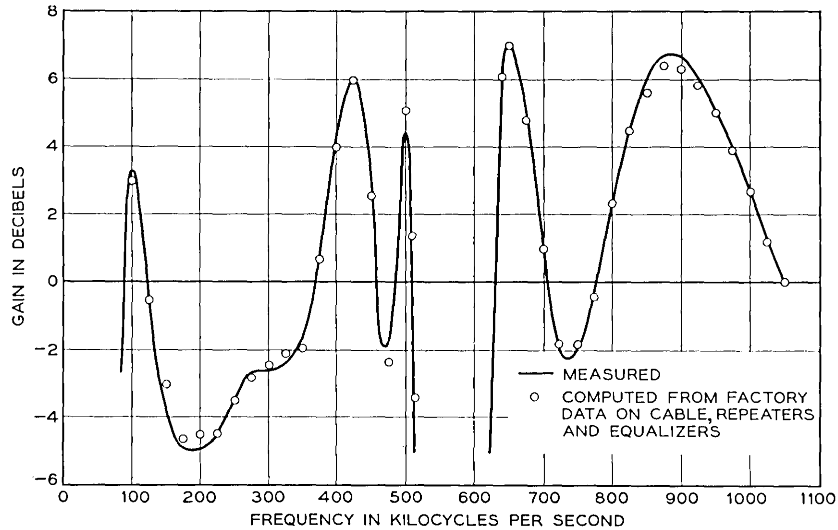



Fig. 19 — Net gain of undersea TAT-3 system.

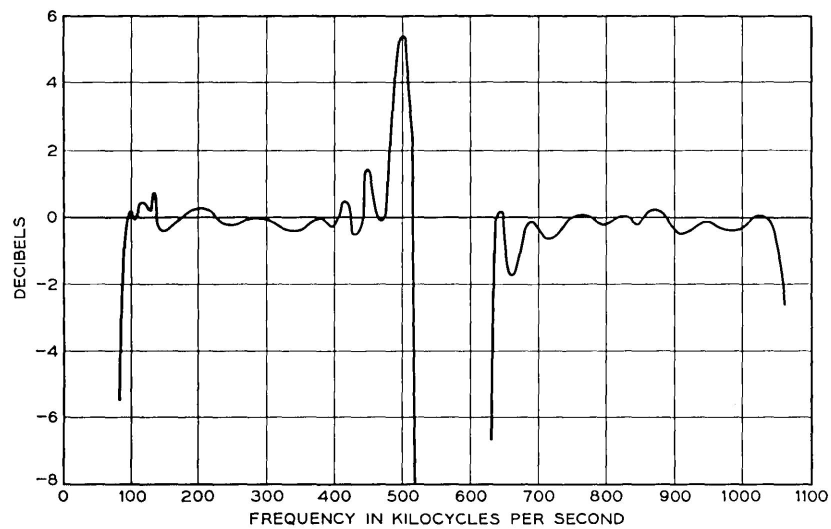



Fig. 20 — Net gain of TAT-3 system after shore terminal equalization.

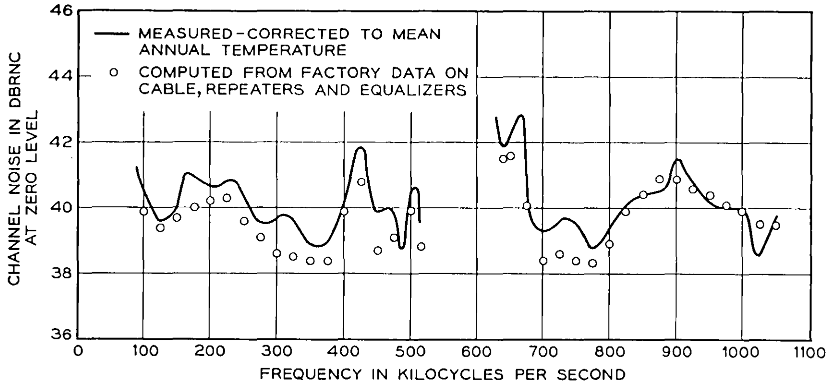



Fig. 21 — Random noise of TAT-3 system at channel bank outputs.

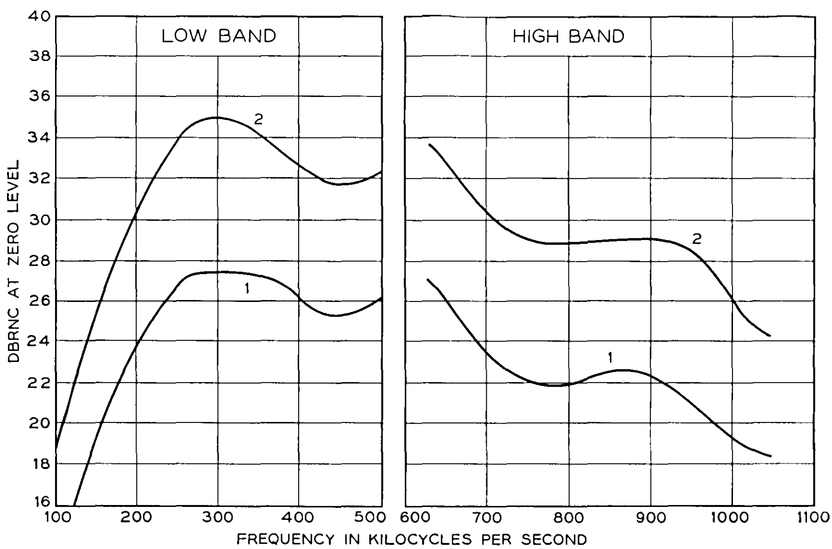



Fig. 22 — Computed modulation noise — TAT-3 system. Load assumptions: talker volume, −10.8 VU; standard deviation, 5.8 db; activity, 0.75. Curve 1 shows average modulation noise; curve 2 shows noise level that will be exceeded only 1 per cent of the time.

8.5 *Change in Transmission with Time (Aging)*

As of March 1964 the Florida-Canal Zone system had been in operation for 13 months and TAT-3 for 6 months. There has been no significant change in transmission that could not be accounted for by temperature changes. It appears that the aging of cable and repeaters will be very small.

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# Design of Armorless Ocean Cable

By M. W. BOWKER, W. G. NUTT and R. M. RILEY

(Manuscript received April 15, 1964)

*A low-loss coaxial ocean cable has been developed to be used as the transmission medium for the SD system. The strength member of the new cable is located inside the inner conductor. In deep-sea applications only a plastic jacket is required to protect the coaxial; in shallow water, where mechanical hazards are great, armor wires are applied over the coaxial in a more or less traditional manner.*

*A major concern in the development of the cable was that its transmission characteristics be predictable and be stable with time. This necessitated the consideration of mechanical and electrical requirements as one problem. Over 10,000 nautical miles of the new cable is performing satisfactorily in systems reaching to Europe, Asia, and Central America.*

## I. BACKGROUND

Development of cable for long, ocean-bottom, repeatered telephone systems is a process of engineering analysis, test, and evaluation. The objective is to provide a transmission medium that is predictable and reliable at reasonable cost. The development of cable for the SD system was carried on simultaneously with development of repeaters and facilities for placing cable in the ocean. Especially critical was the coordination of cable design with repeater design. This required that the cable engineers make early estimates of the cable attenuation characteristic so that repeaters could be designed with a gain characteristic to compensate for the loss of the cable. For instance, a 3500-nautical mile SD system has a cable loss at 1 mc of 8500 db. This means that uncompensated deviations in total cable loss of a few parts in a thousand would result in the received signals varying by tens of decibels.

To achieve an adequate match between cable loss and repeater gain requires first that the designs of both be predictable and stable. It requires that tolerances be placed on manufacturing processes, including precise measurement of final products with possible tailoring of characteristics. It requires that the ocean-bottom environment for each length of cable be determined in advance of manufacture and that the effect of that environment on cable loss be estimated.

Deep-sea cables traditionally have been armored cables which have performed satisfactorily in both telegraph and narrow-band telephone systems. These cables generally have a relatively small central portion of the cross-sectional area devoted to the transmission function. The larger part of the cross section is required for helically applied steel armor wires and jute wrappings. This traditional approach can be characterized as one which first satisfies the electrical need and then adds strength members.

Early in the 1950's, cable designers began to consider larger, lower-loss coaxials which would be needed in broader-band systems. These considerations led engineers from both the Laboratories and the British Post Office to the same general conclusion: future deep-sea cables could be "inside out" cables. The conducting material would need to be only a thin layer because of the elevated frequency band and thus, for a larger coaxial, considerable space would be available in the heart of the structure for a strength member.

Furthermore, an integrated electrical-mechanical approach to the design problem was possible. This approach provided the possibility of minimizing torque-tension coupling, thereby preventing much of the twisting and stretching that had been characteristic of traditional armored cables. The reduced coupling has further advantages during laying operations in that it results in a higher probability of consistent and predictable sea bottom performance and a decreased risk during laying and recovery of kinking at the mechanical discontinuities presented by the rigid repeaters proposed for the system.

The design which evolved is shown in Fig. 1; it consists of an inner strength member, copper inner conductor, low-density polyethylene dielectric, copper outer conductor and an outer jacket of high-density polyethylene.

In deep-sea telephone systems more than ninety per cent of the total distance from shore to shore requires no special protective armor or electrical shielding. This is why most of the design effort concerning transmission predictability, reproducibility and economy has been expended on the basic armorless coaxial structure. The design must be strong enough to survive the rigors of laying and recovery, to resist the crushing pressure of deep water, and to provide a reasonable ratio of strength to weight in water. The armorless cable described herein is not as strong as its armored predecessor, but the above ratio has been main-

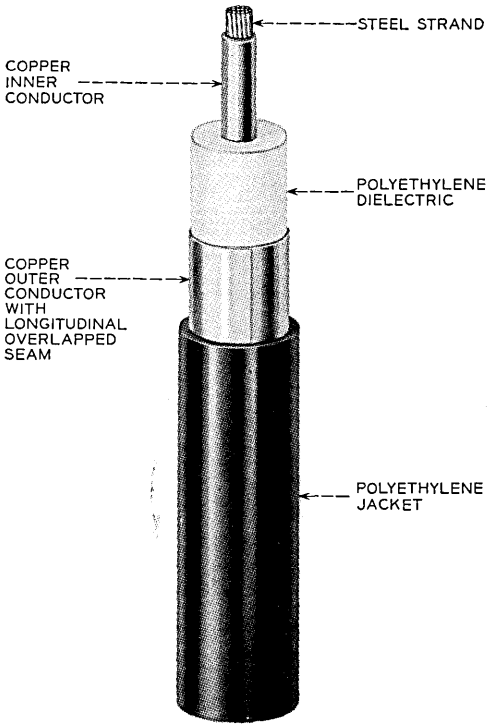


Fig. 1 — Armorless ocean cable.

tained because of the lower weight of the new cable. Once laid, the cable must have adequate resistance to attack by the various organisms that inhabit the ocean bottom and by the adverse chemical environment encountered at shore ends. The jacket of polyethylene seems to be the optimum answer to this protection problem.[1]

Inevitably, the deep-sea cables must be joined to the shore by cable which passes through shallow water. The shallow water environment is such that mechanical protection must be added around the coaxial, and in very shallow water this must be supplemented with electrical shielding. Various amounts of mechanical protection and electrical shielding are provided in special shallow water designs which are shown in Figs. 2–5. Some of the mechanical hazards which the cable encounters are tidal abrasion, tension failure and cutting by trawlers and anchors, crushing by icebergs, and attack by marine life. One or two layers of neoprene-jacketed steel armor wires are used as a protective cage around

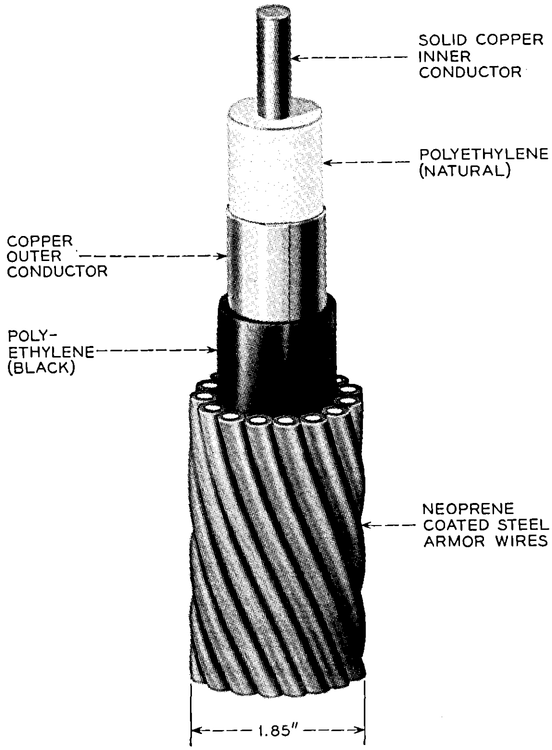


Fig. 2 — SD cable for shallow water.

the coaxial to minimize these hazards. When required, five layers of high-permeability steel tapes are applied over the coaxial to make an effective electrical shield. When external armor wires are used, the inner conductor is made entirely of copper. This is done to provide the ductility required for the conductor to elongate when the armor wires are subjected to tensile loads and concomitant cable elongation.

## II. BASIS FOR DESIGN

The basis for the design is the combined electromechanical goal of providing a transmission line that is stable and predictable after laying and for its entire life on the sea bottom. The important electrical properties are the propagation constant and characteristic impedance. The most critical of these is the real part of the propagation constant. The mechanical constraints include those required to achieve predictable and stable electrical performance.

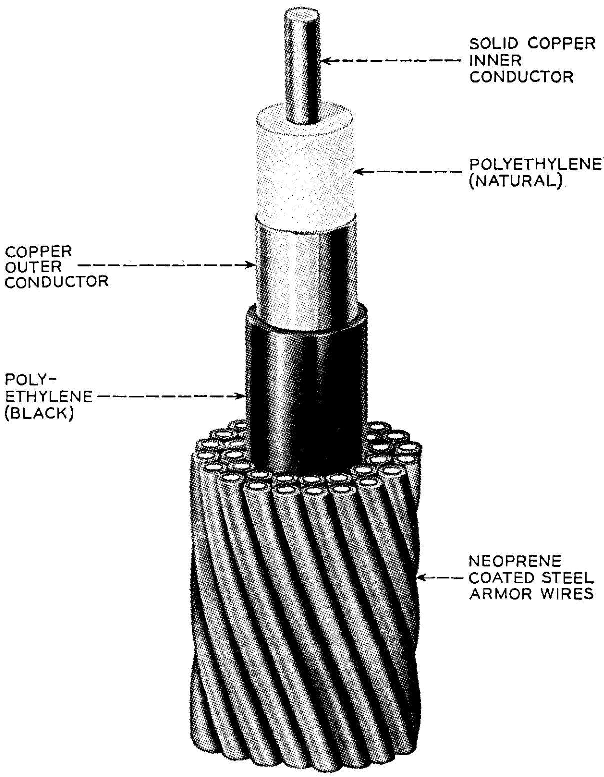


Fig. 3 — SD cable for shallow water, maximum protection.

### 2.1 *Electrical Diameter of Coaxial*

Economic constraints required selecting a size consistent with minimum over-all annual system costs and compatible with the technology of the time. Roughly, cable loss is inversely proportional to diameter, which means that, over some range, cable costs can be traded for repeater costs. A cable with a diameter of one inch over the dielectric falls into the optimum range for systems with a bandwidth of the order of 1 mc. Because of uncertainties in the ultimate economics of the system, other advantages and disadvantages of making a cable with a diameter of more or less than one inch were considered.

To exceed one inch would aggravate two basic uncertainties of that time. The extrusion of core as large as one inch, free of voids, required a significant step from any previous practice, including the experience of making the 0.620-inch armored cable used in the SB telephone systems.[2]

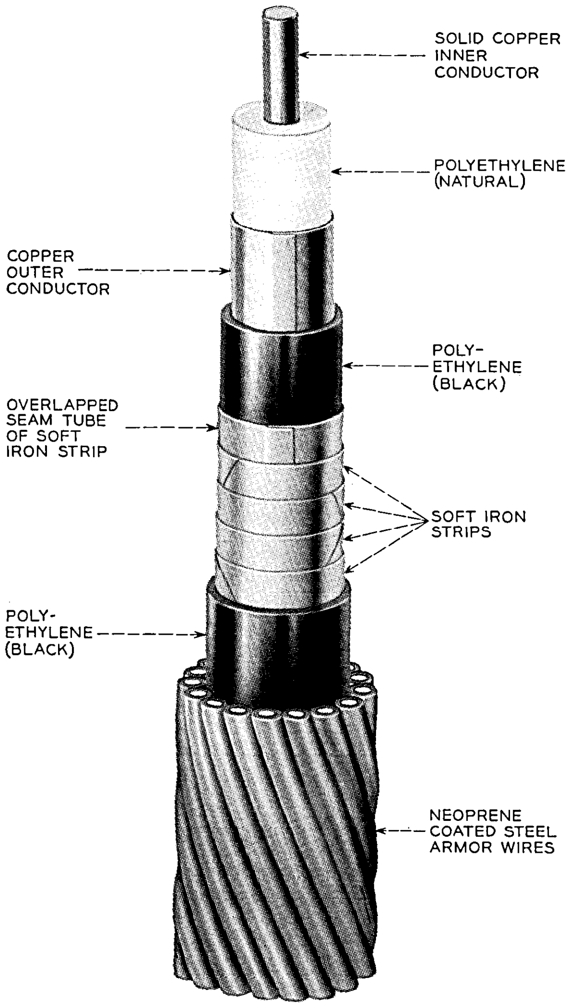


Fig. 4 — SD cable for shore ends.

The capability of a one-inch cable to withstand handling over reels of practical diameters and through cable machinery without serious buckling and perhaps rupturing of the outer conductor was questioned. Conversely, to reduce the diameter and thereby alleviate the above problems would increase the attenuation. This would require more repeaters in a given system and aggravate alignment and reliability prob-

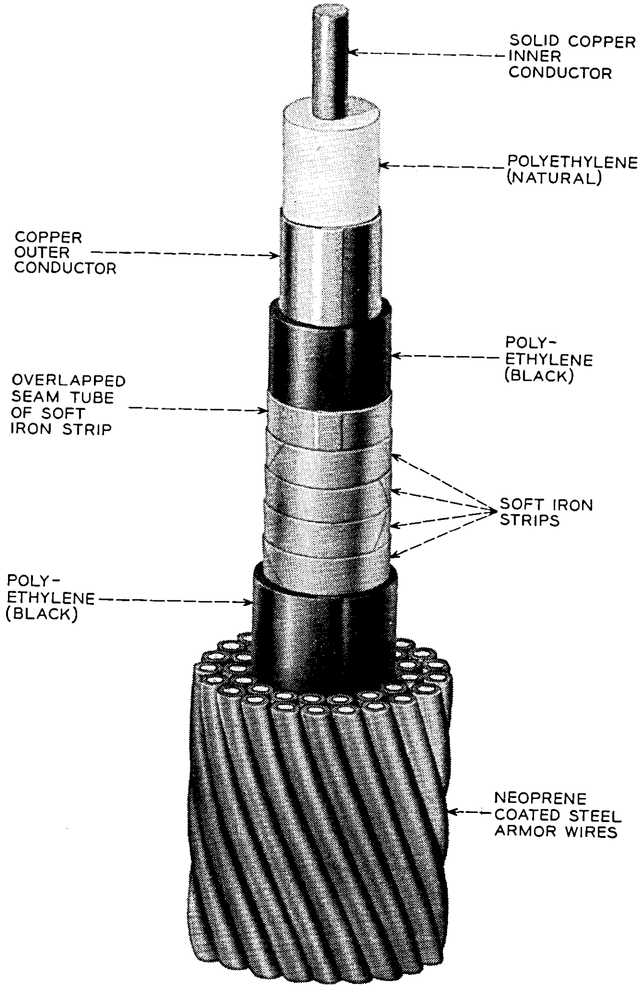


Fig. 5 — SD cable for shore ends, maximum protection.

lems. One inch appeared to be a reasonable diameter from the standpoint of cable mechanical properties and system transmission considerations.

### 2.2 *Mechanical Requirements*

From a mechanical viewpoint the basic design requirements are: (1) the ability to withstand the pressure at depths over 4000 fathoms (12,000 psi), (2) sufficient tensile strength to recover cable plus one repeater from depths of 3000 fathoms, and (3) protection from environmental hazards, both mechanical and chemical. The apparent inconsistency between the "pressure" depth and "tensile" depth requirements needs clarification. One is willing to place short portions of a system at depths greater than those from which the cable can be recovered. Laying tension can be limited to safe values, and usually depths greater than 3000 fathoms occur for relatively short distances. Therefore, one is justified in designing for pressures in excess of 4000 fathoms while also designing for a nominal recovery depth of 3000 fathoms.

The first of the above considerations dictates a structure as nearly incompressible as possible. The objective for breaking strength was taken as the sum of the weight in water of 3000 fathoms of cable and one repeater multiplied by a dynamic loading factor of 2.5. This amounts to about 16,000 pounds.

The tensile load of the inner conductor must be transferred to the shipboard machinery through the various cable layers. This requires careful control of the interlayer shear strength.

### 2.3 *Specific Dimensions and Materials*

Starting with one inch as the diameter of the dielectric, the inner conductor diameter was chosen on the basis of its influence on strength (directly proportional to the cross-sectional area of steel that can be included) and its influence on attenuation (relatively slight over a broad range).

The tensile requirement of 16,000 pounds led to a 0.29-inch stranded strength member consisting of 41 high-strength steel wires (Fig. 6). The lay-up of the strand was chosen for maximum strength in a limited area and has a single direction of lay. The other elements of the cable add to the 16,000-pound strength of the strand so that the cable has a breaking strength of approximately 18,000 pounds. However, only the strength of the strand can be transmitted through a repeater, and hence this becomes the controlling strength of the system. The length of lay of the strand is chosen on the basis of two considerations: (1) it must be short compared to a 90° arc on a 3-foot radius so that when the cable is tensioned over a sheave all wires are equally stressed. (2) it should be long enough so that the untwisting torque produced under tension can easily be restrained by the torque-tube action of the copper inner and outer conductors, and the polyethylene dielectric and jacket. Since the untwisting torque is portional to tension, a single curve may represent the torque produced by different lengths of lay. Fig. 7 shows that increas-

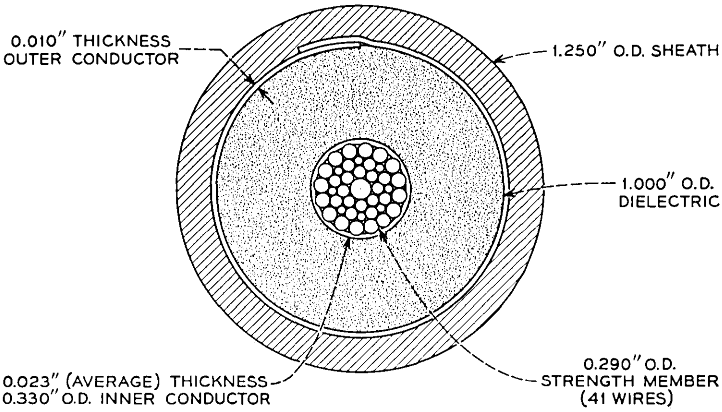


Fig. 6 — Cross section of armorless ocean cable.

ing the lay beyond six inches does not significantly reduce the torque. At normal laying loads, the restraining action of the cable components in the assembly allows a twist of less than one turn in 100 feet of cable length with a 6-inch lay strand. Thus the 6-inch lay meets both objectives. This lay is too long for a strand to hold its pattern by itself

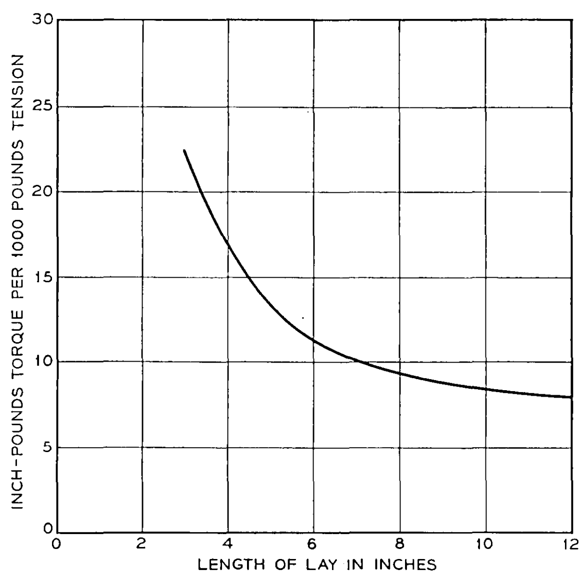


Fig. 7 — Torque vs length of lay for steel strand.

and was one of the factors that dictated the combining of stranding and inner conductor formation into a tandem operation.[3]

The copper conductor which surrounds the steel strand is hermetically sealed by inert gas welding and driven into intimate contact with the strand. The hermetic seal prevents volatiles in the strand from blowing holes in the dielectric during extrusion and also prevents substances on the steel that might be cracking agents for polyethylene from coming into contact with the dielectric. The intimate contact of the copper with the steel assures (1) the necessary transfer of longitudinal shear forces from the steel strand to the copper, (2) the transfer of resisting torque of the tubular members to the strand, and (3) that the tubular conducting member will not be crushed by the high ocean-bottom pressures.

The thickness of the copper portion of the inner conductor is chosen to provide sufficient electrical shielding so that at the lowest frequency very little current penetrates into the steel. Concurrently, there must be sufficient copper to hold the voltage drop for the repeater power current to a reasonable level. These considerations dictated an average copper thickness of about 23 mils with a nominal outside diameter of 0.330 inch.

For a dielectric, low-density polyethylene has a good balance of electrical properties, mechanical properties and cost. It has a low dielectric constant (approximately 2.28) and dissipation factor (approximately 0.0001). It is readily processed, has reasonable handling characteristics and is satisfactory over a wide range of environmental conditions.

Early in the development, it was recognized that for a stable transmission characteristic an ideal outer conductor would be a longitudinal copper one with a thickness of approximately 10 mils. Traditionally, outer conductors greater than about $\frac{1}{2}$ inch in diameter had been made up of multiple helical tapes so that they could be bent at reasonable radii without buckling. Such a conductor has uncertain current paths through changing intertape contact resistances. It also needs additional shielding to prevent crosstalk to any other nearby cable. Crosstalk is especially critical for the period when transmission measurements are being made aboard ship as the cable is being placed in the ocean. Here, interlayer crosstalk is aggravated by the gain of repeaters and may preclude accurate transmission measurements.

The seam in the outer conductor is simply an overlap of about one-quarter inch. Pressure and temperature effects require the outer conductor to expand and contract, changing the circumference of the outer conductor by as much as 30 mils.

To realize the electrical advantages of the longitudinal outer conductor required some means of controlling the buckling when it was handled over reels and sheaves with a radius as short as 3 feet. At this radius of curvature, the outer portion of the 1-inch conductor is stressed beyond its elastic limit. Straightening out the conductor will result in buckling, which can lead to circumferential fatigue cracks unless the copper is constrained in some fashion. Several jacket materials and combinations of tapes and jackets were investigated. Experiments indicated that low-density polyethylene does not develop enough circumferential force to prevent buckling. Polypropylene does, but presents low-temperature and extrusion difficulties. High-density polyethylene $\frac{1}{8}$-inch thick, with properties midway between polypropylene and polyethylene, was found to develop just enough force to prevent any significant buckling for a reasonable number of cycles of reverse bending at a 3-foot radius. Hence, it became the choice for the outer jacket. Carbon black was included to minimize deterioration from photooxidation during the storage period.

The above discussions omitted any consideration of alternatives to copper. Aluminum, with its relatively good ratios of conductivity to cost and weight, was also of interest. However, as an inner conductor material, it imposed too large an attenuation penalty (14 per cent). As an outer conductor material it imposed a modest loss penalty (5 per cent) and additional development problems in the areas of corrosion and buckle suppression. For these reasons copper was selected as the conducting material for both inner and outer conductors.

The nominal attenuation characteristic of the resultant design is shown in Fig. 8.

## III. TOLERANCES

Although the cable quite clearly has both electrical and mechanical functions, most of the tolerances are set primarily on the basis of electrical considerations. The exceptions are the stranded strength member and the outer jacket.

### 3.1 *Tolerances Determined by Mechanical Considerations*

The primary requirement for the strand is to develop the required strength within the allotted space and to be compact and crush resistant. Individual wires are required to have an average ultimate tensile stress of approximately 300,000 psi. There is an ultimate stress tolerance of $\pm 7$ per cent and a diameter tolerance of $\pm 0.5$ mil. Additional requirements are imposed on the selection of combinations of wires to insure

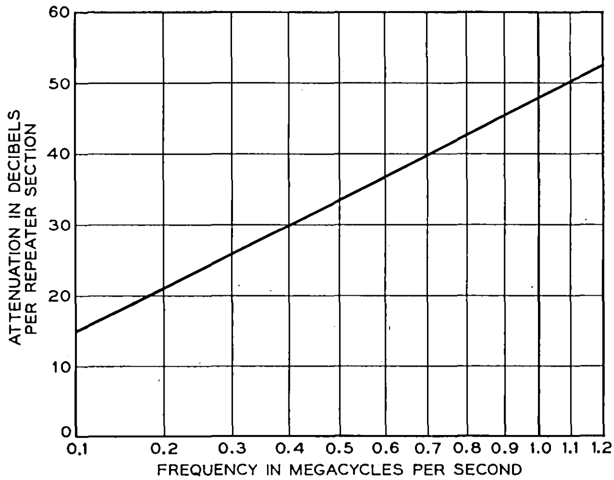


Fig. 8 — Nominal attenuation characteristic.

that the diameter of the completed strand is controlled. The steel wires are stranded in tandem with the copper tube forming, and the two elements are passed through a very tight die which forces the copper into the peripheral vee-shaped spaces between the wires of the outer layer. Thus a compact, concentric and uniform strength member is achieved.

The functions of the outer plastic jacket are protective and structural. Specifications for the properties of the raw material and for the extrusion thereof are chosen to give adequate control, but do not involve close tolerances.

### 3.2 *Tolerances Determined by Electrical Considerations*

As described elsewhere in this issue,[4] approximately 20 nautical miles of cable constitute a repeater section; ten repeater sections constitute an ocean block. The simultaneous development of the repeater and the cable made it necessary to predict the attenuation of the cable in each ocean block to within $\pm 2$ db, which is $\pm 1.2$ per cent at 0.1 mc and $\pm 0.4$ per cent at 1.0 mc. The $\pm 2$-db allowance includes uncertainties due to tolerances in manufacture, measurement errors, effects of handling and placing, inaccurate knowledge of pressures and temperatures along the actual cable route, and errors in estimating the effects of pressure and temperature. Thus the tolerances on the manufacture of the cable must limit attenuation deviations to considerably less than $\pm 2$ db per ocean block.

Equations for computing the propagation constant and characteristic impedance of a coaxial transmission line are well known.[5] However, most of the parameters of the cable requiring tolerances are evident from considering an approximate expression for the attenuation per unit length at high frequencies.

$$\alpha = k_1\sqrt{f}\left(\frac{1}{d\sigma_i} + \frac{1}{D\sigma_o}\right)\frac{\sqrt{\epsilon}}{\log D/d} + k_2 f F_p \sqrt{\epsilon}$$

where

$f$ = frequency
$d$ = diameter of inner conductor
$D$ = diameter of the dielectric
$\epsilon$ = dielectric constant
$\sigma_i$, $\sigma_o$ = conductivities of inner and outer conductors
$F_p$ = dissipation factor of the dielectric
$k_1$, $k_2$ = constants of proportionality.

Omitted from the above expression are second-order or smaller terms which take into account the thicknesses of the inner and outer conductors.

In considering tolerances for the cable parameters, it is convenient to distinguish between tolerances that cause the attenuation to deviate by a constant percentage at all frequencies and tolerances that cause the attenuation to deviate in more complicated ways. A constant percentage deviation is said to have "cable shape" and may be compensated by adjusting the length of the cable. Tolerances that cause deviations having cable shape are those on the dielectric constant and the length measurement itself. Also closely approaching cable shape are the deviations caused by variations in the diameters of the inner and outer conductors, the diameter of the dielectric, and the conductivities of the inner and outer conductors. The percentage deviations, $\Delta\alpha/\alpha$, caused by the parameters having cable shape are plotted versus frequency in Fig. 9. Eccentricity of the inner conductor and deviation from circularity of the cross section are held so that their effects on attenuation are much less than $\pm 0.1$ per cent. To the extent that they exist, however, they also have cable shape.

The remaining tolerances — dissipation factor and thickness of the conductors — do not have cable shape (see Fig. 10). Deviations caused by variations in the dissipation factor increase percentage-wise with frequency and are therefore not well compensated by adjusting length. The tolerances placed were as small as practicable. To reduce the requirements in this area equalizers were designed with a frequency characteristic that could compensate for variations in dissipation factor.[6]

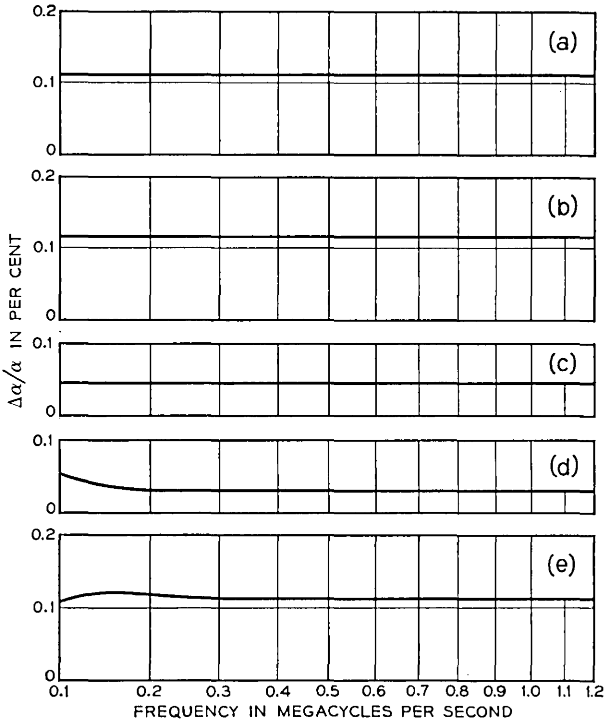


Fig. 9 — Tolerances having approximately cable shape: (a) per cent change in attenuation due to an increase in the dielectric constant of 0.005; (b) per cent change in attenuation due to a decrease in the diameter of the dielectric of one mil; (c) per cent change in attenuation due to an increase in the diameter of the inner conductor of one mil; (d) per cent change in attenuation due to a decrease in the conductivity of the outer conductor of 0.3 per cent; (e) per cent change in attenuation due to a decrease in the conductivity of the inner conductor of 0.3 per cent.

The thickness of both the inner and outer conductors was limited by strength-to-weight and cost considerations. Although the inner conductor thickness is such that very little current flows in the steel, at the lowest frequency there is some sensitivity to thickness variations. For the outer conductor, variations in thickness cause significant variations in attenuation throughout the bottom half of the transmitted band. Concerning the lapped seam of the outer conductor, some variations in contact resistance are possible and cannot be controlled, but fortunately the effect is essentially negligible.

One approach would be to select tolerances so that a length of cable exactly equal to the nominal repeater section length would meet all

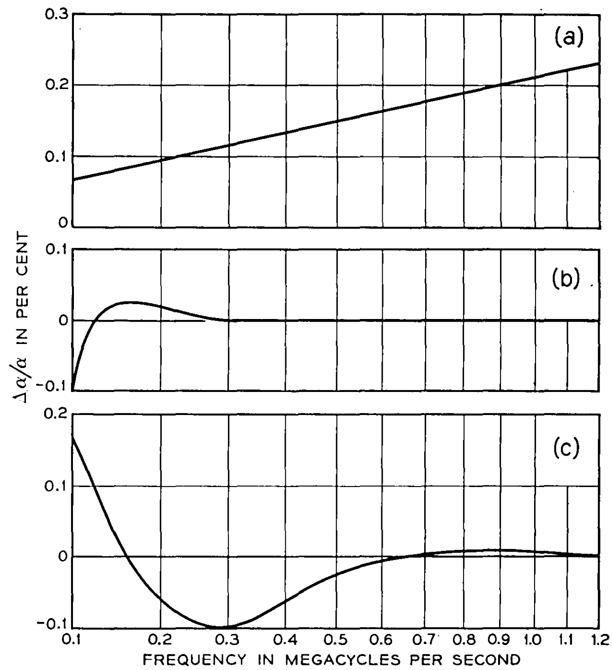


Fig. 10 — Tolerances not having cable shape: (a) per cent change in attenuation due to an increase in dissipation factor of 0.00002; (b) per cent change in attenuation due to a decrease in thickness of the inner conductor of 0.5 mil; (c) per cent change in attenuation due to a decrease in thickness of outer conductor of 0.2 mil.

transmission objectives. However, it was more economical to set the tolerances with cable shape a little wider than this, measure the attenuation of each length of cable after manufacture, and then adjust the length of some of the sections to compensate the cable shape deviations accumulated in previous lengths.

Table I lists the tolerances selected and the attenuation deviations that would be caused by their extreme values. In the extremes, these tolerances would result in deviations in attenuation of an ocean block of $\pm 1.2$ db at 0.1 mc and $\pm 3.0$ db at 1.0 mc. Random combination of the tolerances would result in attenuation deviations of $\pm 0.5$ db at 0.1 mc and $\pm 1.5$ db at 1.0 mc. Adjusting length after manufacture was expected to reduce the range of the deviations at all frequencies to within $\pm 1.0$ db. As a result of favorable experience with the design, the present objective at the manufacturing locations is $\pm 0.5$ db.

TABLE I—TOLERANCES FOR CABLE PARAMETERS

| Parameter | Dimension and Tolerance | | Effect on Attenuation (Per Cent) | |
|---|---|---|---|---|
| | | | 0.1 mc | 1 mc |
| Inner conductor diameter | 0.330″ | ±0.001 | ±0.04 | ±0.04 |
| Diameter over dielectric | 1.000″ | ∓0.001 | ∓0.12 | ±0.12 |
| Thickness of inner conductor | 0.023″ | ±0.0005 | ±0.10 | ±0.00 |
| Thickness of outer conductor | 0.010″ | ∓0.0002 | ∓0.18 | ±0.01 |
| Conductivity of inner conductor | 99.1% | ∓0.3 | ∓0.11 | ±0.11 |
| Conductivity of outer conductor | 100.6% | ∓0.3 | ∓0.05 | ±0.03 |
| Dielectric constant | 2.282 | ±0.005 | ±0.11 | ±0.11 |
| Dissipation factor | 0.00012 | ±0.00002 | ±0.07 | ±0.21 |
| Totals | | | | |
| Algebraic | | | ±0.78% | ±0.63% |
| Root sum square | | | ±0.30% | ±0.29% |

## IV. MODEL MAKING

Armorless cable differs enough from the traditional that attempts to make models on available machinery resulted in samples unsuitable for electrical and mechanical evaluation. For this reason a special laboratory was equipped early in the development period to determine the feasibility of several different armorless cable designs. The cable fabrication laboratory, located at Cambridge, Massachusetts, was operated by the Simplex Wire and Cable Company under contract to Bell Telephone Laboratories. In it were produced the cable samples needed for making the mechanical and electrical tests to verify the design principles and to establish the necessary manufacturing tolerances. Approximately fifty miles of cable were fabricated for this purpose. These experimental lengths permitted Bell Laboratories engineers to determine the feasibility of manufacturing the cable and to establish an optimum balance among the several tolerances. Finally, the experience provided a basis for the study of factory layouts adapted to the manufacture of armorless cable.[3,7]

## V. LABORATORY ELECTRICAL MEASUREMENTS

Equipment and methods for making appropriate electrical measurements were developed concurrently with the cable. For the purpose of discussion the measurements can be divided into those made on short, medium, and sea-trial lengths.

### 5.1 *Short Lengths*

Primary constants measured on short samples are important for the following reasons:

(1) Since the test specimens should be less than one-eighth wavelength at the top measurement frequency, a process not yet refined may be adequate to produce samples.

(2) The quantities measured — resistance, inductance, conductance, and capacitance — are directly related to dimensions and physical properties of materials, and therefore cause and effect may be readily related.

(3) Since the sample lengths are short, the problems of control and determination of environment are easier than for long samples.

The main disadvantage of the measurement of primary constants is associated with the short length, namely that the quantities measured are electrically so small that connecting leads and terminations must be designed and evaluated with considerable care. Resistance and conductance measurements require particular attention to connecting leads. Special facilities were designed and built to meet the accuracy objectives. These included:

(1) a 32-foot long environmental tank capable of simulating pressure and temperature conditions for depths up to 4000 fathoms,

(2) special measurement bridges, and

(3) coaxial comparison standards with electrically thick conductors and a minimum of disc insulators.

To evaluate the effect of pressure seals at the ends of the environmental tank, a two-foot tank was provided that was identical in every respect except length. The bridge and associated leads were located so that lead length and configuration were not changed as the bridge was connected to the standards and to the samples. Special low-resistance coaxial plug and jack connectors were developed to reproduce contact resistance of connections at 1 mc to 0.1 milliohm.

The bridges were maintained at essentially constant temperature. The exteriors of the tanks, including end seals and associated connectors, were well insulated to minimize temperature gradients in the 30-foot test length. The water temperature of each tank was measured at several points along its length to determine the temperature profile of the cable sample. In addition, the average temperature along the length was determined by measuring the dc resistance of an insulated copper wire also contained in the pressure tank.

TABLE II—THEORETICAL VS MEASURED VALUES OF TEMPERATURE AND PRESSURE COEFFICIENTS

| Primary Constant | Temperature Coefficients % per °C | | Pressure Coefficients % per 1000 Fathoms | |
|---|---|---|---|---|
| | Measured | Theory | Measured | Theory |
| $\frac{\Delta R}{R}$ | 0.20 | 0.202 | 0.05 | 0.05 |
| $\frac{\Delta L}{L}$ | 0.026 | 0.021 | −0.20 | −0.22 |
| $\frac{\Delta G}{G}$ | 1.5 | | −4 | |
| $\frac{\Delta C}{C}$ | −0.064 | −0.060 | 0.56 | 0.68 |

Theoretical and measured values of pressure and temperature coefficients at 1 mc are compared in Table II.

The corresponding temperature and pressure coefficients of attenuation may be derived from the measured primary constant coefficients. With regard to temperature coefficients, $\Delta R/R$ accounts for over three-quarters of the effect on attenuation; with regard to pressure coefficients, $\Delta C/C$ accounts for over half of the effect on attenuation, with much of the balance due to $\Delta L/L$. The derived attenuation coefficients are given in Table III, as well as the coefficients observed in placing transoceanic systems. The experience with long systems indicated a temperature coefficient 6 per cent smaller than predicted and a pressure coefficient 8 per cent smaller than predicted.

The small conductance loss of the cable made the determination of its pressure and temperature coefficients less exact than desired. The tests did indicate, however, that the effective conductance at ocean bottom conditions would be less than at factory conditions. Experience with

TABLE III — TEMPERATURE AND PRESSURE COEFFICIENTS OF ATTENUATION

| Attenuation | Temperature Cofficients % per °C | | Pressure Coefficients % per 1000 Fathoms | |
|---|---|---|---|---|
| | Derived from Primary Constants | System Experience | Derived from Primary Constants | System Experience |
| $\frac{\Delta\alpha}{\alpha}$ | 0.17 | 0.16 | 0.38 | 0.35 |

actual ocean systems has confirmed this, observed decreases in conductance being as much as 50 per cent larger than these coefficients would indicate.

It was also observed in the measurements on short lengths that the effective dissipation factor of the cable increased with increasing frequency, from about 0.00012 at 0.1 mc to 0.00014 at 1.0 mc. When 6-foot samples were carefully dried in a vacuum, the dissipation factor decreased and was essentially constant with frequency. One theory advanced to explain the behavior was that a small gap existed between the dielectric and the outer conductor, and that in this space a conducting film formed. Such a film, being in series with the coaxial capacitance, would cause an apparent variation in dissipation factor with frequency. Either removing the film by thorough drying or bringing the outer conductor into intimate contact with the dielectric would reduce the conductance and therefore the attenuation.

### 5.2 *Measurements on Intermediate Lengths*

To reduce the uncertainties of making connections, measurements were made on samples several hundred feet long where the attenuation at one mc might be at least a good fraction of a db. Two types of measurement were in this category.

Chronologically, the first of these was a resonant-type measurement made on samples from 1000 to 3000 feet in length. The measurement was made using a symmetrical bridge and consisted of measuring the input impedance of a short- or open-circuited sample. The reactive component was eliminated by adjusting frequency and the real component was balanced using deposited carbon resistors mounted on special plugs. The measurement showed an excellent agreement between theoretical and measured phase delay (see Fig. 11).

The second type of measurement of intermediate-length samples was an aging test to determine the stability of the attenuation of the cable.* In this test 600-foot lengths of cable were subjected to a simulated laying cycle, after which they were maintained at a typical sea-bottom pressure and temperature. The attenuation was monitored for any change. The facility was arranged so that the cable could be tensioned and water pressure applied simultaneously to simulate the pressure-tension cycle of a laying operation. The attenuation was

* This test was the primary responsibility of T. Slonczewski, then of Bell Telephone Laboratories.

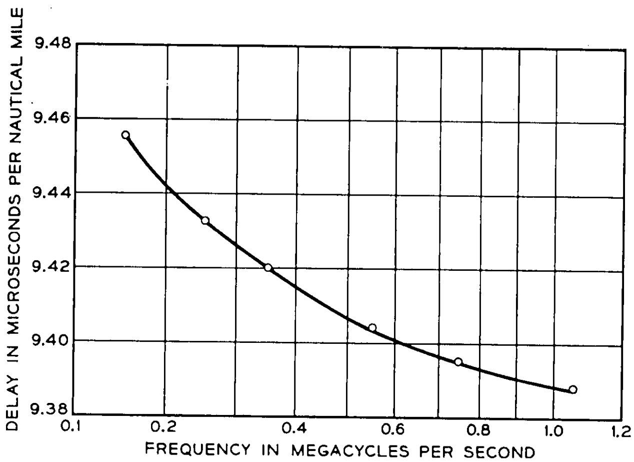


Fig. 11 — Measured phase delay (open circles) compared to theoretical (curve).

measured on an absolute basis to an accuracy of $\pm 0.00002$ db, temperature maintained at 3°C and measured to $\pm 0.01$°C and pressure was maintained at 5000 psi and measured to $\pm 10$ psi. The over-all accuracy of the measurement facility permitted detecting a change of 0.02 per cent at one megacycle. The test has been in progress for more than three years and no change has been observed.

The question of possible aging was so critical that shore-controlled equalizers were then being developed. With the favorable results from the aging tests, it was concluded that shore-controlled equalizers were not necessary.

### 5.3 *Sea Trials*

The final experiment of the design portion of the development program was to fabricate 35 miles of cable in five-mile lengths. Three of these were placed and measured on sea bottom — one each at approximately 500, 1500, and 3000 fathoms.

The cable was placed by the cable ship *John W. Mackay*. The procedure in placing the sea-trial cable was to first establish stable laying conditions by paying out wire rope and scrap cable. This was followed by the test sample, a repeater housing, and a test lead coming on board ship (see Fig. 12).

The test method utilized echo techniques in that a long single-frequency pulse was reflected from open-circuit terminations. The sea end of the five-mile test sample was open circuited. In the repeater housing

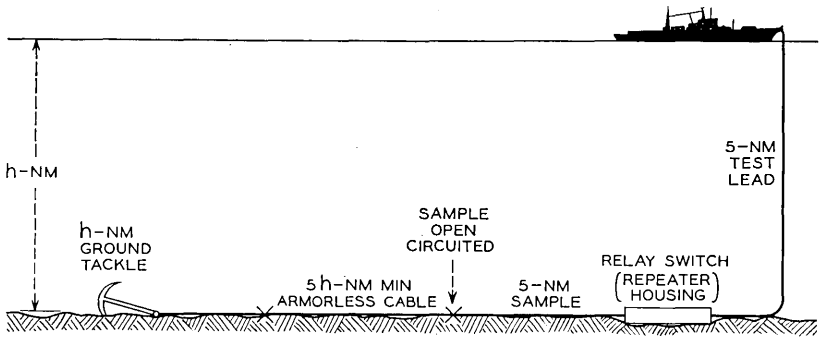


Fig. 12 — Cable arrangement for sea trial.

between the test sample and the test lead, switching was provided to either connect the sample to the test lead or to open circuit the test lead. By alternately measuring the test lead and the test lead plus sample, the attenuation of the sample was determined.

The three lengths as measured at the pilot plant had losses at 1 mc that averaged $\frac{1}{2}$ per cent less than had been predicted. The attenuation at 1 mc after placing in the ocean averaged $\frac{1}{4}$ per cent greater than had been predicted (see Fig. 13). This pattern of behavior is reasonably characteristic of all the cable that has been manufactured and placed.

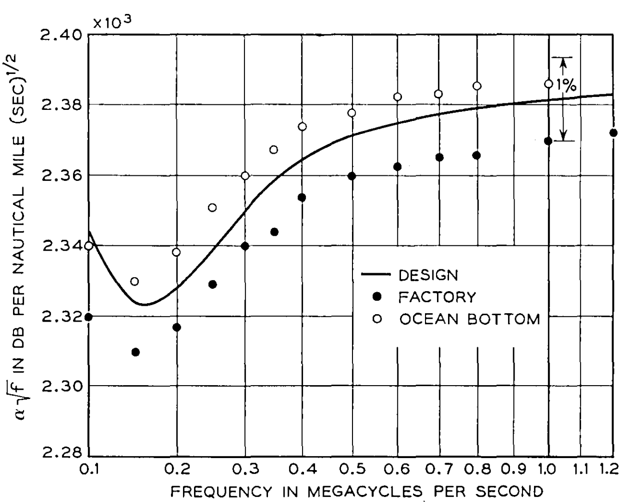


Fig. 13 — Attenuation of sea-trial cable design, as manufactured and on ocean bottom.

The predictions of the cable attenuation at atmospheric pressure were based upon intimate contact of the outer conductor with the dielectric. Such a situation certainly obtains at sea-bottom pressure. However, under factory conditions, in spite of the hoop stresses of the outer jacket, it is conceivable that a minute air space exists between the copper and the dielectric, particularly in the vicinity of the overlap seam. Therefore, it is believed that the $\frac{1}{4}$ per cent difference at sea-bottom conditions is the true prediction error and that the $\frac{1}{2}$ per cent difference in the factory is due to uncertainties in the precise dimensions of the outer conductor and the concomitant effects on conductance mentioned above.

### 5.4 *Laboratory Mechanical Tests*

The calculated mechanical properties of the cable were confirmed experimentally. In the case of tension, torque, bending, and reasonable combinations of these, the cable was tested until one of its conducting or protective components failed.

One of the mechanical properties studied was the torque-tension characteristic, which can be approximated by

$$\text{twist/unit length} \equiv \theta = \alpha T + \beta M$$

where $T$ is the tension in pounds and $M$ is the applied external torque in inch-pounds. The constant $\alpha$ is in radians per foot per pound of tension; the constant $\beta$ is in radians per foot per inch-pound of torque. Both $\alpha$ and $\beta$ are functions of cable geometry and material properties, some of which are nonlinear. In addition, they are combined in such a way that the resulting structure is nonisotropic as well as nonlinear. By making certain simplifying assumptions, it was estimated that $\alpha$ and $\beta$ would have values of $2 \times 10^{-6}$ and $3.3 \times 10^{-4}$, respectively.

Values of $\alpha$ and $\beta$ were measured on 100-foot lengths of cable hanging from a tower. To the bottom end of the cable was fastened a large container that could be filled with water. Tension was applied free of torsional restraints or, alternatively, tension was applied and the torque measured that was required to prevent twist. The resulting values of $\alpha$ and $\beta$ were $1.2 \times 10^{-6}$ and $2.5 \times 10^{-4}$, respectively.

## VI. CABLE JOINING

In order to transfer the tension between two lengths of cable or join a length of cable to a repeater, it is necessary to make a high-strength splice to the steel strand. This requires that all of the polyethylene and cable layers be removed and the steel strand carefully cleaned. A copper-plated steel ferrule is then swaged onto the strand to bridge the strength (and conductivity) to a repeater housing or to another length of cable. Polyethylene layers are restored by molding, and the outer conductor is restored by brazing in new material.

Cable repairs are made so that no external bulge exists and therefore there is no problem in coiling or handling repaired cable. The use of the steel ferrule gives an electrical impedance discontinuity, but this is tolerable so long as splices are infrequent and at random locations.

## VII. SUMMARY

The objective of the development program was to design an ocean cable having lower loss than previous cables. The cable program was concurrent with a program to develop a new repeater. Thus it was necessary to predict the attenuation-frequency characteristics of the cable as it would be on the ocean bottom after all changes due to factory and shipboard handling, the placing operation, and ocean-bottom pressure and temperature had taken effect. It was also required that this attenuation characteristic should not change with time.

By now, experience with armorless cable systems placed between Florida and Jamaica, Jamaica and Panama, plus systems from the United States to England and from Hawaii to Guam, indicates that the attenuation has been predicted to better than 1 per cent over the frequency spectrum of interest. This achievement has permitted the use of relatively simple and inexpensive procedures to maintain system alignment. Furthermore, in the first year of experience there has been no detectable aging in the transmission characteristic. Thus the most important goals of predictability and stability appear to have been attained.

## VIII. ACKNOWLEDGMENTS

The authors wish to acknowledge the many contributions made by the members of the staff of the Simplex Wire and Cable Company and the Bell Laboratories groups involved in the cable design and development.

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# Armorless Cable Manufacture

By B. W. LERCH and J. W. PHELPS

(Manuscript received April 17, 1964)

*The major portion of the cable used in an SD system is of an armorless coaxial design, with a strength member within the inner conductor structure. It is fabricated in continuous 20-nautical mile repeater sections and is stored, when finished, in individual pans. Every section is therefore available in any sequence to facilitate the most nearly ideal ship loading schedule.*

*This paper summarizes the process experience gained during the cable design and development program, details the processes involved in the purchase of cable raw material, discusses the manufacturing operation, and includes a measure of cable reproducibility for the Baltimore plant of the Western Electric Company.*

## I. MANUFACTURING BACKGROUND

It had been the intent, during the design and development program for cable for an SD system, that the specification defining and covering the cable would be written in terms of end product requirements, insofar as the necessary guarantees of long and stable cable life would permit. For this reason, laboratory work on the cable design, including the production on a semi-pilot plant basis of perhaps 50 or 60 nautical miles (nm) of cable samples, was conducted with primary attention placed on the product and not on the process or machinery. It was deemed sufficient to demonstrate that cable of adequate reproducibility and stability could be produced on at least one combination of cable making machines.

It was apparent, however, that an appreciable amount of factory planning time might be saved and some duplication of effort eliminated if a record of the experiences obtained in the cable laboratory was made available to prospective cable manufacturers. The intent was not to make process a specification requirement but merely to outline diagrammatically the processes used in the experiments; to list certain types of machines known to have adequate capacity and reliability; to delineate the need for machinery for which there was no prototype; to show approximately the lengths of the several manufacturing lines needed to achieve realistic manufacturing speeds; and to estimate adequate material and in-process storage areas.

There had been, additionally, several pieces of test equipment devised specifically for the measurement, recording and control of certain process parameters. It was not thought necessary to specify the use of these pieces of test equipment, since other devices could be found that would work adequately well. However, it was felt that information on the experience with these devices should also be made available.

As a result of the above, a study was made of an idealized ocean cable factory layout by an outside engineering organization in consultation with Bell Laboratories employees who were familiar with the operation of the cable laboratory. The report emanating from this organization gave a summary of laboratory experience and a point of departure for factory design and equipment purchase and installation programs.

A second, and equally important, by-product of the operation of the cable laboratory was the opportunity for appraisal of preliminary specifications for the several materials used in cable fabrication and a study of the changes wrought in material properties due to processing. Initial operation of the laboratory was accomplished through use of standard materials, with only minor emphasis on the level and dispersion of the critical material parameters. As cable samples were produced with more finesse and more meaningful experience, more attention was paid to the procurement of material and to the properties of that material before and after processing. Toward the end of the operation, the laboratory materials were purchased under tentative issues of material specifications. Through comparison of the data obtained from the basic raw material, from cable produced from this material, and from the basic computational analysis of cable parameters, it was possible to assess changes that occur to the material in process and to improve upon the predicted cable characteristics for matching to the amplifier and equalizer designs.

The overriding requirement for successful operation of an ocean cable system is continuous, uninterrupted life. Experience in the cable laboratory demonstrated that cable making machinery must be of such quality and stability that continuous operation can be achieved in the production of a 20-nm length of cable (a repeater section) to assure that the structure will be strong and stable and without discontinuities. Obviously this implies the use of quite massive machinery throughout and very precise coordinated drive systems for the several pieces of powered equipment in each of the production lines. In addition, the usual methods of product inspection, such as quality control involving sampling for attribute averages, cannot be used. Instead, measurement of each of the critical parameters in cable processing must be done on a continuous basis, and the results obtained must be put into a continuous permanent record. In many cases a strip chart recorder is used.

The Baltimore plant of the Western Electric Company* was selected for production of armorless cable in March, 1961, and factory planning began immediately. Ground was broken for plant construction in August, 1961, and the first cable footage was made in April, 1962. Manufacturing capacity is 5000 nm per year.

The factory building is a windowless, steel-sheathed structure with building columns and heavy machine loads set over approximately 1000 piles. The 170,000 square feet of floor space comprises four basic areas. Inner conductor, dielectric, and jacket operations are all done in an atmosphere of filtered air maintained at a slight positive pressure, and the concrete floor is non-dusting. The temperature-controlled room for dielectric sizing and repair and outer conductor application is maintained at 72°F and at a dust count level of less than 6000 parts per million. The floor is tiled. The terminating and test rooms are temperature and humidity controlled, the floor is tiled and the walls are vinyl coated. The finished cable storage area is arranged for the stacking of pans four high with a floor load under each stack of 256 tons, and has minimal light and heat requirements.

An access channel has been dredged in the waterway adjacent to the plant to a depth of 34 feet, sufficient to accommodate any existing fully loaded cable ship.

The cable factory and loading facilities are shown in Fig. 1, along with C. S. *Long Lines.*

## II. RAW MATERIAL PROCUREMENT AND INSPECTION CONTROL

There are five materials used in the structure of the armorless cable. They are:

(1) steel wire
(2) inner conductor copper strip
(3) polyethylene dielectric
(4) outer conductor copper strip
(5) ethylene plastic jacket.

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* Cable to the same specification, though not necessarily by an identical process, has also been made by Standard Telephones and Cables, Ltd., Southampton, Hampshire, England, and by Ocean Cable Co., Ltd., Yokahama, Japan.

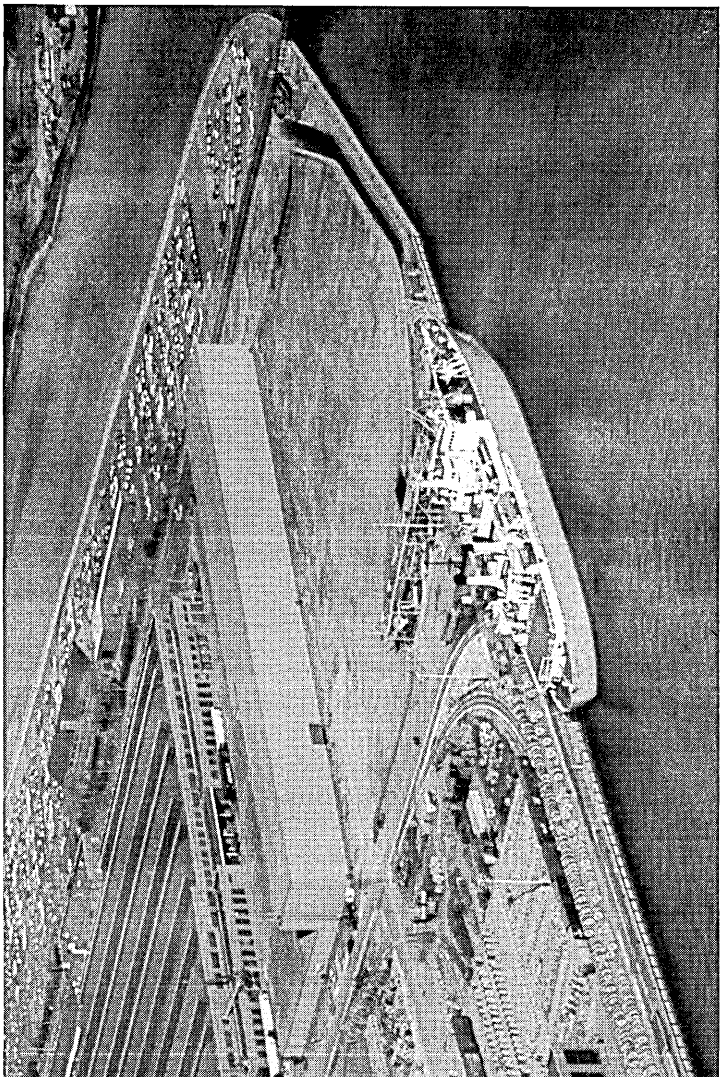

Fig. 1 — Cable factory and loading facilities, with C.S. *Long Lines*.

### 2.1 *Steel Wire*

The strength member of the cable consists of forty-one high tensile strength, medium to high carbon steel wires of five different diameters, 0.069 inch, 0.047 inch, 0.041 inch, 0.039 inch, and 0.030 inch, each having a tolerance of $\pm 0.0005$ inch. The tensile strength tolerance for the 0.069 inch wire is 280,000 psi to 320,000 psi; for the other sizes it is 290,000 psi to 330,000 psi. The supplier conducts 100 per cent inspection for wire diameter and tensile strength. After the wire is received at the cable factory, Western Electric inspectors randomly select and check twenty samples for diameter and ten samples for tensile strength from normal lots of fifty reels.

To achieve a firm, well fitting pattern of strand wires, it is necessary not only to hold tight tolerances on individual wires, but also to specify that the diameters of a lot be uniformly distributed about the nominal diameter. Fig. 2, showing the effect of die wear on a 0.069-inch wire, illustrates that a 4000-pound lot would have diameters individually within tolerance limits, but with an average diameter appreciably greater than nominal. This is not tolerable and accordingly it was specified that, in any given lot inspected, the diameters of twenty randomly selected samples had to meet the following additional tolerance:

$$x = \frac{\sum_{1}^{20} (d_x)}{20} = d \pm 0.0001$$

where $d$ = nominal wire diameter and
$d_x$ = measured diameter.

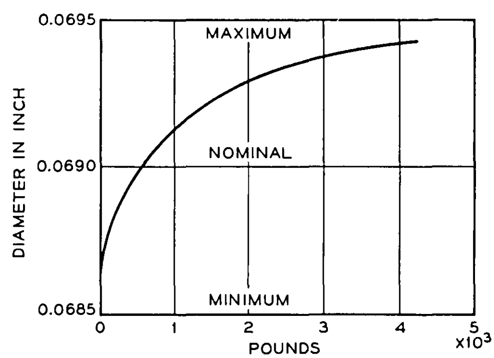


Fig. 2 — Wire diameter changes due to die wear.

It is not necessary to make a similar type of analysis for tensile strength. If all measured samples fall within the tensile strength tolerances, the lot is acceptable.

### 2.2 *Inner Conductor Copper Strip*

This material is rolled from oxygen-free copper cake having a conductivity of 101.4 per cent ± 0.3 per cent I.A.C.S., measured on a 0.0808-inch wire drawn from the cake at the copper refinery. The width and thickness dimensions on finished strip are 1.600 inches ± 0.005 inch and 0.023 inch ± 0.0003 inch, respectively. In order to assure that the finished lot of material is uniformly distributed about the nominal dimension, a sample size of twenty is selected, and charts of grand averages and deviations from the nominal are generated. The grand average is computed from the following formula:

$$\bar{x} = \frac{\sum_{1}^{20} (x)}{20}$$

where $\bar{x}$ = grand average and $x$ = measured dimensions.
The deviation from the nominal is then computed as follows:

$$\sigma = \left[\frac{1}{19} \sum_{1}^{20} (x - \bar{x})^2\right]^{\frac{1}{2}}.$$

Typical charts are shown in Fig. 3.

### 2.3 *Polyethylene Dielectric*

Polyethylene is delivered to the factory in 100,000-pound capacity hopper cars to minimize the number of times the material is exposed to contamination. A representative sample of material is obtained as the hopper car is being loaded at the supplier's plant. This sample is molded into sheets and extruded into tapes for inspection of electrical, mechanical, chemical and cleanliness properties. The most stringent inspections are for dielectric constant, dissipation factor and contamination. Failure to meet any one of the requirements is cause for rejection of the entire hopper car section.

### 2.4 *Outer Conductor Copper Strip*

This material is electrolytic tough-pitch copper having a conductivity of 101.2 per cent ± 0.3 per cent I.A.C.S., determined by conductivity tests at the copper refinery. The width and thickness requirements on processed strip are 3.430 inches ± 0.005 inch and 0.010 inch ± 0.0002 inch, respectively. Deviation charts similar to those in Fig. 3 are designed around these dimensions.

### 2.5 *Ethylene Plastic Jacket*

The jacket material is also received in the factory in 100,000-pound capacity hopper cars. It does not have to meet the same electrical and cleanliness requirements as the polyethylene insulation. However, quite stringent requirements are placed on the material physical properties to assure that it will do an adequate job of protecting the cable outer conductor under conditions of environmental stress.

## III. CABLE FABRICATION AND STORAGE

Fabrication of ocean cable for SD system use is a four-step process. First, and most difficult, is fabrication of the inner conductor. This is

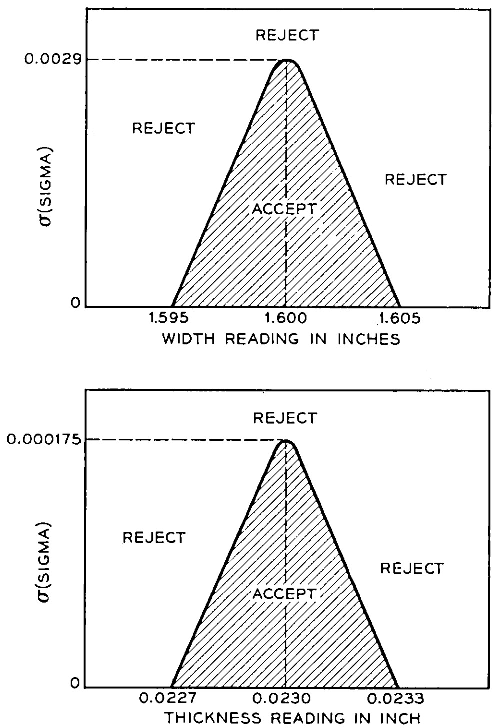


Fig. 3 — Copper strip quality control — acceptance ranges for width and thickness variations.

followed by the extrusion of polyethylene dielectric. As it is not possible in the present state of the art to control dielectric diameter variations to the very small tolerance dictated by transmission requirements, it is necessary to follow extrusion with a core sizing operation. At this point it is possible also to improve upon the as-extruded core concentricity, if necessary. The fourth and final operation in cable fabrication is the tandem application of outer conductor and jacket. In some sections a fifth operation, dielectric repair, is necessary.

Completed sections of cable are used in groups approximately 200 nm in length, called "ocean blocks." As each section made varies slightly from the nominal design characteristic of attenuation, it was concluded that more uniform blocks could be assembled if sections were selected from the total lot available rather than taken in order of manufacture. For this reason, each completed section is taken up and stored in an individual pan capable of holding 20 nm of cable with both ends accessible. Any cable ship loading sequence can therefore be specified and followed.

### 3.1 *Formation of Inner Conductor*

The inner conductor (see Fig. 4) is a composite copper-jacketed steel wire rope. The process by which it is made is shown diagrammatically in Fig. 5. Steel wire is purchased in nominal lengths of 124,000 feet wound on the bobbins used in the tubular strander. Wire is drawn from the 41 bobbins in the strander and formed into the strand pattern in a

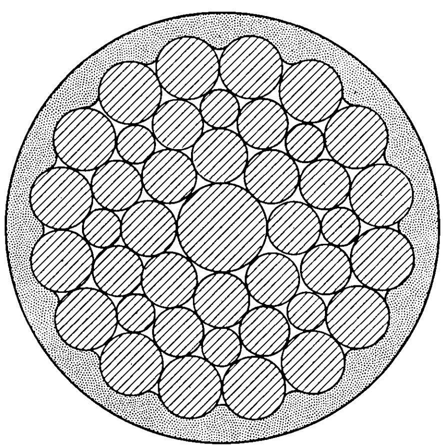

Fig. 4 — Cross section of finished conductor.

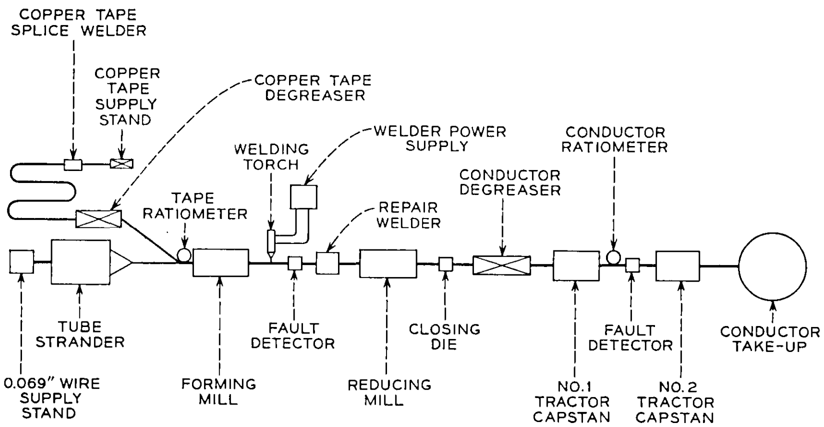


Fig. 5 — Inner conductor line.

special strander closing die. In a parallel operation, a strip of oxygen-free copper 1.6 inches wide by 0.023 inch thick is fed from the pay-off stand into an accumulator, then to a vapor degreaser, and then into a conventional tube forming mill in which certain rolls are grooved to straddle the strand. The edges of the copper strip are sheared to 1.533 inches to form a tube of precise diameter with clean abutting edges for welding. The strip is then formed around the steel strand and positioned so that the strand rests in the bottom of the tube, as shown in Fig. 6, to keep the steel strand remote from the heat of the welding arc and so prevent degradation of its tensile properties.

The butted edges of the formed copper tube are welded in a continuous seam, using tungsten inert gas arc welding techniques. The welded tube is then reduced in successive steps with reducing rolls until the inner diameter is a close fit over the steel wire strand. The copper tube and steel strand are then drawn through a die. This results in a tightly compacted structure with close control on conductor diameter and with copper forced into the interstitial strand spaces. This assures that the inner conductor will be structurally firm under the forces of ocean-bottom pressures. The operation of the copper die is as much an extrusion operation as a drawing operation because of the pressures involved in forcing copper into the interstices.

The copper exerts a tight grip on the steel strand, and it is therefore necessary that the strand be formed with essentially no differences in the lengths or tightness of the 41 wires. Bobbins of steel wire are selected prior to loading the machine with wire sizes that minimize the

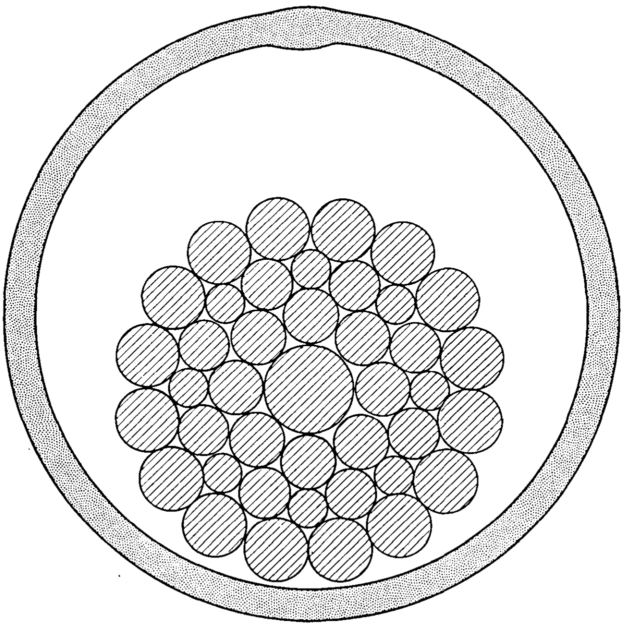

Fig. 6 — Steel strand and welded tube.

strand diameter deviation from nominal. These bobbins are then positioned in the strander to make a most nearly round and compact strand. Steel wire size and position control, along with a special strand closing die, assures that the strand, as it is formed, will have no incremental differences in length in the several wires that would subsequently be squeezed back at the copper closing die position. The special die is shown in Fig. 7.

Alternative methods of tube welding had been tried in the laboratory, but tungsten inert gas welding was shown to be superior at that time. Four items need to be controlled to have a long-life welding operation:

(1) The inert shielding gas supply must be very pure and dry and be uninterrupted. Gas impurity affects the tungsten electrode, promoting excessive erosion and the formation of "whiskers" on the electrode tip.

(2) The surfaces of the copper strip must be free from deposits of oil, water or other contaminants, as the volatilization of these materials results in contamination of the emitting electrode tip and increases the level of porosity in the welded seam.

(3) The butting edges of the tube must be freshly slit, level and parallel, and under a slight amount of positive pressure when passing

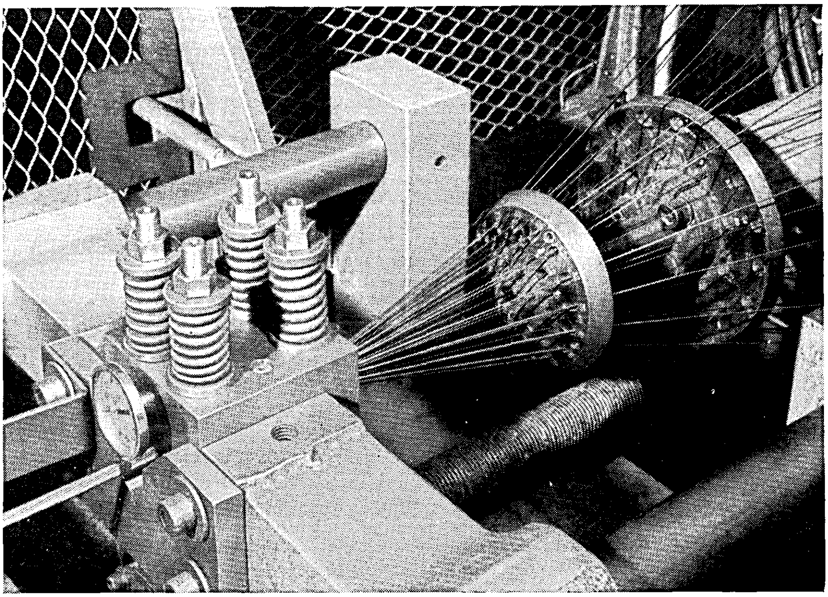

Fig. 7 — Strander point and closing die.

under the welding arc. To maintain seam alignment, the tube must be in slight tension in the welding rolls and the tube forming and reducing rolls must be in precise alignment to eliminate tendencies to roll the tube.

(4) The welder power supply must have ample capacity for 100 per cent duty and control must be precise to track tube speed with weld current. It must be stable over long periods of operation and be capable of repeating current values at particular settings corresponding to particular line speeds.

Successful operation for long periods of time is partly a matter of tube forming and seam alignment and partly a function of precise control of weld current, electrode position, and electrode tip configuration. By selecting a mixture of helium and argon gases, a maximum weld penetration-to-width ratio with minimum electrode tip erosion is obtained, making possible welding runs of from 60,000 to 124,000 feet, depending upon the purity of the shielding gases. With careful attention to the tube forming process and with automatic arc length control and precise speed relationship of all the machines in the system, the welding operation need be interrupted only when defects in the copper strip occur or a steel wire breaks.

Experimentation has shown that in a sufficiently clean shielding gas atmosphere and with a sufficiently clean metal, variation in the composition of the electrode has little effect on electrode life. Electrodes are normally made of sintered tungsten with 1 or 2 per cent of thorium added. The 2 per cent thorium content electrodes do not last as long as those of 1 per cent, but their characteristics enable an arc to be more easily established.

Oxygen-free copper was selected early in the development program as the material to be used in the inner conductor. The principal reason for its selection is that in the oxygen-free condition there are no oxide or gas pockets formed under the heat of the welding torch to weaken the tube structure. Additionally, oxygen-free coppers can be obtained with high levels of ductility and conductivity. These are important, as there is an appreciable amount of work hardening of the copper during the reduction and die drawing operations.

Inner conductor copper is purchased in coils of strip as large as possible, weighing approximately 350 pounds per coil. The transition from coil to coil is made without stopping the line by storing approximately 400 feet of strip in the accumulator, thereby providing sufficient time to substitute a new coil for the exhausted one. The copper strip is spliced by joining ends which are sheared at an angle of 20° from the transverse, overlapped $\frac{1}{32}$ inch, and welded with a tungsten inert gas arc. The weld penetrates through both sections, fusing them together and leaving a rounded section somewhat thicker than the original strip. As this section will not form properly, nor pass through the reducing die, the weld is peened to uniform thickness. The peened section is then annealed to recrystallize the grain structure. This operation produces a joint very much like the original strip in dimensions and metallurgy.

Both of the welding operations in the inner conductor line — i.e., tube welding and coil-to-coil welding — are in some respects self-checking processes. The reducing and die-sinking operations will, in most cases, rupture the copper tube either longitudinally or circumferentially if the weld is not of the proper size or density. In order to assure complete success in these operations, certain qualifications of operators and equipment are necessary. Periodic checks of coil-to-coil welds are made with selected samples that are subjected to tensile and elongation tests. Checks are made of the tube welding process at the beginning and end of each manufactured length. These involve samples of unreduced tube that are subjected to a flare test using a 60° included angle steel cone. Properly welded tube will take elongations of 35 per cent.

It is necessary that the copper jacket of the inner conductor be continuous and fault-free throughout its length to assure isolation of the polyethylene dielectric from the steel strand. Consequently no holes, slits, or unwelded seam portions are allowed in the copper jacket. By arrangement of the equipment in the inner conductor line, space has been provided, between the tube welding area and the first pass of the reducing mill, in which partially welded or unwelded tube can be rewelded while the line is moving. If a hole or a slit not on the welded seam occurs, the line must be stopped after the fault has passed through the die and a strip of 0.005-inch copper brazed over the fault under controlled conditions. The repair, smoothed and polished, will withstand polyethylene extrusion temperatures and subsequent bending stresses.

A testing device, shown schematically in Fig. 8, was developed at Bell Laboratories to detect faults in the welded tube. A pair of coils surrounding the tube are mounted approximately 2 inches apart. These coils form two sides of a very sensitive bridge circuit. In effect, the welded copper tube is a shorted secondary winding to each of these coils, and changes in the tube unbalance the bridge circuit. By phase comparison

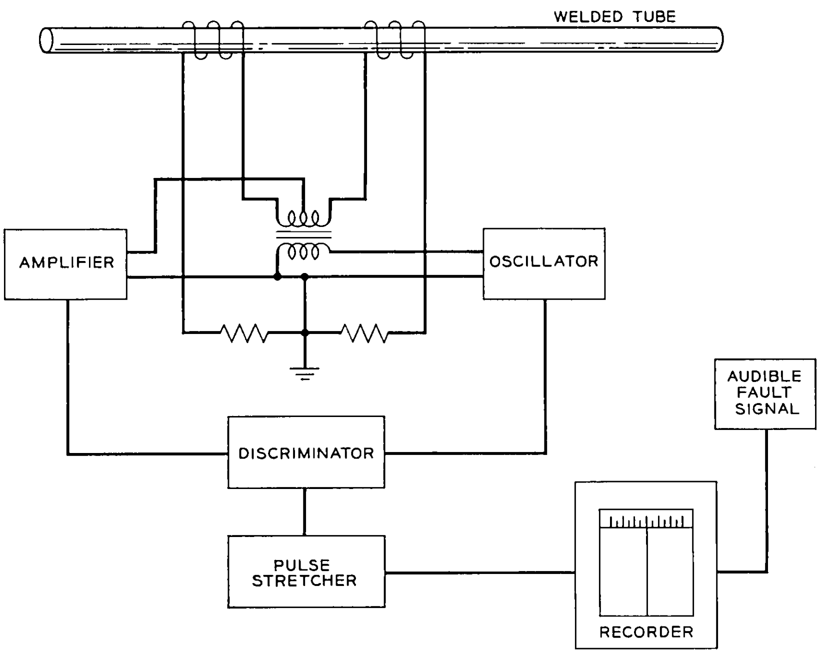


Fig. 8 — Weld integrity test set.

of the input and output bridge signals, it is possible to ignore changes in copper conductivity, wall thickness and tube surface smoothness and to detect faults in the tube. This allows the operator of the inner conductor line to survey over-all operations without paying constant attention to the weld seam, and thereby reduces operator fatigue while certifying the soundness of the welded tube.

The copper strip, formed in an oversized tube, can be formed most readily and handled safely in the reduction process if the tube wall is approximately 0.023 inch thick prior to reduction. It is apparent then that the cross-sectional area of the tube prior to reduction is appreciably greater than that required in the finished conductor, and that the relative speeds of the steel strand and the copper are not equal until they join at the copper sinking die. This difference in speed is used to determine the effective wall thickness of the copper in the finished product. The ratio of the speeds of the two elements is determined by monitoring the copper strip and the finished conductor with two photo tachometers. The differential count on the strip tachometer is compared to a thousand counts supplied by the conductor tachometer and is "read-out" on a decade counter display. The system resets itself and repeats periodically. The ratio is varied as the conductor diameter and tape thickness vary to maintain the required effective wall thickness.

### 3.2 *Extrusion of Dielectric*

Extrusion of the polyethylene dielectric material on SD system cable is much more difficult than conventional insulation or wire jacketing processes in that the ratio of extrudate wall thickness to conductor diameter is appreciably greater. The cable dielectric must remain for a long period of time with a constant potential gradient applied, and voids in the material might initiate corona discharges that would introduce noise into the system. The prevention of voids in the polyethylene is achieved through careful control of the heat extracted from the material as a function of time. The outer fibers of the material must not be allowed to solidify in too great a depth while they are at too large a diameter and while the inner fibers are still in a plastic state. If this occurs, the dimensional contraction of the material upon cooling must extend radially outward and, hence, pull the dielectric away from the conductor in the center. The rate then which can be approached, but not surpassed, is one in which the dielectric heat is extracted radially outward such that the entire mass approaches the crystalline phase state with small temperature differential between the inner and outer layers.

In order to extract heat from the dielectric at a maximum safe rate and thereby achieve high production speed, a trough system with graduated water temperatures is used. In essence, the hot extrudate is run first into water close to the boiling point. It is kept in this medium until the average temperature of the material and the temperature differential between inner and outer surfaces has fallen to a point where the rate is somewhat lower than optimum. The material is then passed into a trough with a water temperature cooler than the first trough. The temperature difference between the first and second troughs is obviously a function of the state of the extrudate at the time of transition, and can be greater if the extrudate has approached the water temperature in the first trough. This scheme of successive changes in cooling rate can be repeated any number of times until the entire mass of polyethylene material passes through the crystalline phase change. From this point onward, the material is solid; it changes dimension as a unit mass and may therefore be led into cold water so that it may be handled around sheaves without damage. A schematic layout of the dielectric extrusion line is shown in Fig. 9.

The polyethylene used as the dielectric is an electrical-grade material with a very low (0.3 maximum) melt flow index and is characterized by a very narrow spread of dielectric properties and by extreme purity. As the end product desired is a transmission line whose electrical properties are essentially invariant throughout its entire length, and as the raw material dielectric properties are ever so slightly altered by the extrusion process, it is necessary that variations in extrusion conditions be minimized through control of the entire extrusion and cooling process. This is accomplished partly by the design of the extruder and the extruder screw and partly through automatic control of temperatures in each of the extruder zones, in the extruder die and in each of the trough zones. Typical temperature changes in the troughs, for instance, are $\pm 3°F$.

Control of the extrudate dielectric properties is also maintained by rigorous attention to possible sources of material contamination. The resin, as produced by the polyethylene supplier, is kept within a closed system from the time of packaging until it is extruded on the inner conductor. It is shipped from the supplier's plant in nominal 100,000-pound quantities in railroad hopper cars. These cars discharge into outlets at the bottom of each of the three car sections. Compressed filtered air is used to blow the material from the hopper car to an in-building storage bin and from the bin to the extruder hopper. The duct system is aluminum throughout. Classifiers and separators are located in the pipelines just above the extruder hoppers to remove

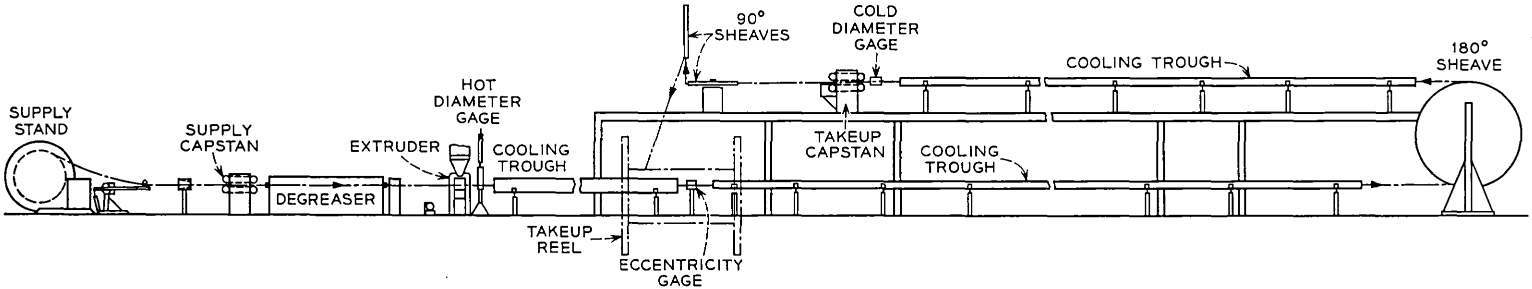


Fig. 9 — Elevation of ocean cable dielectric line.

smaller than normal polyethylene granules and dust (called fines) generated during conveying.

The sizing operation that follows extrusion is somewhat sensitive to changes in the depth of material to be removed and is therefore more accurate if tight control is held on the as-extruded diameter. The hot material is measured between the extruder die and the input to the first trough section by a gauge having a swept light beam that travels across the extrudate. Indications from this gauge permit the operator to make corrections in core size by manually adjusting the extruder screw speed.

It is essential also that the dielectric be extruded as concentrically as possible. Concentricity is normally maintained within 0.007 inch and cannot exceed 0.020 inch without jeopardizing the sizing operation. Eccentricity is minimized in the extrusion process by manually adjusting the relative positions of the extruder tooling according to information received from an eccentricity gauge. This gauge, operating on the principle of capacitance unbalance as measured between the grounded inner conductor and pairs of electrodes contacting the dielectric, is placed between the first and second trough zones, where the material has solidified sufficiently to allow a slight pressure on the surface. Adjustments to improve concentricity are not required very often, as the drive systems coordinating the several elements of the line will remain constant for long periods.

### 3.3 *Dielectric Repair*

Among the several ways in which the extrudate may be damaged while in a heated, softened condition are line stoppage due to power failure and machinery malfunction. The most common type of damage is caused by imperfections in the inner conductor resulting from an imperfect weld or poorly rolled copper strip. As the inner conductor passes through the heated zone of the extruder head, air and other gases within the conductor expand. Gas escaping from any hole in the copper will swell the extrudate and form a permanent void pocket next to the conductor.

The principal mechanism for the detection of voids is the eccentricity gauge on the extrusion line, although the occurrence of most voids can be predicted by continuous surveillance of the inner conductor during production, both visually and with the conductor integrity tester. Voids that occur are repaired in an operation subsequent to core extrusion, at which time the inner conductor fault is also repaired.

Soldered sleeves, to provide a gas-tight seal over small copper cracks, are made by first tinning both the inner conductor and a presized 0.012-

inch thick copper sheet. The sheet is tightly formed around the inner conductor, with nearly butting edges, and heat is applied to fuse the bond. The applied temperature is held under 450°F to prevent annealing of the steel strand wires.

Copper-plated steel sleeves are inserted at points where the strand may have been damaged or where more than 2.0 inches of missing copper is encountered. They are approximately 6 inches long, with a 0.750-inch outer diameter before crimping. As such repairs are potential weak points in the cable strength member and are also undesirable from a signal echo standpoint, no more than two splice sleeves are permitted within any 20 nm length of cable. No splice sleeve is permitted within 3 nm of either end, and splices may be no closer together than 1.5 nm. Fig. 10 shows the sleeve application and steps in dielectric repair.

In order to transfer the full strength of the steel through the splice with a sleeve of reasonable length, it is necessary to prepare the strand wire ends so that each of the strand wires will contribute to tensile strength within the sleeve area. The bonding agent used to hold all of the strand wires together as a unit is an epoxy that is cured at a temperature of approximately 385°F. The strand wires are parted,

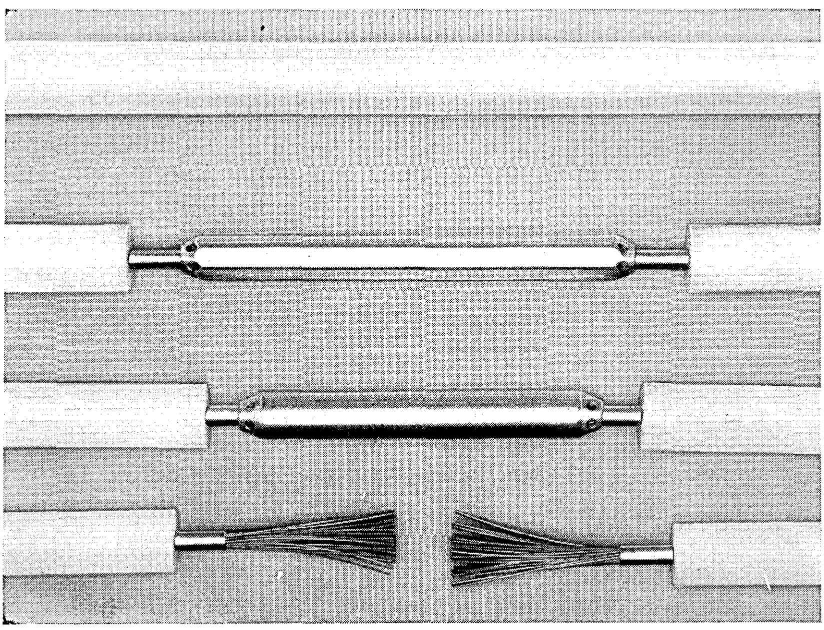

Fig. 10 — Steps in repair of inner conductor, and dielectric remolding.

cleaned in an ultrasonic bath of trichloroethylene, coated with epoxy and then re-laid in pattern. The two prepared strand ends are inserted into the sleeve and the sleeve is pressed with dies, hexagonal in shape, that produce a finished sleeve approximately 0.640 inch across the flat faces. The elongation of the sleeve after pressing is sufficient to capture the inner conductor copper at the ends. A heat fixture is used to cure the enclosed epoxy.

Restoration of the dielectric is done with an extrusion molding technique. A $1\frac{1}{4}$-inch vertical extruder, crosshead and die are used to convey a homogeneous melt of compound into the die cavity. Extruder barrel, head, and die inner and outer zone heats are individually temperature controlled. The crosshead is fitted with a bleeder plug so that compound can be continuously purged, thereby preventing oxidation of compound within the extruder barrel. Water-cooled dies up to 30 inches long for 15-inch repairs are used. After molding, the flash and sprues are trimmed, and the joint is X-rayed to check for unacceptable inclusions, voids, and eccentricity.

### 3.4 *Dielectric Sizing*

It is possible, through close attention to the extrusion process, to maintain a diameter variation about the nominal of approximately $\pm 0.005$ inch. Such variation would be intolerable in this design, as the effects on attenuation of positive and negative diameter excursions are not self-cancelling, and it would therefore be impossible to achieve the computed cable characteristics. For this reason, it is necessary to put the extruded dielectric through a supplementary sizing operation.

The machine used, shown in Fig. 11, works like an oversized pencil sharpener. The polyethylene is cut with three tool steel cutter blades arranged symmetrically on a rotating head. Finished diameter is measured with a diameter gauge, and the measured diameter is displayed on a strip chart recorder. The sensitivity of the gauge is such that $\pm 0.0001$ inch can easily be read; adjustments in diameter, when necessary, are made manually. The concentricity of the dielectric surrounding the inner conductor is also monitored, as shown in Fig. 12. Measurements are made of capacitance unbalance between two pairs of electrodes and the inner conductor. The electrode pairs, acting independently, are arranged in horizontal and vertical planes. The capacitance information is fed into amplifying and recording circuitry, where the unbalance is displayed on two pens on a strip chart recorder and is also fed into a two-channel servomechanism system. The servo signals actuate motors that cause

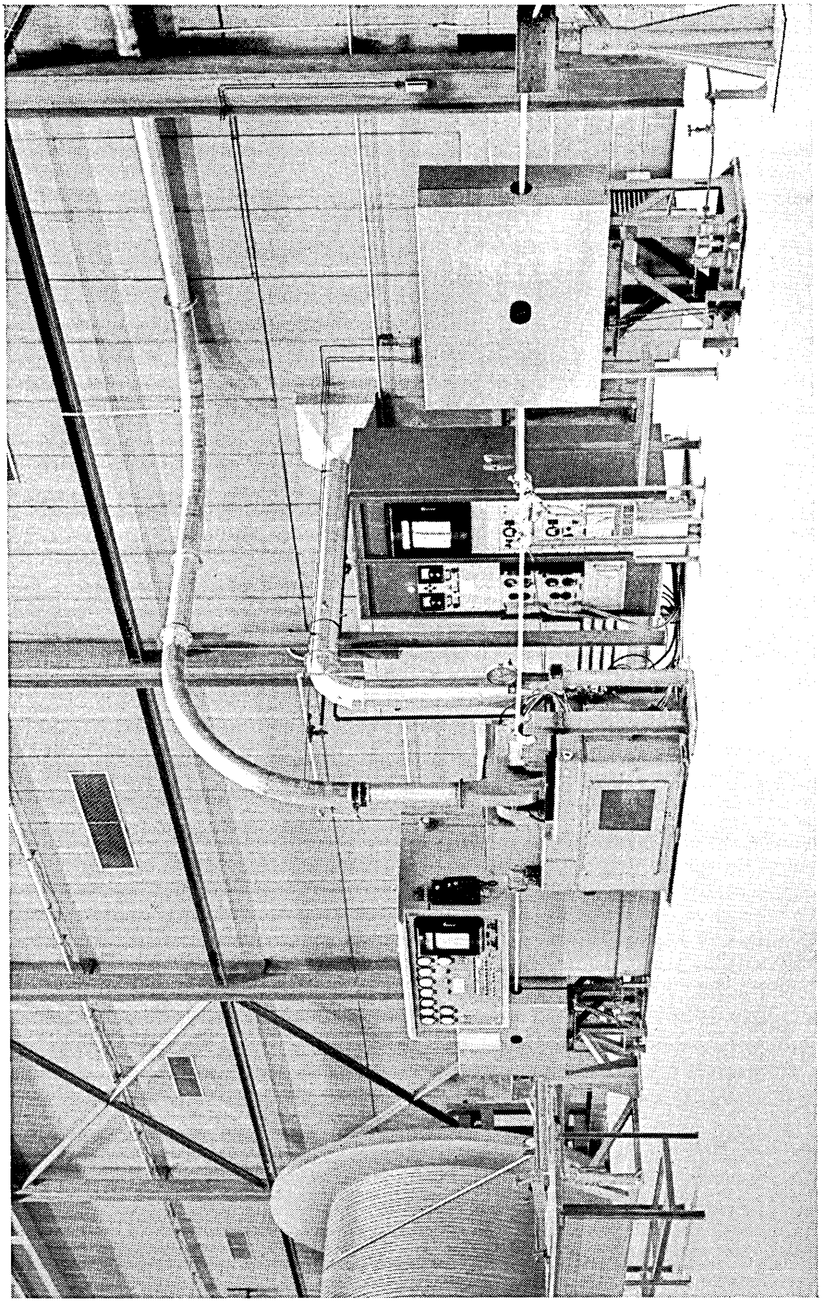

Fig. 11 — Dielectric sizing machine.

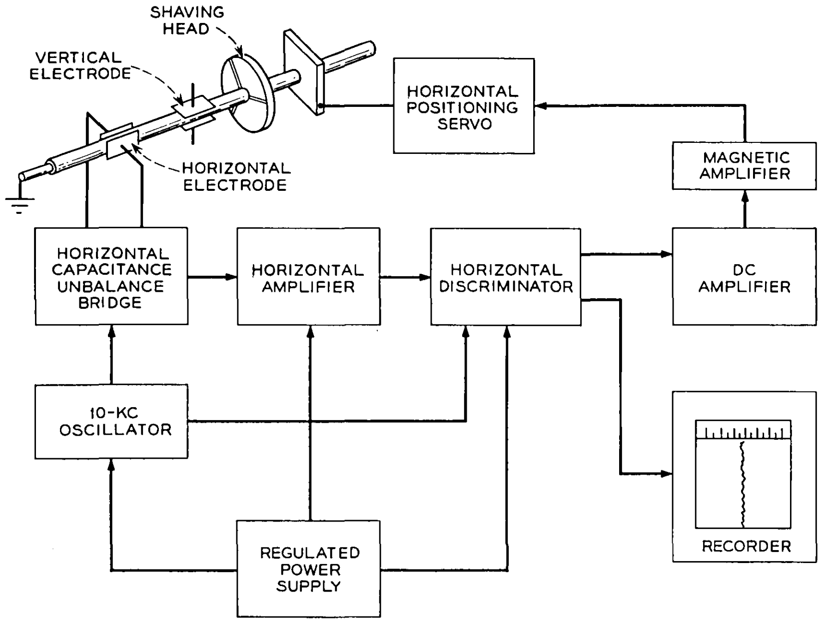


Fig. 12 — Shaver eccentricity control system — horizontal half.

the movement of pairs of positioning fingers bearing on the unsized material. The servo systems are zero-seeking devices and as such are insensitive to diameter variations.

The nominal diameter of the as-extruded dielectric is 1.050 inch. Experience has shown this to be the optimum depth of cut for the machine used. This also allows corrections in eccentricity up to 0.025 inch to be made without departing from a circular cross section.

### 3.5 *Application of Outer Conductor*

The outer conductor structure is ideal electrically. It is of high-conductivity material, is cylindrical in shape, and has an overlap in the longitudinal seam to reduce signal radiation to a tolerable order of magnitude. Mechanically, the outer conductor requires special treatment both in fabrication and in subsequent cable handling. It is not possible to apply the outer conductor and store the completed coaxial before jacketing, as the outer conductor would be wrinkled. Consequently, outer conductor forming and cable jacketing are done in a straight line, uninterrupted, tandem operation.

Outer conductor copper is purchased in coils weighing approximately 430 pounds. Coils of copper are added to the system as required, with an overlap braze connection between coil ends. The braze is made at an angle of 65 to 70 degrees with respect to the strip edge to distribute the double thickness of copper axially along the cable after forming. Forming is done in a special pull-through forming machine that applies the conductor strip with minimal stretch. The path of the strip and the sized core through the mill is not horizontal but follows a parabolic curve having the general formula $y = kx^a$, as shown in Fig. 13. This is done in an attempt to cause the center elements and edge elements of the strip to travel equal distances between the point at which the strip is first bent and the point where forming is completed.

A peculiarity of the forming process is inserted in the last set of tooling in the machine. The top sector of the roll, that portion which embraces the overlapped joint, is cut to provide a nonsymmetrical amount of relief to the overlapped edge as shown in Fig. 14. The heat and pressure of the jacket extrusion process are transmitted through the copper conductor, causing the underlapped edge to be pressed into the heat-softened dielectric. The amount and position of the indentation of the underlapped edge are controlled by the roll to minimize any tendency to produce an air gap in the structure.

Outer conductor forming and jacket extrusion are shown in Fig. 15.

### 3.6 *Extrusion of Jacket*

The jacket material is a high-density ethylene plastic requiring higher extrusion temperatures than those used with the dielectric material. The presence of carbon black in the material makes necessary the use of a hopper dryer system. This is because the material is highly hygroscopic

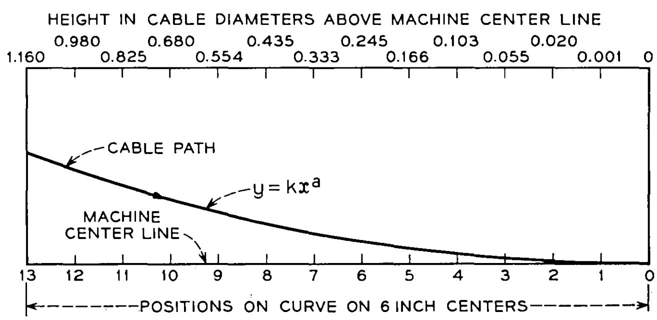


Fig. 13 — Path of cable through forming mill.

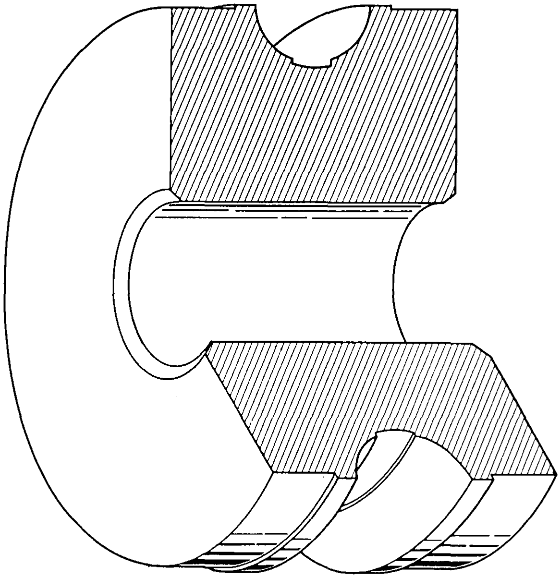

Fig. 14 — Last-pass forming roll.

and water in concentrations greater than 0.04 per cent weakens the extruded material to a degree sufficient to prevent the necessary outer conductor protection.

Relaxation times of the jacket extrudate are appreciably longer than those for the dielectric material. They typically run several minutes at the crystalline melt temperature, as compared to less than a second for the dielectric. It is not possible, therefore, to apply the jacket in the relaxed state typified by low measures of material retraction. It is possible, however, to achieve shrink-back levels sufficiently low to assure a service life expectancy in excess of 40 years.

The completed cable structure is shown in Fig. 1 of Ref. 2.

## IV. ELECTRICAL TESTING

As the cable is jacketed in 20-nm lengths, it is coiled into a storage pan and subsequently immersed in a test tank of circulating water held at 10°C ± 0.2°C. About twenty-four to thirty hours in the water tank is required for the cable to reach temperature equilibrium. Fig. 16 shows the test tank with pans of cable in place.

The two ends of the cable to be tested are brought out of the tank

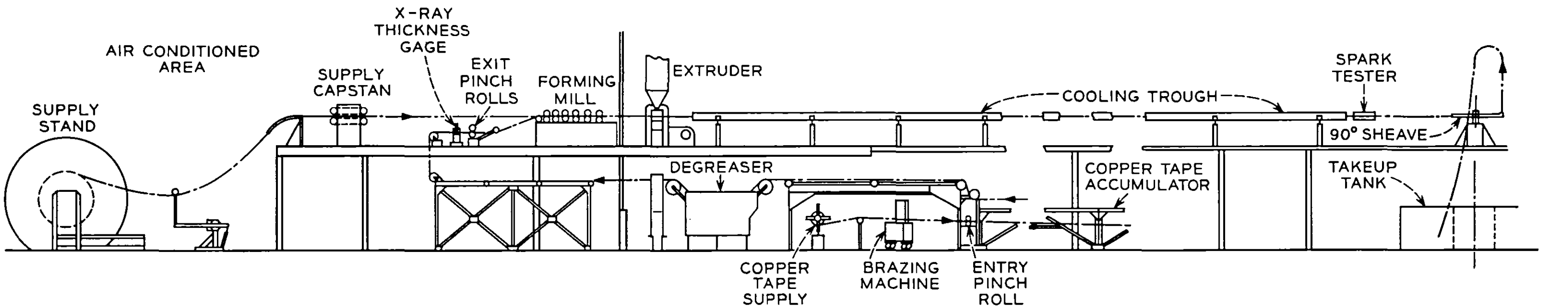


Fig. 15 — Elevation of outer conductor forming and jacketing line.

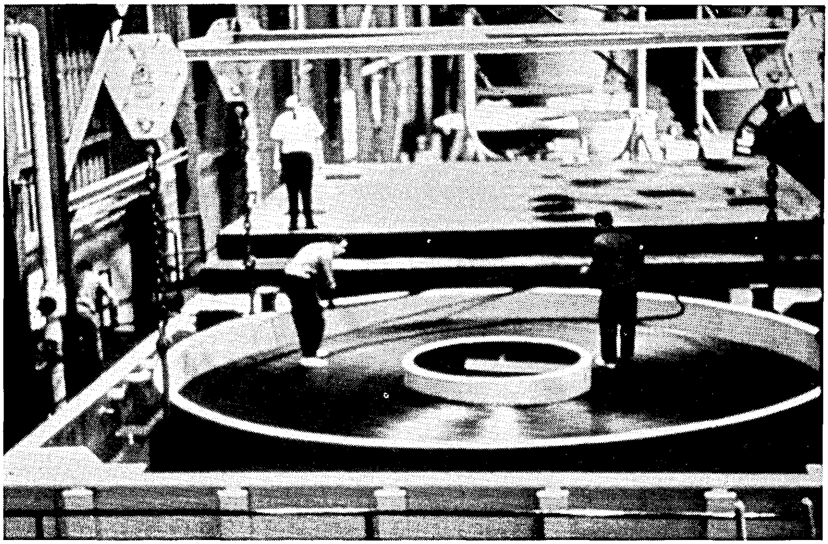

Fig. 16 — Test tank.

and into the test room (See Fig. 17) through an access port. In the test room, temperature is maintained at 73°F and humidity at 55 per cent. The measurements made here include inner and outer conductor dc resistance, insulation resistance, dielectric high-voltage breakdown, pulse echo, delay, low-frequency capacitance and attenuation.

Conductor resistance readings are made using a Wheatstone bridge of 0.01 per cent accuracy. Measurements are made initially of the inner conductor to determine when the cable temperature has stabilized. After three consecutive readings of the same values are obtained at one-half hour intervals, temperatures are considered stabilized and the outer conductor resistance is measured and recorded.

Insulation resistances of both the dielectric and jacket are obtained at 500 volts using a megohm bridge. Minimum insulation resistance requirements are 100,000 megohm-miles for the dielectric and 15,000 megohm-miles for the jacket.

Breakdown tests are made at a potential of 35,000 volts dc between the inner and outer conductors. Both positive and negative potentials are applied at both ends of the cable for periods of one minute each.

The pulse echo test set, shown schematically in Fig. 18, is used to determine the magnitude of reflected signals due to impedance mismatches within the cable. The magnitude of the reflected signals is

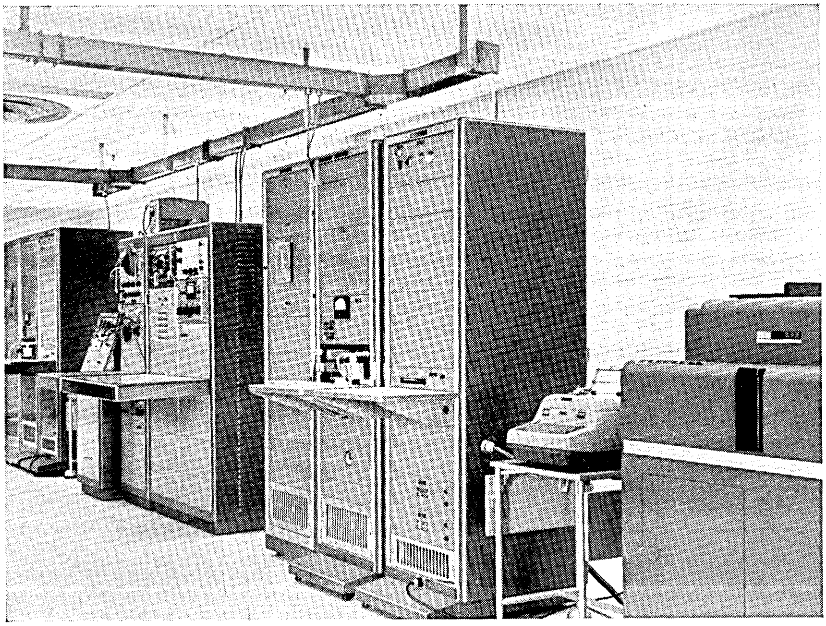

Fig. 17 — Test room.

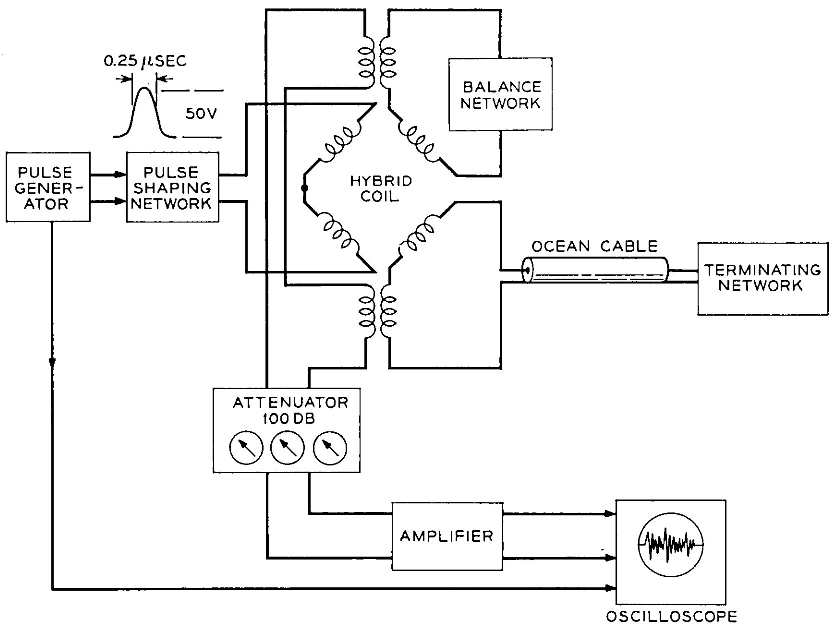


Fig. 18 — Pulse echo set.

measured in db below the test pulse, and is referred to the point of incidence. A 0.25-microsecond raised cosine pulse is used, and the reflected pulses or echoes are required to be 55 db or more below the incident pulse. Tests are made from each end of the cable to a point 13 nm in from the end. Echo magnitudes are corrected for the distance from the end, and photographic records are made of the patterns obtained from each cable. The accuracy of the echo test set is ±1 db.

The delay test set measures the delay encountered by a 1-mc signal traveling through a 20-nm cable section. The set uses an extremely accurate oscillator with a short-term stability of ±1 cps at 1 mc, a narrow-band receiver, and an electronic frequency counter, as shown in Fig. 19.

Capacitance measurements are made at a frequency of 21 ± 1 cps to avoid errors which result from standing wave and resonance effects that occur if the wavelength of the signal is not long with respect to the cable length. This frequency also avoids subharmonics of the 60-cps power line frequency, but is high enough to be insensitive to dielectric absorption effects. Cable capacitance is measured to an accuracy of ±0.1 per cent.

The most important electrical test is the cable attenuation measurement. This test is made using an autobalance transmission measuring set, designed by Bell Telephone Laboratories and built by Western Electric at Kearny, New Jersey. A block diagram of the set is shown in Fig. 20. It measures the attenuation of a 20-nm cable length as a

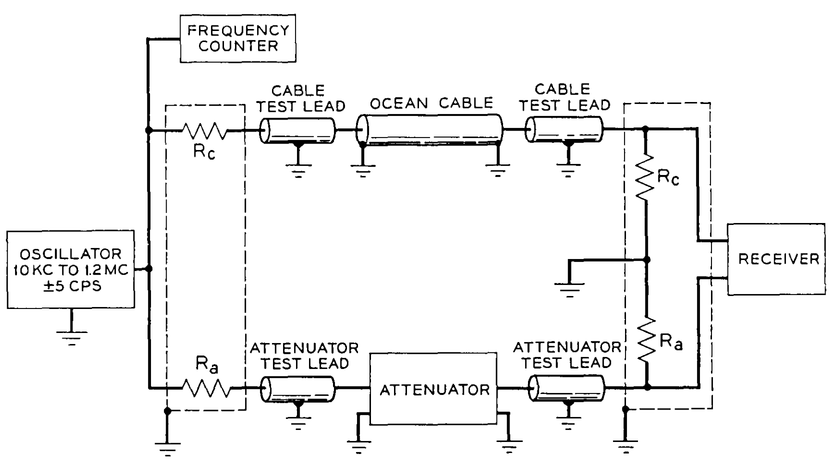


Fig. 19 — Delay set.

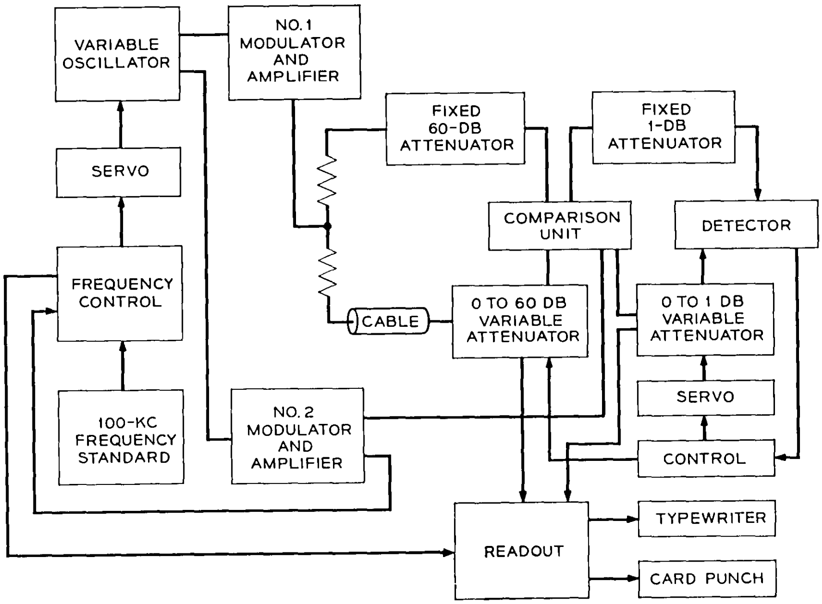


Fig. 20 — Auto-balance attenuation test set.

function of frequency with an accuracy of ±0.4 per cent over the frequency range from 50 kc to 1200 kc, in increments of 50 kc ± 25 cps. The set is automatic, with servo-driven frequency control of the signal source and self-balance of the loss measuring circuit. Readout is automatic and, upon completion of each loss measurement, the data are printed by an electric typewriter and punched on cards by an IBM summary punch. Subsequent calculations are made by processing the cards in an IBM calculating punch. Finally, the cards are fed through an IBM interpreter which prints the punched data across the top of the card, making the results readily available.

Orders for cable are placed with the factory, specifying the nominal length and desired 1.0 mc attenuation in db. Finished cable is accepted if the attenuation values are within 0.4 per cent of the ordered values.

## V. CABLE TERMINATING

Part of the cable manufacturing process is the assembly of the cable termination.[1] The space in which this operation is conducted is a dust-free air-conditioned room with good lighting, manned by operators garbed in nylon dress. Slots in the wall enable the cable ends to be brought into the room. The following sequence of operations is followed:

(1) The cable end is cut back and a threaded steel strength member is crimped onto the steel strand.

(2) A T-shaped anchor assembly is screwed, then pinned, to the threaded steel sleeve. The anchor has an insulated conductor attached for subsequent joining to a similar conductor coming from the repeater.

(3) The gap in the dielectric between the cable and the anchor is replaced by injection molding.

(4) A housing, which becomes the outer conductor structure, is joined to the cable and assembled over the anchor.

(5) The ethylene plastic jacket is replaced by injection molding.

(6) A gimbal joint which enables the cable to be flexed at angles up to 45° with respect to the repeater axis is assembled.

After each of the two molding operations, sets of radiographs are taken to inspect for voids and/or contamination.

When the terminations are completed on both ends, the cable is tested a second time for high-voltage breakdown, resistance of inner and outer conductors, and dielectric and jacket insulation resistance.

## VI. ARMORED CABLE

Cable to be used in shallow water, where it may be subjected to abrasion or fouled by trawling equipment, is protected by either one or two layers of neoprene jacketed steel armor wire over the basic cable structure.[2] The armor wires are applied helically to provide a degree of flexibility to the composite structure. However, as a result of the stresses in the unidirectional helices, the cable will elongate and twist when subjected to tension. For this reason, an annealed solid copper conductor is substituted for the composite inner conductor used in the armorless structure.

For those cables which will be placed close to shore and which may be exposed to radiation from radio, Lorac or Loran stations, supplemental shielding of the cable is achieved by application of five layers of soft iron strip, one applied longitudinally, the remaining four helically, over the cable jacket. An outer jacket is applied over the strips to a diameter of 1.5 inches. The neoprene-jacketed armor wires are then applied over the outer jacket in either one or two layers, depending upon the degree of abrasion or fouling the cable may be subjected to.

Except for the modified inner conductor, cable operations and tests are identical to those used for the armorless design.

Cable, before armoring, is moved in the twenty-foot diameter pans by trailer from the ocean cable factory to the armoring building. (See Fig. 21 for a view of the plant layout.) After armoring, the cable is

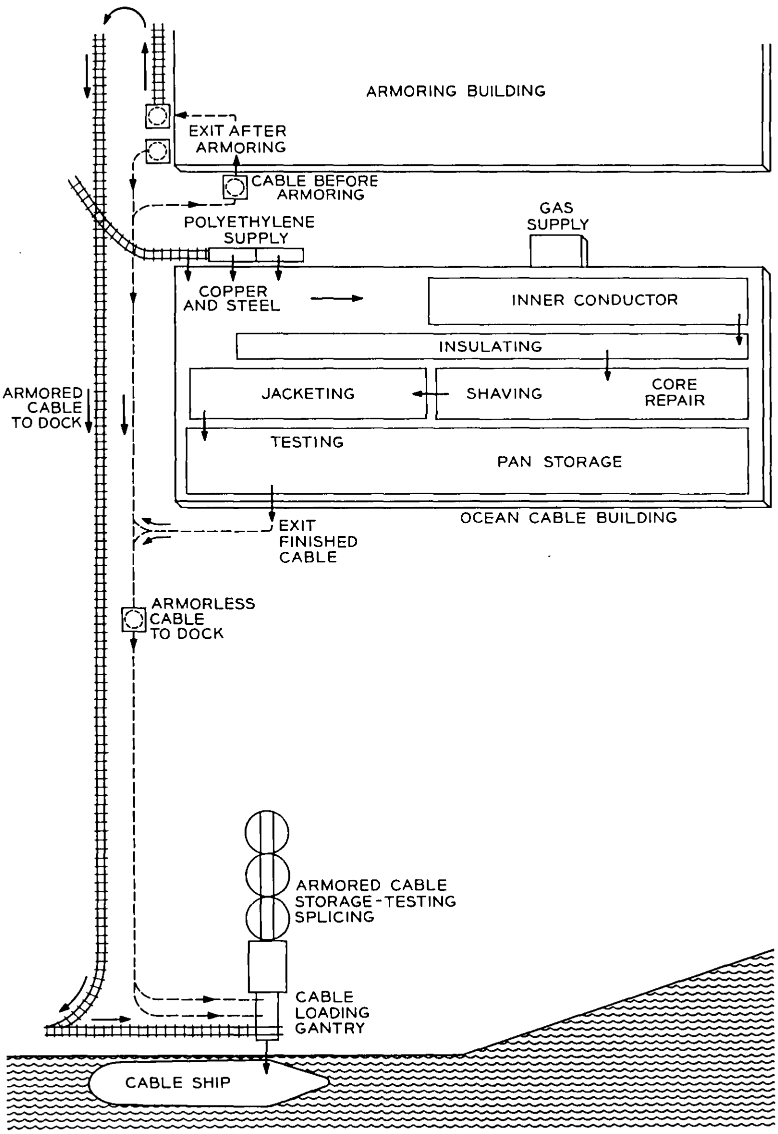


Fig. 21 — Ocean cable manufacturing facility, Baltimore, Md.

coiled into pans located at the exit of the last operation and moved to test and dockside on trailers or railroad flat cars. At dockside the several sections of armored cable may be spliced together or terminated with special couplings, and then stored in concrete tanks.

## VII. TRANSPORT AND HANDLING OF CABLE

All cable is manufactured, transported and stored in nominal 20-nm lengths with gross weights ranging from 20 tons for a full reel of inner conductor to 64 tons for a pan of finished cable. Fig. 21 also shows the cable processing paths. The controlled-temperature, ultra-clean room shown in Fig. 22 is the site where extruded dielectric take-up, dielectric repair, dielectric sizing and outer conductor application are performed as the cable is wound from one 14-foot diameter reel to another. The cable is bent to the minimum drum radius of three feet, but no twist is imparted to the cable. All reels are moved into and out of position by crane. Rotation of the massive reels, coupled with the heavy driving and braking forces, generates high stress concentrations in the reel structures, necessitating the use of bolted construction where possible.

After the last manufacturing operation, the application of the outer conductor and jacket, the cable is distributed into steel pans approxi-

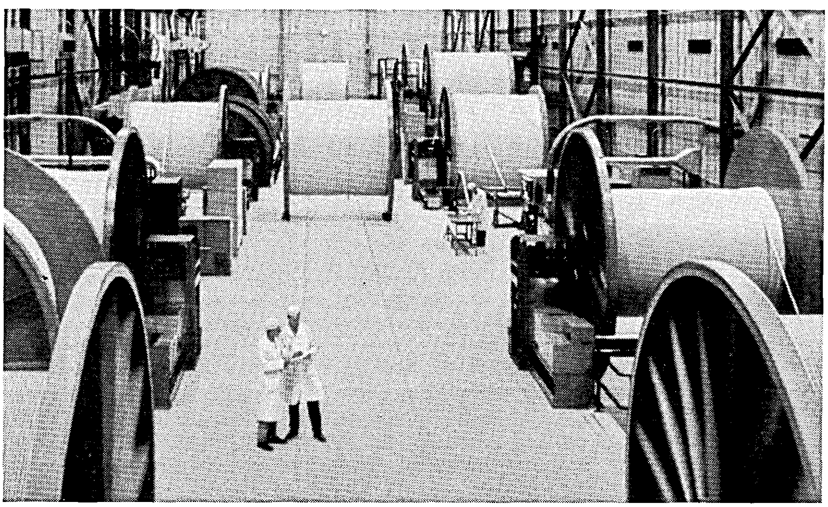

Fig. 22 — Controlled-temperature clean room.

mately twenty feet in diameter. From the jacketing line straightaway to the cable ship tanks the cable is normally bent and straightened eight times around radii of no less than four feet.

Handling of the 20-nm lengths of cable in pans provides maximum flexibility in terminating, testing and storage. Three thousand miles of cable can be stored in the factory (see Fig. 21) and can be transported, as required, to the ship's side in any sequence for loading. From the pan at shipside the cable is uncoiled and transported to the ship tanks through short, smooth troughs. Physical protection of the cable and terminations from abrasion and excessive flexure is thus provided for.

Storage of panned cable at 60°F minimum temperature is essential when ship loadings are made in freezing weather. In several loadings the relatively warm cable was towed to shipside, placed in heated tents (See Fig. 23) and pulled through the troughs without encountering a helical set in the cable despite the low temperature of the atmosphere. If the cable had been stored outside the building, the cable would have been more difficult to load because of increased stiffness in the structure.

## VIII. PROCESS INSPECTION

In addition to final cable electrical requirements, tests are made on all cables for other specification requirements such as lack of contact

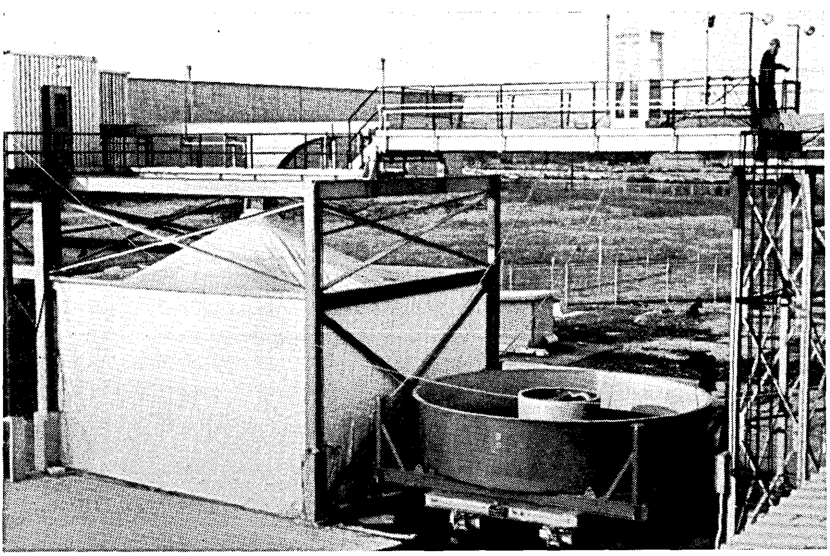

Fig. 23 — Heated loading tent.

between the dielectric and outer conductor, number of reverse bends the cable will withstand before outer conductor failure occurs, and ethylene plastic jacket retraction.

All operators are periodically checked for qualification. No unqualified operator is permitted to work on the product.

There are also many in-process recorder charts which are examined for specification compliance. Typical of these charts are:

(1) inner conductor fault chart,
(2) eccentricity and diameter charts on the dielectric extrusion,
(3) water trough temperatures on the dielectric extrusion lines,
(4) sized dielectric eccentricity and diameter charts,
(5) outer conductor thickness chart,
(6) jacket eccentricity and diameter charts, and
(7) jacket cooling trough temperatures.

All applicable charts become part of the cable history. If a defect is revealed, it is authenticated carefully, and if necessary the cable is rewound to that position and repairs are made, or the cable is discarded.

## IX. PROCESS RESULTS

At the beginning of this article, it was stated that the specification covering SD system cable was written in terms of end product requirements in the hope that cable would be produced to a greater degree of uniformity than had previously been possible. Several things can be enumerated that made this a worthwhile choice. Chief among these is the structure itself. Only three materials, steel, copper, and polyethylene, are used in the basic design, and with the exception of the outer conductor overlap, all of the elements are simple, cylindrical shapes. Perhaps of equal importance are the specifications covering those materials. They assure the procurement of material of a homogeneity rarely seen

TABLE I — CABLE ELECTRICAL PARAMETERS: TEST RESULTS FOR 100 CONSECUTIVE CABLE SECTIONS

| Measurement | Measured Values in Units per nm | | | | |
|---|---|---|---|---|---|
| | Average | Maximum | Minimum | Standard Deviation | Pct. Std. Dev. |
| 1.00-mc loss in db | 2.3900 | 2.4013 | 2.3801 | 0.004803 | 0.2010 |
| I.C. $R_{dc}$ in ohms | 1.7600 | 1.7807 | 1.7388 | 0.009285 | 0.5276 |
| O.C. $R_{dc}$ in ohms | 1.3754 | 1.3831 | 1.3672 | 0.003042 | 0.2212 |
| 21-cps capacitance in $\mu$fd | 0.2135 | 0.2148 | 0.2125 | 0.000513 | 0.2405 |
| 1.0-mc delay in $\mu$sec | 9.4063 | 9.4329 | 9.3849 | 0.009568 | 0.1017 |

in a large-scale manufacturing operation. Other factors worthy of mention include operator selection, training and qualification, use of large but precise machinery, and maintenance of plant cleanliness.

How well this goal has been achieved can best be determined by reference to Table I. In this table are listed several of the critical cable electrical parameters along with results obtained on 100 consecutive cable sections (approximately 2000 nm) made in the latter half of 1963 at the Baltimore plant of the Western Electric Company.

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2. Bowker, M. W., Nutt, W. G., and Riley, R. M., Design of Armorless Ocean Cable, B.S.T.J., this issue, p. 1185.

# Repeaters and Equalizers for the SD Submarine Cable System

By S.T. BREWER, F.R. DICKINSON and C.A. VON ROESGEN

(Manuscript received April 17, 1964)

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

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

## I. INTRODUCTION

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

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

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

## II. REPEATER CIRCUIT

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

### 2.1 *Power Separation Filters*

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

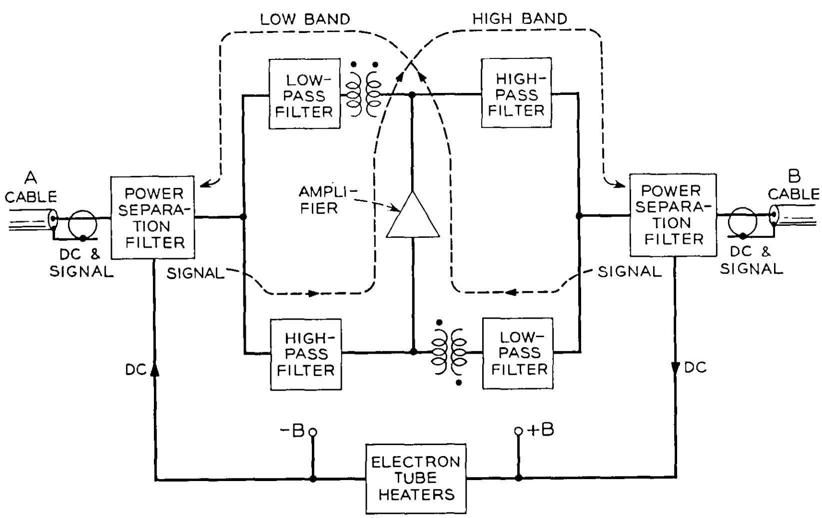



Fig. 1 — Repeater block schematic.

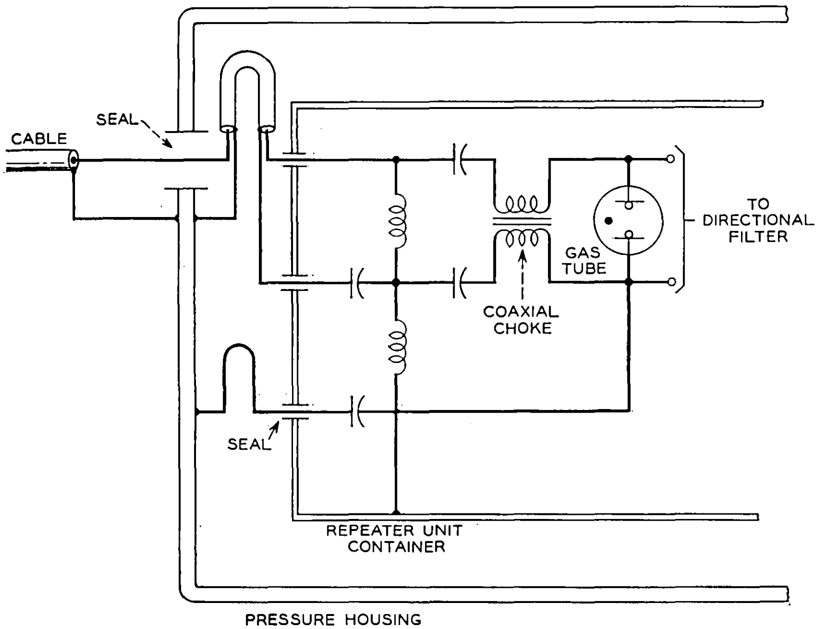



Fig. 2 — Power separation filter.

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

### 2.2 *Directional Filters*

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

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

### 2.3 *Amplifier*

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

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

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

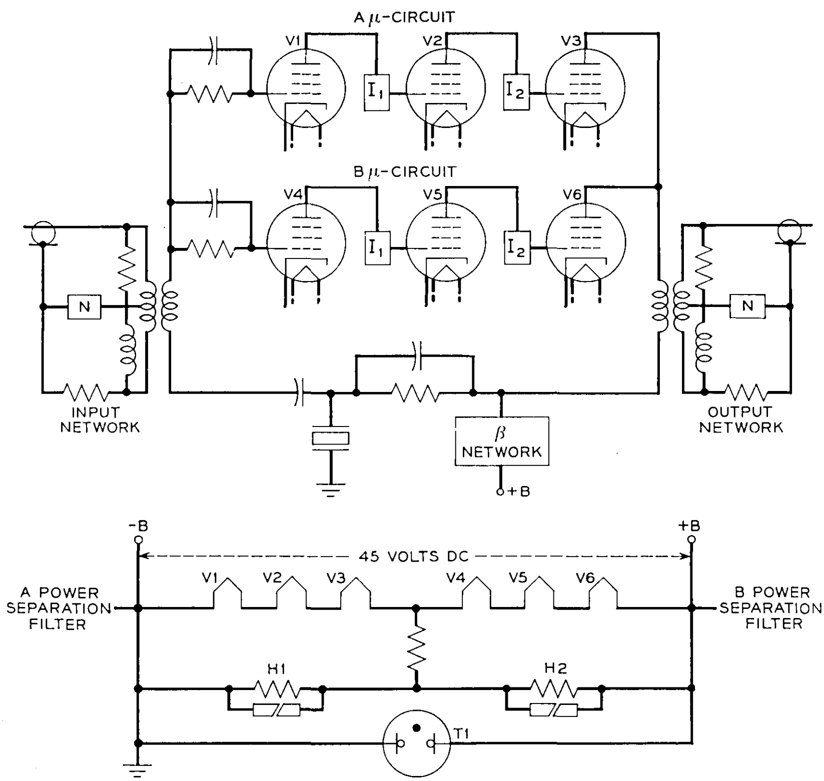



Fig. 3 — Amplifier circuit.

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

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

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

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

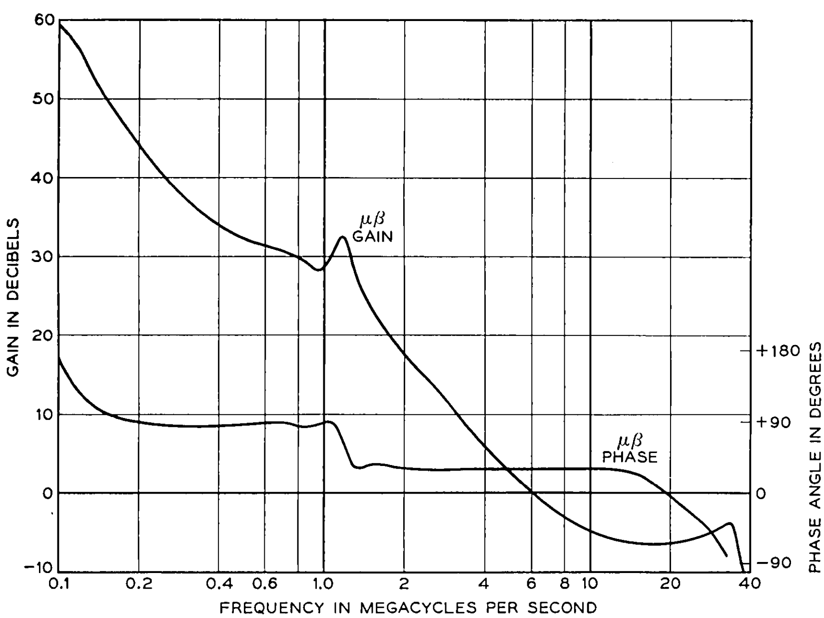



Fig. 4 — Amplifier feedback characteristics.

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

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

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

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

## III. REPEATER PERFORMANCE

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

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

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

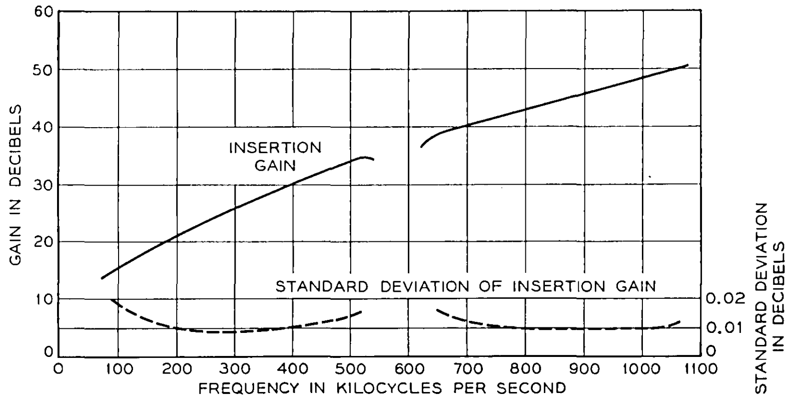



Fig. 5 — Repeater insertion gain.

IV. COMPONENTS

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

Polystyrene capacitors are used in most low-voltage applications for

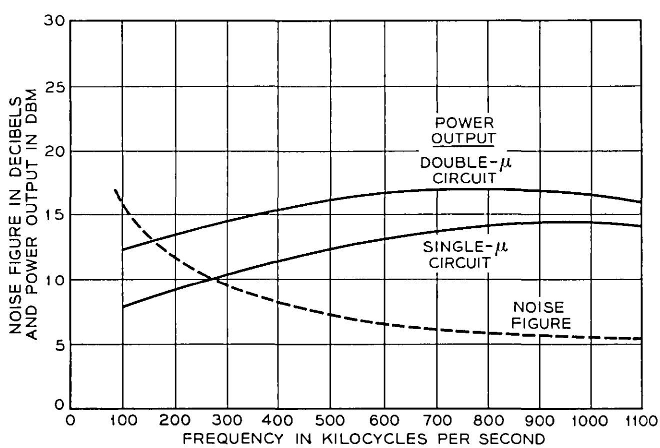



Fig. 6 — Repeater power output and noise figure.

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

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

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

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

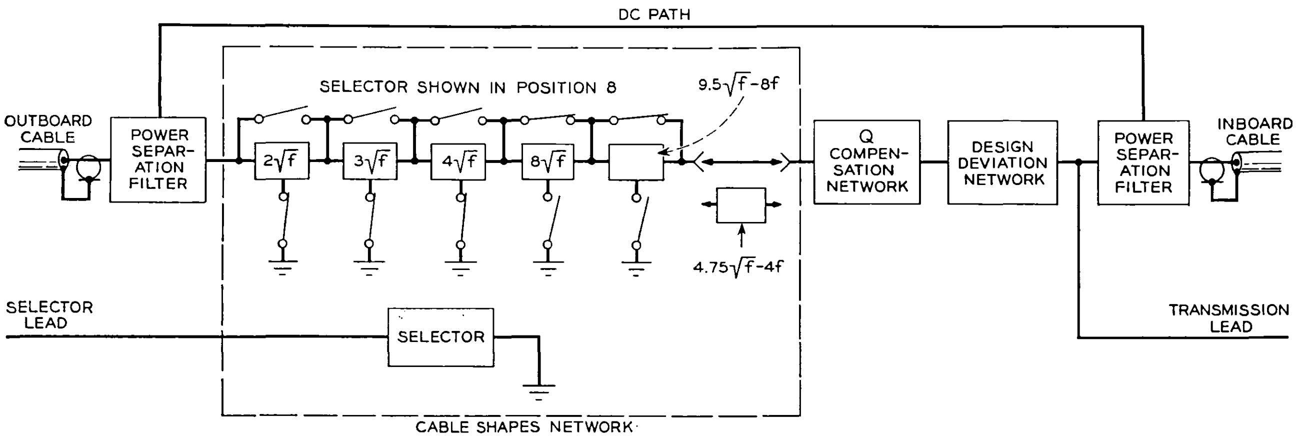
## V. EQUALIZER CIRCUIT

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

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

### 5.1 *Design Deviation Network*

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




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

0 = SECTION OUT
1 = SECTION IN

Fig. 7 — Ocean-block equalizer.

### 5.2 *Directional Filter Q-Compensation Network*

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

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

### 5.3 *Cable Shapes Network*

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

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

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

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

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

## VI. REPEATER MECHANICAL DESIGN

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

### 6.1 *Pressure Housing*

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

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

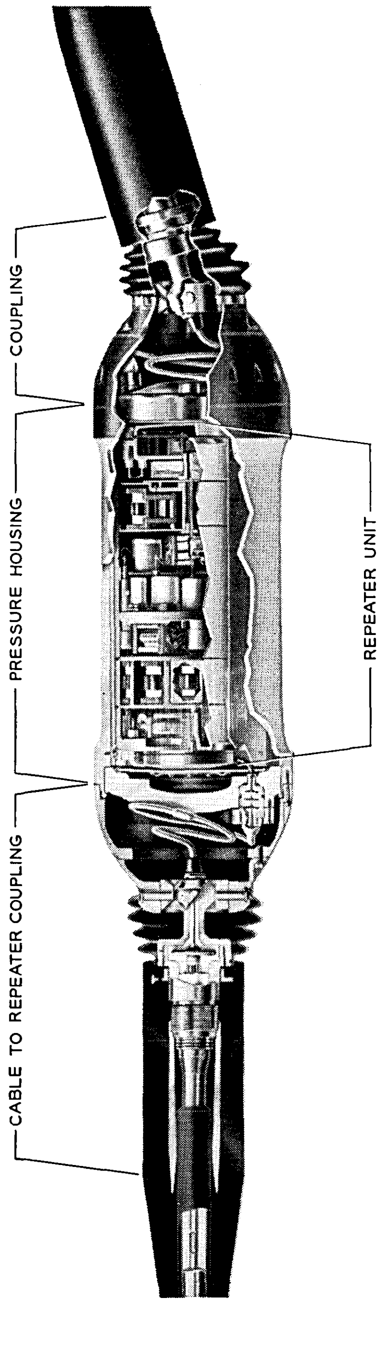



Fig. 8 — Repeater — cutaway drawing.

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

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

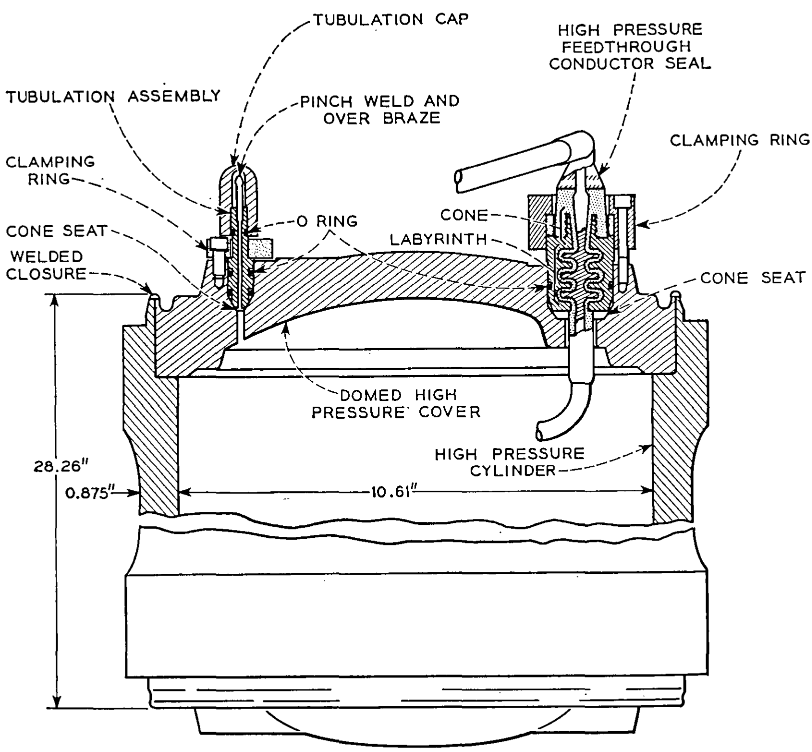



Fig. 9 — Pressure housing.

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

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

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

### 6.2 *Cylinder*

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

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

### 6.3 *Cover*

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

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

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

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

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

### 6.4 *Welding*

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

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

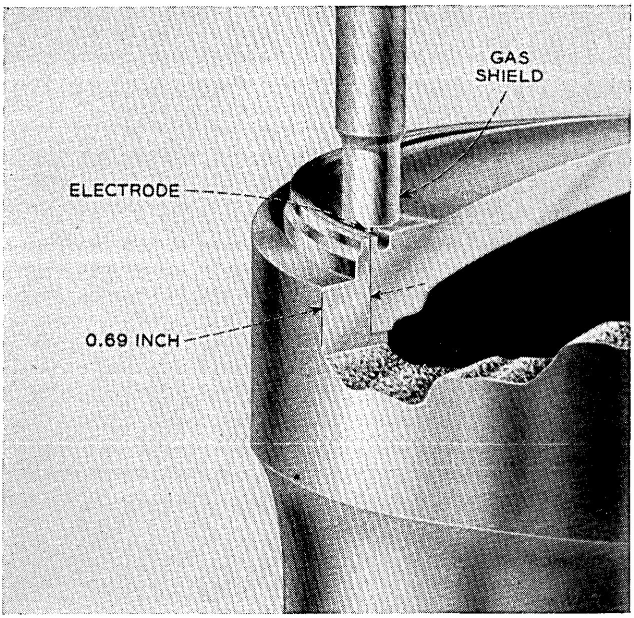



Fig. 10 — Weld process.

### 6.5 *Feedthrough Seals*

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

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

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

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

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

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

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

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

To provide access of leak detector sensing to the inside of the housing while the outside is pressurized, a small tubulation is mounted in one of the end covers. This tubulation is a separate assembly mounted in the cover in the same manner as the seals. After completion of the leak test, the tubulation is pinch welded. The tubulation itself is tested by the high-pressure application of a radioisotope and subsequent searching with a Geiger counter, in a manner similar to that used for the flexible repeater. Since this design is arranged so that less than a thimbleful of radioisotope is used in the test, it can be safely made a more sensitive and meaningful test than heretofore possible.

The radioisotope used is cesium 137. With this material, test time is cut, significantly reducing safety hazards as well as manufacturing costs. Safety hazards are further reduced by the design of the tubulation, which permits complete automation of the test.

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

### 6.6 *Repeater Unit*

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

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

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

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

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

### 6.7 *Amplifier*

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

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

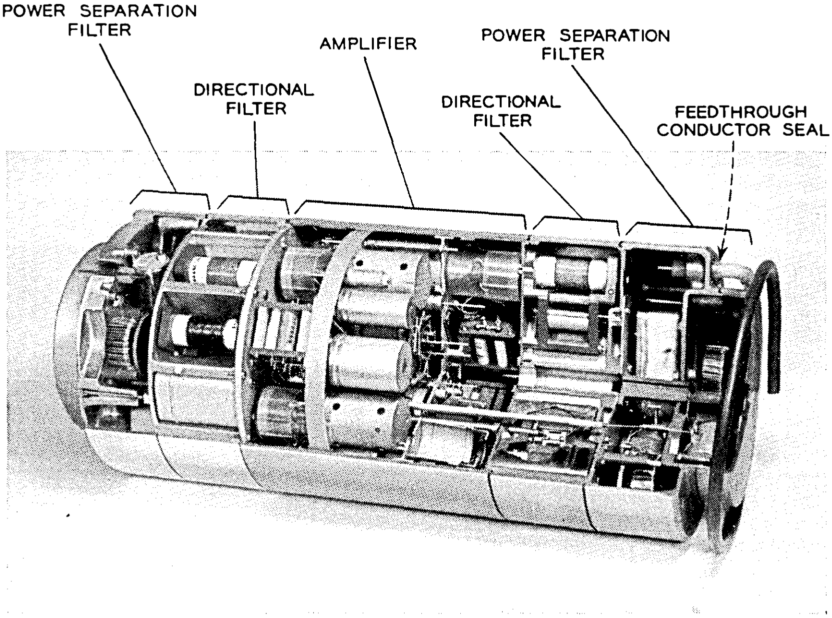



Fig. 11 — Repeater unit — cutaway view.

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

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

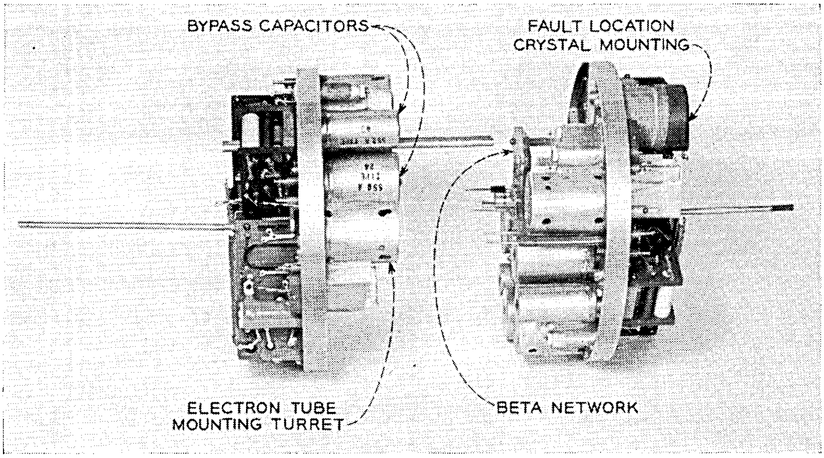



Fig. 12 — Amplifier before final assembly.

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

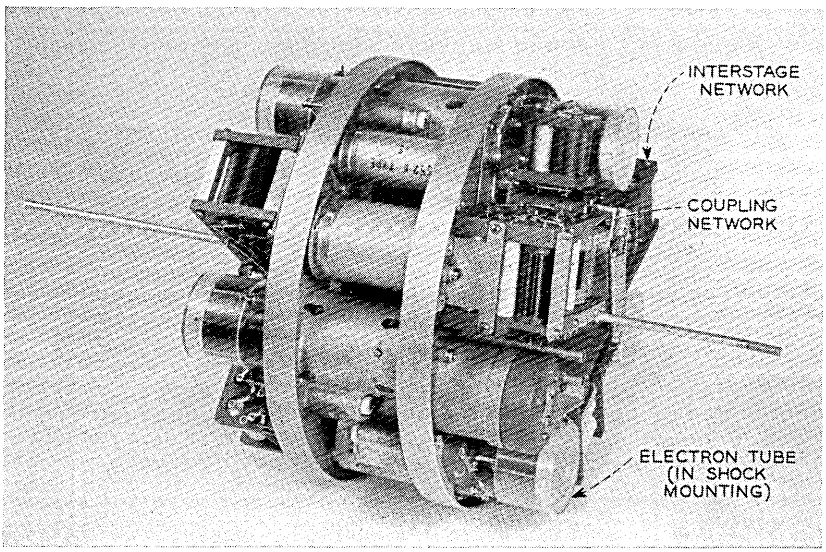



Fig. 13 — Assembled amplifier.

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

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

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

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

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

### 6.8 *Directional Filter*

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

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

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

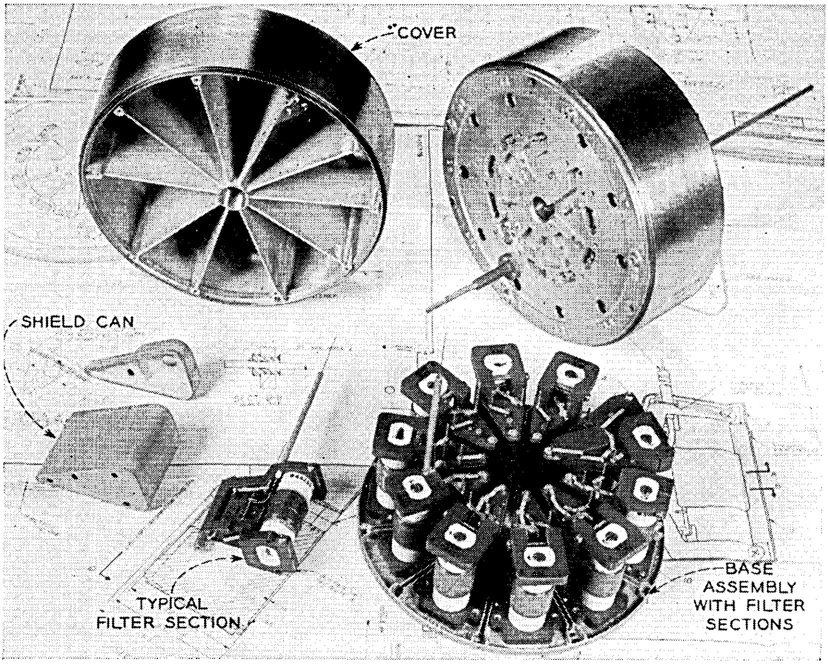



Fig. 14 — Directional filter.

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

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

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

### 6.9 *Power Separation Filter*

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

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

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

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

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

6.10 *Repeater Unit Assembly*

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

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

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

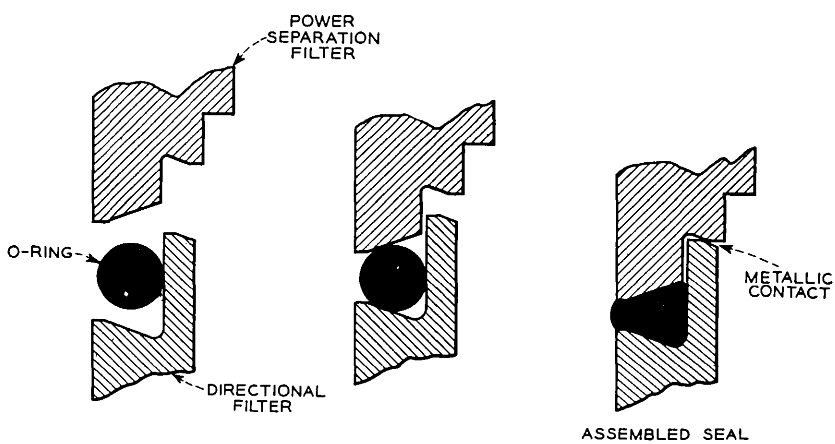



Fig. 15 — O-ring assembly.

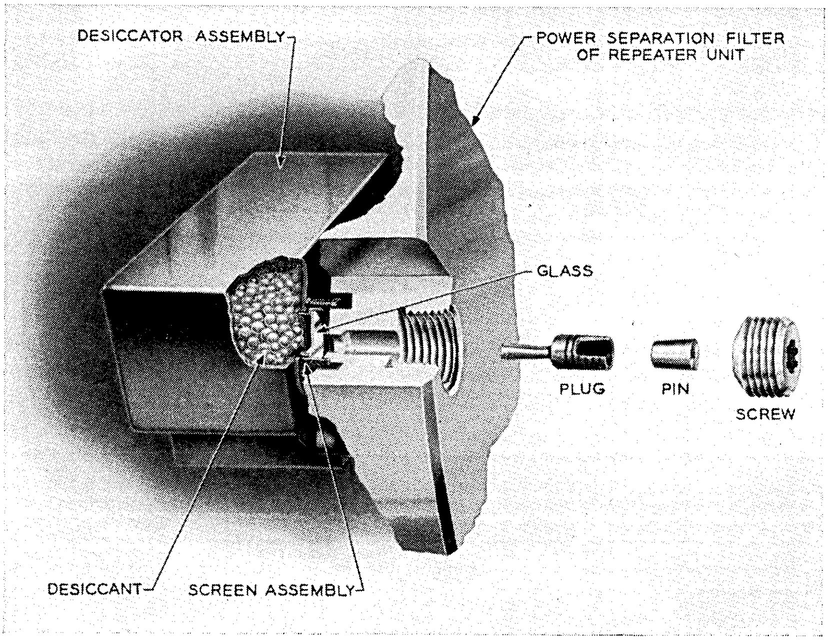



Fig. 16 — Final sealing of tubulations.

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

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

| | |
|---|---|
| length | 23.30 inches |
| diameter | 9.54 inches |
| weight | 65 lbs. |

### 6.11 *Shock Mounting*

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

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

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

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

### 6.12 *Complete Repeater*

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

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

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

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

### 6.13 *Cable Connection*

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

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

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

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

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

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

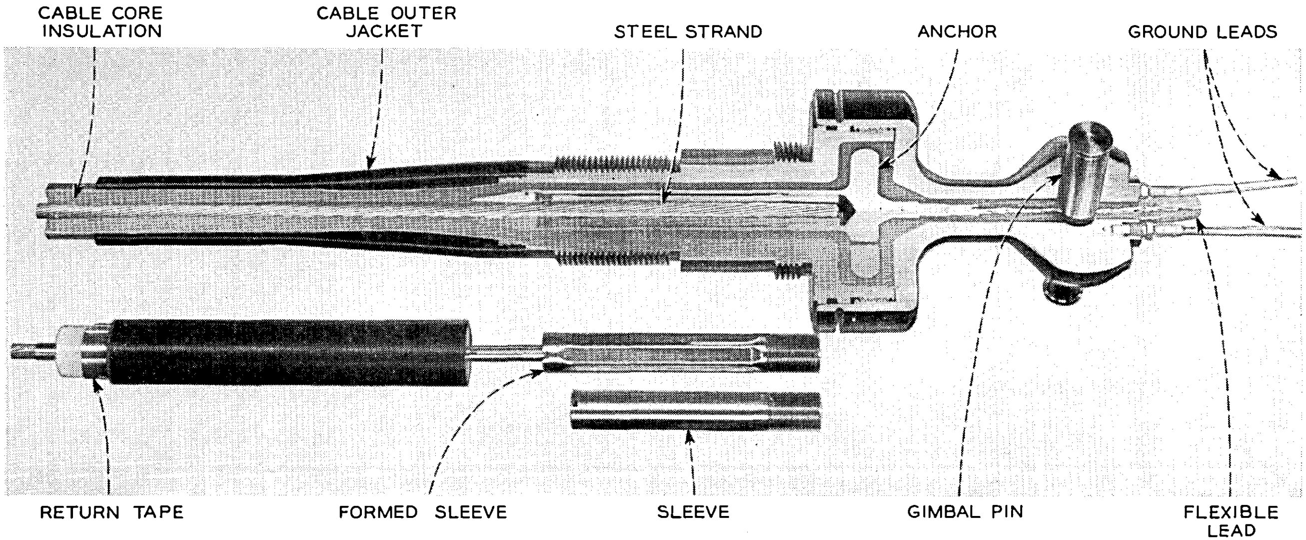



Fig. 17 — Repeater-cable coupling.

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

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

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

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

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

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

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

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

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

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

## VII. CONCLUSION

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

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

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

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# Manufacture of Rigid Repeaters and Ocean-Block Equalizers

By S.G. JOHANSSON

(Manuscript received January 22, 1964)

*Manufacture of two-way rigid repeaters and ocean-block equalizers at a rate equivalent to approximately 7000 miles of cable a year required the establishment of a new plant. A suitable building was constructed and equipped to maintain the closely controlled environmental conditions essential to attaining the quality required to assure a minimum product life of 20 years. An organization was established and trained to operate the plant. Special facilities were developed for manufacture and testing, including automatic readout and transmission of the test information to a data center where the results are recorded in a punched card system and analyzed by machine.*

*The facilities, their use, production methods from procurement of materials to packing of completed repeaters and equalizers, and precautions taken to attain and assure the required high quality are reviewed on the following pages.*

## I. INTRODUCTION

Early in 1959 a decision was made to start production of a new rigid repeater for SD submarine cable telephone systems.[1]

Since repeater manufacturing know-how was available at the Kearny, New Jersey, plant of the Western Electric Co. from earlier production of flexible repeaters for SB cable systems,[2] the manufacture of the SD repeater was also allocated to Kearny. The same general philosophy of building integrity into the product to the limit of practicability was again to apply. The same manufacturing requirements on environment, personnel, wage payment, training program, and inspection on a 100 per cent basis were also to be used.

In the following information reference will occasionally be made to flexible repeater manufacture at Hillside, New Jersey, with the assumption that interested readers have previously read or now have access to the information published in 1957.[2]

## II. PLANNED CAPACITY AND DELIVERY SCHEDULES

The manufacturing planning was based on a capacity of six repeaters per week on a one-shift five-day basis. It was estimated that this capacity would permit production of up to eight repeaters per week on an all-out basis when all processes had been shaken down and operators fully trained.

The initial estimated manufacturing interval was 90 weeks, which should be reduced to between 60 and 65 weeks when production got underway with fully-trained operators. In reality, operations were started by the middle of September, 1960, and the first repeater was shipped by the end of June, 1962. This initial interval amounted to 92 weeks. The normal manufacturing interval is about 63 weeks, the greater portion of which is used for temperature cycling and aging of components.

Schedules called for delivery of 66 repeaters by the end of 1962 and, during 1963, 108 in the first quarter, 110 in the second quarter, 83 in the third quarter, and 123 in the fourth quarter. To meet these schedules required spurts in the output rate of up to ten enclosures per week. This was accomplished by earlier start of apparatus production and more rapid build-up to a rate corresponding to eight repeaters per week. By providing some additional testing capacity and extending enclosure operations into a second shift, it was possible to assemble repeater units and enclose repeaters at the higher rate required to meet over-all schedules. Nearly a year was required from the time of shipment of the first repeater to build up to maximum production capacity.

## III. HIGHLIGHTS OF CLARK BUILDING

From the design information available at the time authorization to go ahead was received, a rough shop layout was made. Based on Hillside experience and the nearly sevenfold increase in quantity of apparatus to be manufactured, a minimum need for 85,000 square feet of floor space was indicated.

After inspection of several buildings contractual agreement was entered with a contractor to build and lease to Western Electric a 97,000-square foot building at Terminal Avenue, Clark, N. J. This location was deemed satisfactory from the standpoint of availability of the required type of labor within the nearby areas. The building was designed and built to meet the specifications for a repeater shop and other Western Electric standards.

Construction of the building was started in June, 1959, and completed in July, 1960. Only the land and building shell were leased from the contractor. All installations of lights, drop ceiling, special rooms, floor tile, heating boilers, air-conditioning equipment, and cafeteria facilities were provided by Western Electric. Although the building was originally acquired on a ten-year lease with option to buy, it was purchased by Western Electric in July, 1962.

The building is of one-story steel and masonry construction, 360 × 270 feet, with 40 × 30 foot bays. In office areas and "white" (i.e., super-clean, controlled-environment) areas, ducts for power, telephone, and other communication circuits were installed on ten-foot centers, with knock-outs every two feet, in the concrete floor slab. A sheet rock drop ceiling was installed 11 feet above the floor. All air-conditioning ducts, piping, and other services were installed in the six-foot space between the roof and drop ceiling. In office areas and cafeteria, acoustic ceiling tile was used. To avoid pipes in the open, water, compressed air, deionized water, dry nitrogen outlets, and outlets from the central vacuum cleaning system were, wherever possible, installed in partition walls and inside the covering over the building columns. The back wall of the building was constructed with future expansion in mind. The columns are provided with plates for connecting joists to them, and the wall is cinder block construction for ease of removal in part or whole. A general block layout of the building is shown in Fig. 1.

To meet the New Jersey manufacturing building code without having to erect internal firewalls which would have interfered with the general layout, ten-foot-wide main aisles are provided. These aisles would allow movement of standard mechanized fire-fighting equipment and thus provide the required protection.

The state code also specified heat vents in the roof, which would have required undesired openings in the ceilings of the white areas. However, mechanical fire baffles in the air-conditioning ducts and means for exhausting the return air completely to the outside in case of smoke satisfied this requirement and eliminated the need for openings in the ceilings.

Since eating in places other than the cafeteria is undesirable in a plant of this type, the size of the cafeteria had to be increased somewhat over the normal requirements for the plant. The cafeteria seating capacity at Clark is 354, with facilities for cooking, dishwashing, etc.

The conditions of temperature, humidity, and ventilation are provided by five separate air-conditioning systems with a total capacity of 600 tons and with one common chilled water supply for cooling. Two of the systems, each with a large plenum chamber which includes the filtering equipment and a circulating blower, cover the main portion of the building. The filtering equipment consists of a mechanical filter

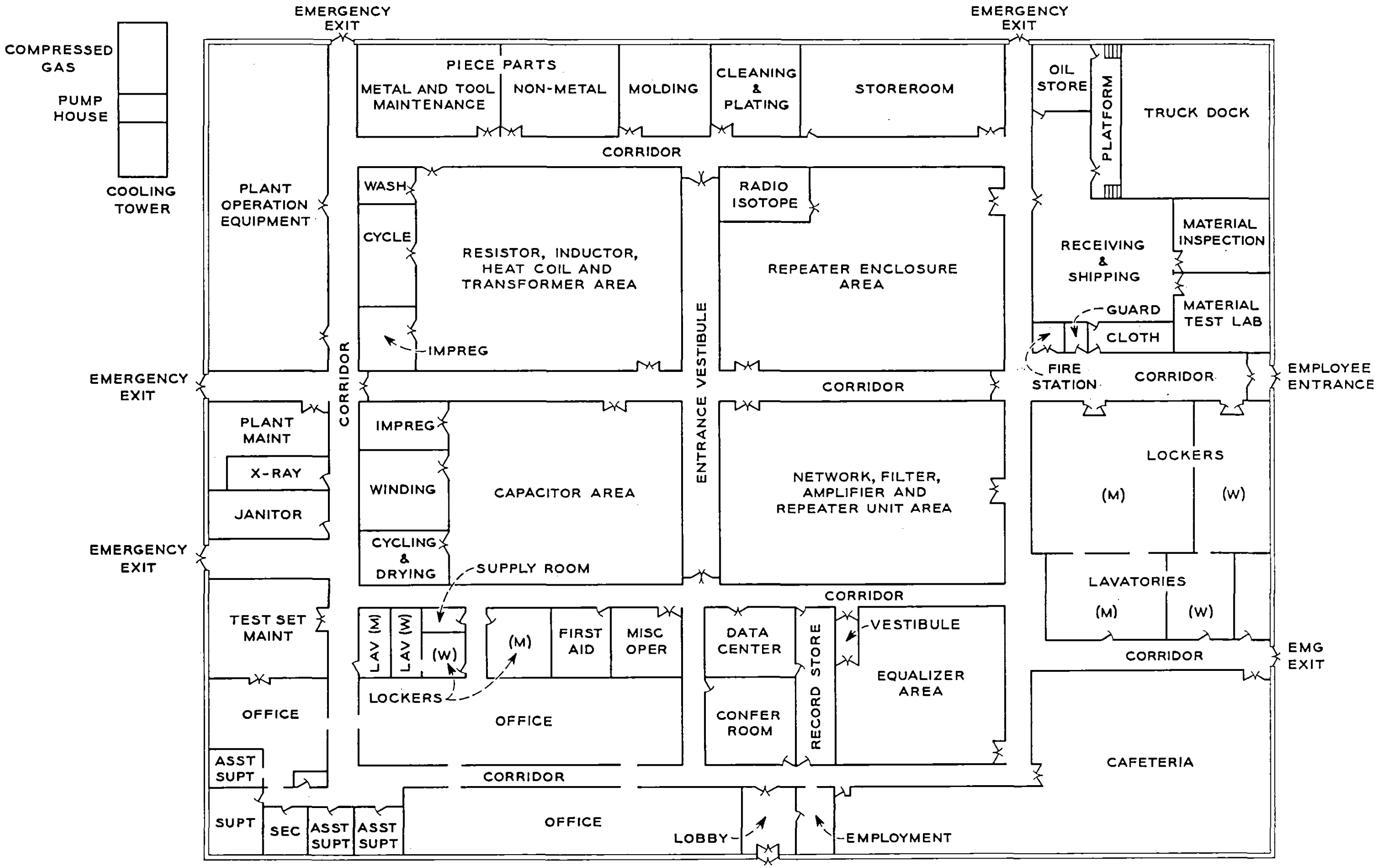


Fig. 1 — Plant layout.

followed by an electrostatic filter and a second mechanical filter. Originally the design called for a cold water spray for cooling the air, which would have been simple and efficient and would have stabilized the humidity at the desired value. However, this proved unsatisfactory due to minerals and algae in the water, which were precipitated upon evaporation and circulated out through the ducts in the form of fine dust. To attain the desired low dust count, a change was made to the use of cooling coils in place of the water spray; the change eliminated direct contact between the chilled water and the air and the associated evaporation and precipitation. The air is circulated by two blowers in series: one 40-hp unit in each plenum chamber, which provides positive pressure in the supply duct, and a 15-hp unit at the end of the return duct in a penthouse on the roof above the entrance to each plenum chamber, which provides a negative pressure in the return duct. The latter blowers also provide the means of exhausting directly to the atmosphere any smoke or fumes from fire or other causes through a system of louvers operated by a photoelectric smoke-detecting device. One of these main systems serves the four large white areas in the center of the building, shown in Fig. 1. The second system provides air conditioning for all of the peripheral areas, including offices but excluding the cafeteria. Means are also provided to interchange these systems.

Since smoking is permitted in the cafeteria, a separate system is used, which recirculates and provides the necessary make-up air for the cafeteria only. The air supplied to the locker and toilet rooms is not recirculated. To maintain uniformity of temperature during severe outside climatic conditions, means are provided for heating or cooling the air above the drop ceiling. In case of extreme cold, the space above the drop ceiling is heated by steam coils installed in several locations. To attain the desired low humidity of 20 per cent maximum in the capacitor winding area, a secondary cooling system is used which takes the approximately 55-degree air from either of the large plenum chambers and cools it down to approximately 22°F to precipitate the moisture. Since this is below the freezing point of water, dual cooling coils are provided: one is defrosted while the other one is in use, and vice versa. This switching is done by an automatic timing device.

The cooling facilities consist of three separate 200-ton centrifugal refrigerator units with chilled water outputs connected to a common header. The chilled water is retained in a closed-loop circulating system. A common cooling tower is used for cooling the water from the individual condensers. This arrangement permits one, two, or three of the machines to be used as required, resulting in good efficiency for the varied load encountered during the year. Except during the very few days of extreme high temperature and humidity encountered during the year, two of the units are sufficient to carry the load. This provides the required standby capacity for maintenance and repairs.

Two 200-hp boilers provide the necessary steam for heating and humidifying during the cold season and for dehumidification during hot weather. (To remove excess moisture, the air is cooled to approximately 45°F and then reheated to meet temperature requirements in the different areas.) One of these boilers is sufficient to carry the load, except possibly during a few days in the year when extreme temperatures may be encountered. During the winter, steam heat is also provided under the outside windows throughout the plant to offset cold air circulation and draft.

Approximately $2\frac{1}{2}$ miles of ducts are installed above the ceiling for circulation of the air. The supply air is admitted to the rooms through the outer opening of coaxial diffusers, and the return air is pulled back through the center opening. The circular return ducts from the diffusers run right through the supply ducts to the return ducts, which are located directly above the supply ducts. Sufficient blower capacity is provided to change the air in the building completely every five minutes. Up to 25 per cent of make-up air can also be provided. This is adjustable to the comfort needs of the building population.

The control circuit for temperature and humidity is air-operated. To ascertain that the air is sufficiently dust-free, a dust count is taken every morning in a number of different locations. A special Bausch and Lomb microscope is being used for this purpose. In making a test, air is pumped past a slide where any dust particles stick to a predetermined surface area. From the amount of air that passes this surface and the number of dust particles found on it, the average number of particles per cubic foot is obtained. In general, the dust count at Clark is comparable to the conditions obtained at Hillside and is considered quite satisfactory.

The over-all illumination of 85 foot-candles is provided by means of fluorescent lights in the ceiling. Certain of these lights are on a special emergency lighting circuit supplied automatically by a motor generator set in case of power failure. Provision has not been made for operating the plant in case of general power failure, since the power requirements are nearly 1500 kva. However, to assure maintenance of power, the plant is connected to a power loop which can be fed from several points.

The floor covering consists of one-foot squares of vinyl asbestos tile, which is a compromise with the original plan of using long lengths of wide material to avoid the possibility of dirt catching in the cracks between tiles. The tile has, however, proven quite satisfactory, since it has expanded and nearly eliminated all openings between tiles.

The walls or partitions for the different rooms in the building are commercial standard steel partitions having a baked enamel finish. Since these partitions were not of sufficient height to reach the ceiling, they were extended by an upper fabricated wall section of mineral boards. The partitions are insulated with rock wool, and the seams between panels are caulked to eliminate seepage of dust. Any openings at the floor are sealed by a flexible plastic base. To provide a more desirable environment, better possibilities for supervision and inspection, and, to some extent, an easy way to view operations, large windows were included in the partitions. For safety, this is wire-type glass.

To attain the best possible clean conditions in the white areas, the ceilings were covered with a washable vinyl fabric cloth. The same type of covering is also used on the portions of the walls above the metal partitions in these areas. For cleaning purposes, a central vacuum system has been included. Outlets are installed throughout the building for connection to the cleaning and scrubbing equipment. The acoustic ceiling tile in the office areas and cafeteria is a washable type which has a smooth surface without perforations. In aisles and locker rooms, the sheet rock ceiling is finished by painting. This also applies to the upper portions of the walls above the metal partitions in these and the non-"white" areas.

## IV. CLARK ORGANIZATION

The same basic pattern as used at Hillside on the flexible repeater project, of having the organization report to the engineer of manufacture, is followed. However, since the operation is considerably larger, it is a full-time job for one superintendent, who is assigned to this project only.

There are four levels of supervision: superintendent, assistant superintendent, department chief, and section chief. At Clark there are three assistant superintendents — one responsible for engineering, one for inspection, testing and plant maintenance, and one for operating and production control. The responsibilities in each of these areas are, in turn, broken down into three departments with up to seven section chiefs in each, excluding engineering, which has no sections. On the average there are 16 operators reporting to each section chief.

The total population at Clark is 550, of which approximately 75 per cent are performing actual shop operations. Of the latter, approximately 40 per cent are female and 60 per cent male.

## V. REPEATER ASSEMBLY

An outline of the major assembly steps from apparatus to completed repeater is shown in Fig. 2.

## VI. TYPES AND QUANTITIES OF APPARATUS

In each repeater there is a total of 201 items of apparatus such as capacitors, inductors, transformers, resistors, heat coils, crystal units, electron tubes, and gas tubes. Crystal units are manufactured at Western Electric's Merrimack Valley Works and electron and gas tubes at the Allentown Works. Composition-type resistors and vitreous enameled resistors are purchased from outside suppliers. The remaining items, 86 codes, are manufactured at Clark; samples are shown in Fig. 3. A tabulation of apparatus used in the repeater is shown in Table I.

In addition to the items used in the repeater, there are 36 capacitors of 33 codes, 35 inductors of 31 codes, 53 resistors of 42 codes, and a stepping switch for the equalizer.

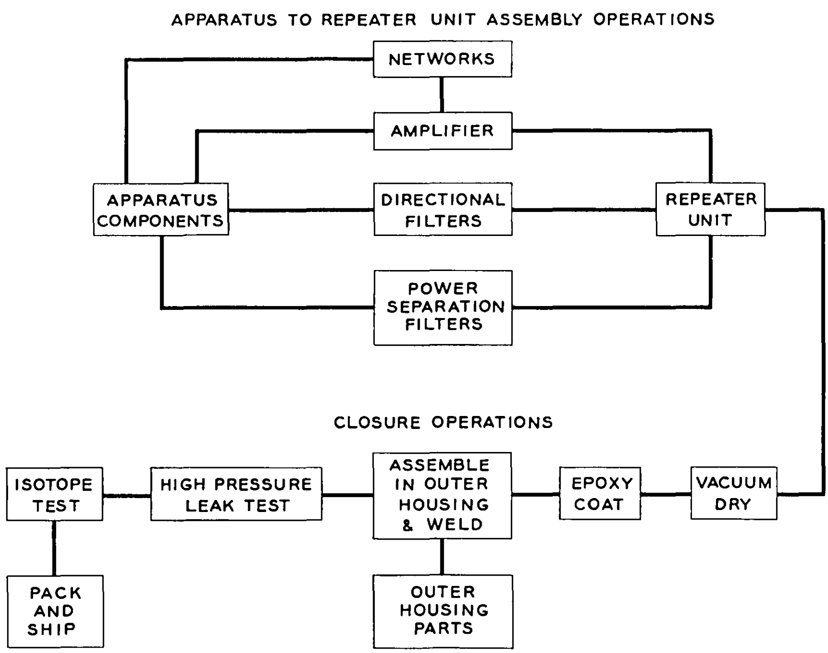


Fig. 2 — Major repeater assembly steps.

In general, the type of apparatus is similar to that used in the flexible repeater. However, the method of manufacture and the detail design in a number of cases are quite different.

## VII. TYPE OF MANUFACTURING FACILITIES

A number of new manufacturing facilities were developed.

### 7.1 *Machinery*

Of the machinery for producing apparatus, capacitor winding machines, mica lamination silver coating machines and washing facilities, and some of the coil winding machines were new. After requesting bids from several companies, a manufacturer specializing in capacitor winding machines was selected to design and build machines to our specifications. Two types of machines, one for high-voltage capacitors and one for low-voltage capacitors, were built to these specifications, which also embodied some of the manufacturer's own outstanding features. The latter included a magnetic braking device to apply the proper tension to the paper spools, dual winding spindles, and electronic means for determining the foil length. The high-voltage capacitor winding machines, shown in Fig. 4, have as many as 18 spindles for paper and foil, which require, among other things, very close mutual line-up and tension adjustment to produce the required quality of winding.

An adaptation of a commercial machine was used for silk screening the silver coating on mica laminations. Better mechanical alignments were required, the right squeegee material had to be found, and the silk screens had to be made to closer tolerances and standards than ordinary. The originally planned number of openings in the screen and the number of parts coated at one time also had to be decreased, because it was not possible to maintain close alignment between the different openings in the screens.

New washing facilities for mica laminations were also developed. At Hillside, acetone was used for washing laminations, but with the larger quantities involved at Clark, the greater amount of acetone needed would have produced too great a fire hazard. A method using hydrogen peroxide and centrifugal drying was therefore selected. The new washing facilities are safe and require less space.

The design of coils for the one-megacycle repeater permitted all of them to be machine wound, whereas for the flexible repeater the majority had to be hand wound. Commercial machines are used for straight

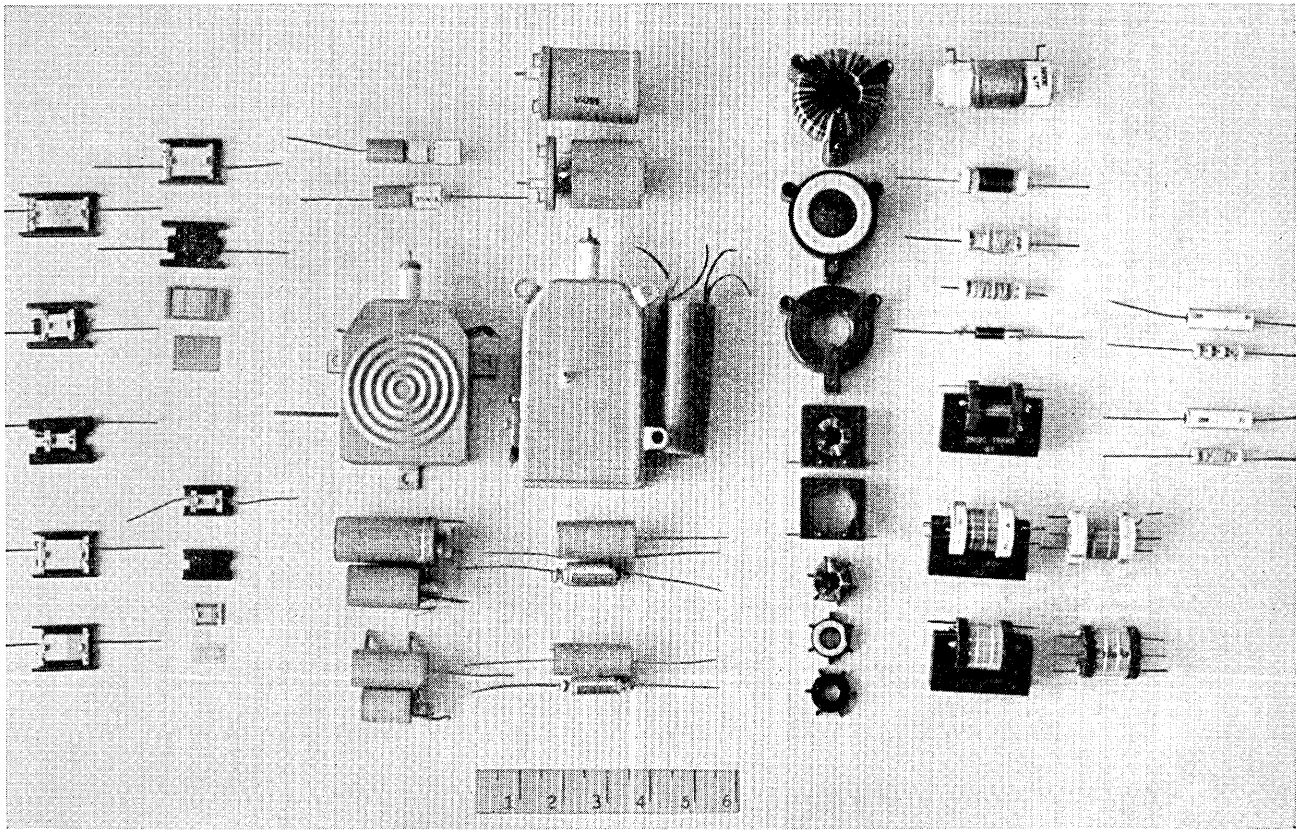


Fig. 3 — Sample parts.

TABLE I — APPARATUS USED IN REPEATERS

| Part | No. of Different Codes | No. of Units | Value Range | Accuracy Range |
|---|---|---|---|---|
| Capacitors | | | | |
| High-voltage paper | 2 | 3 | 0.074–0.120 mf | 3–5% |
| Low-voltage paper | 9 | 22 | 0.001–2.0 mf | 2.5–5% |
| Polystyrene film | 6 | 12 | 0.0075–0.0192 mf | 1–2% |
| Mica | 24 | 46 | 0.000050–0.010350 mf | 0.2–2% |
| Inductors | | | | |
| Air core solenoid type—adjustable | 15 | 24 | 3.45–415 μh | 0.7–1.5% |
| Air core solenoid type | 11 | 16 | 0.34–1000 μh | 0.5–3% |
| Dust core toroidal type | 4 | 8 | 115–9200 μh | 1–2% |
| Transformers | | | | |
| Ferrite core | 4 | 6 | — | — |
| Resistors | | | | |
| Bifilar wire wound | 14 | 25 | 15–600 ohms | 0.1–1.1% |
| Mandrellated wire wound | 4 | 10 | 1100–3800 ohms | 0.4–0.8% |
| | | | 73.2 ohms | 1.5% |
| Vitreous enameled type | 2 | 3 | 890.0 ohms | 3.5% |
| Composition type | 4 | 16 | 11,000–500,000 ohms | 2% |

solenoid, duolateral, progressive duolateral, and toroidal windings. However, a number of refinements were required to provide the proper wire tension, wire guide, and uniformity of winding.

Operations connected with enclosure of the repeater also required a number of new type facilities. Among these are vacuum drying stations, epoxy coating facilities, repeater assembly machine, welding machine for end covers, ultrasonic testing facilities, high-pressure helium leak testing facilities, isotope testing facilities, repeater handling facilities including trucks and hoists, and polyethylene molding facilities.

Considerable simplification of the vacuum drying stations and lower cost were accomplished with the use of a heating blanket to provide the specified bake-out temperature for the assembled repeater unit. The blanket, which completely surrounds the repeater unit, is equipped with thermostatic control to maintain the temperature.

Considerable development work was done by Bell Laboratories on a process for welding the beryllium copper end covers into the beryllium copper housing cylinder. Based on the process criteria established by Bell Laboratories, specifications for a production welding machine were prepared.

The machine, shown in Fig. 5, has two turntables to hold the repeater in a vertical position and means for centering it on the turntable so that the welding area runs true. The pedestal, which holds the welding head and a milling head, can be turned to either of the two turntable

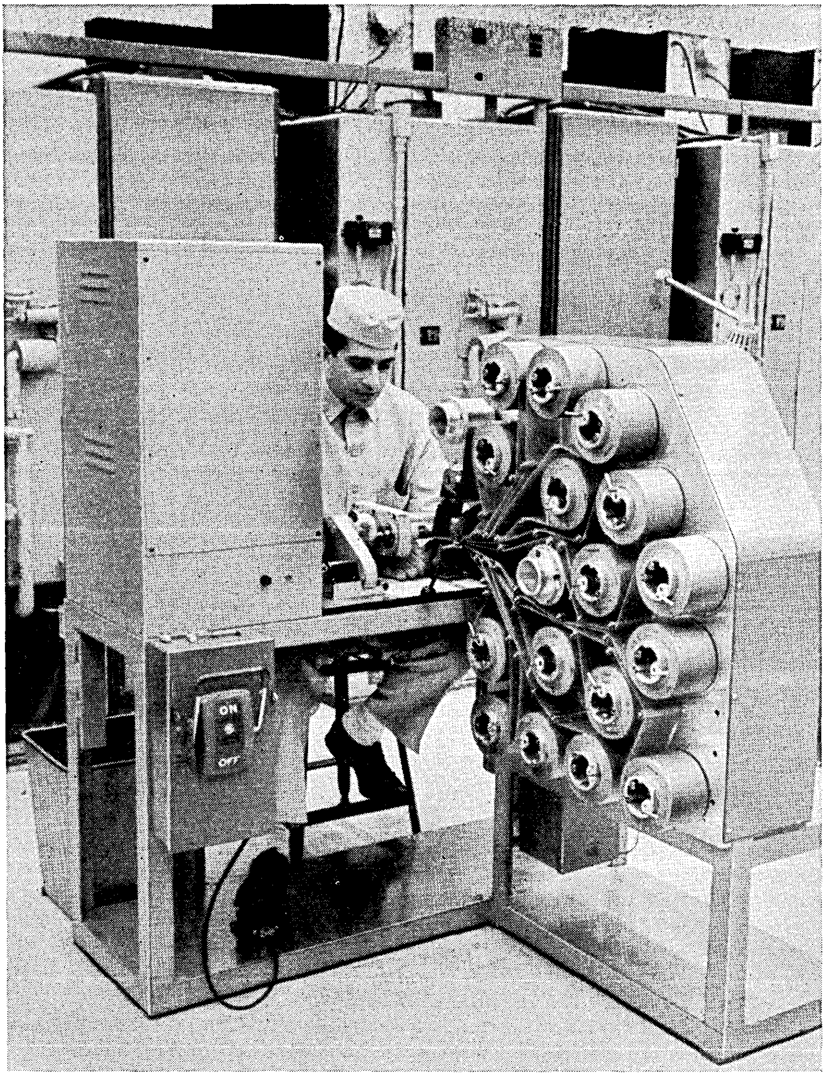


Fig. 4 — Capacitor winding machine.

positions. The milling head can be swung in position over the repeater welding area for removal of the surface layer to expose a clean metal surface for welding. The milling head is also used for removing the weld when repair is necessary.

The welding head uses nonconsumable tungsten electrodes with

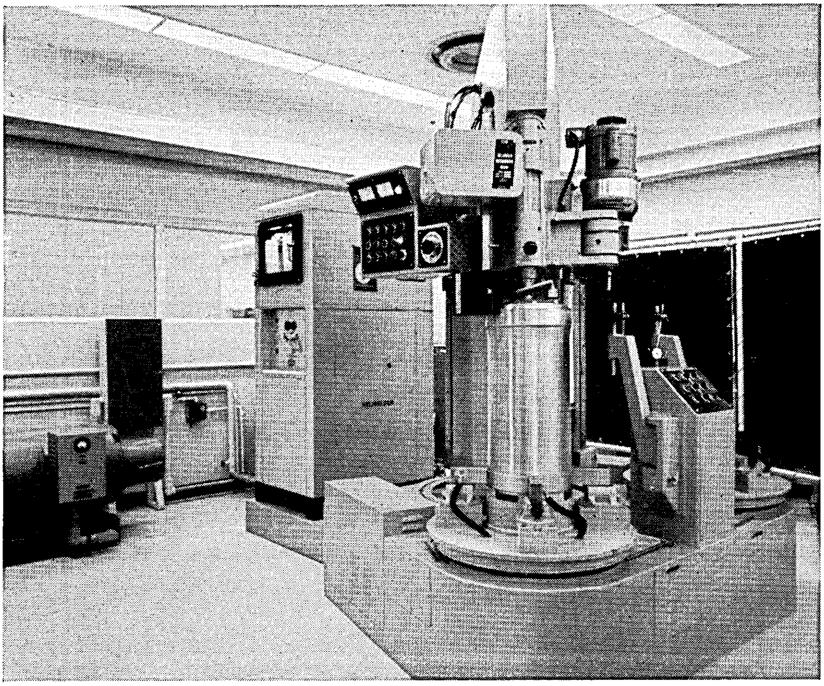

Fig. 5 — Repeater welding machine.

means for automatic control of the electrode gap. The current to the arc is furnished by a balanced-wave ac power supply which eliminates the dc component produced by the rectifying action of the beryllium oxide formed from beryllium in the copper alloy. A large dc component will reduce the stirring action produced by the ac current. A 30 kva regulated motor generator set is provided to eliminate the variations caused by the usual fluctuations in line voltage. The welding arc is shielded by an argon gas curtain.

The whole welding cycle, which takes approximately three minutes, is automatic. The cycle is started by pressing a button, and at the completion of the weld the current is tapered off to eliminate lap in the weld.

The high-pressure helium leak testing facilities will permit testing at pressures up to 12,000 lbs per square inch. Three-stage piston pumps are used with velocity and glass wool filters to keep the helium gas free of oil vapors from the pump lubricant. The pressure vessels are made from alloy steel and all gas-tight seals are made with O rings. The closure plugs for the vessels are held in place by heavy threaded sleeves which screw into the mouths of the vessels. To prevent extrusion of the O rings as the clearance between the vessel and the end plug increases due to expansion of the vessel at the higher pressures, a double O ring arrangement with an auxiliary steel ring is used. The steel ring fits inside the vessel and rests against the closure plug. Between the ring and the vessel is an O ring, and between the end of the steel ring and the closure plug is another O ring. As the pressure inside the vessel is increased, the steel ring expands and is also pushed up against the closure plug by the pressure, thus maintaining a tight gas seal. The lower part of the high-pressure vessels for testing complete repeaters is below floor level in a pit, whereas smaller vessels for testing covers, etc. are above floor level. The high-pressure pumps and test vessels are surrounded by heavy boiler plate enclosures as a safeguard for personnel in case a fitting or pipe should give way. The enclosures are open at the top to permit rapid escape for gas. Access to the vessels is through heavy doors, also of boiler plate, which are interlocked so that pressure cannot be applied while the door is open and so that when pressure is on the door cannot be opened. The application of pressure, the operation of pumps, and the flow of helium are controlled from a common control console. All high-pressure piping interconnecting units in the test set-up is run in troughs in the floor which are covered with heavy steel plates. Hoists on overhead tracks are used for handling repeaters and the heavy fixtures used in the high-pressure testing operations. The hoists are arranged to cover the entire test area.

A lead-shielded room has been provided for isotope testing of the pinch weld on the tubulation which gives access to the inside of the repeater housing. The operation has been automated to a fair extent. The application of isotope solution under pressure and removal of it after a specified pressure holding period and following washing cycle are programmed and controlled by push buttons, eliminating the need for the operator to be close to the source of radiation. The set-up is shown in Fig. 6.

Special molding presses were provided for molding polyethylene in seals and anchor details for repeater couplings. These presses are of three sizes: 10, 15, and 50-ton clamping pressure. Means for programming the molding cycle and recording temperatures and pressures and timing for injection of the polyethylene have been included. Arrangement for stabilizing the temperature of the cooling water for the molds has also been incorporated.

### 7.2 *Electrical Test Equipment*

To avoid operator error in writing down or transcribing test results, test sets are equipped with automatic readout, and, in some cases,

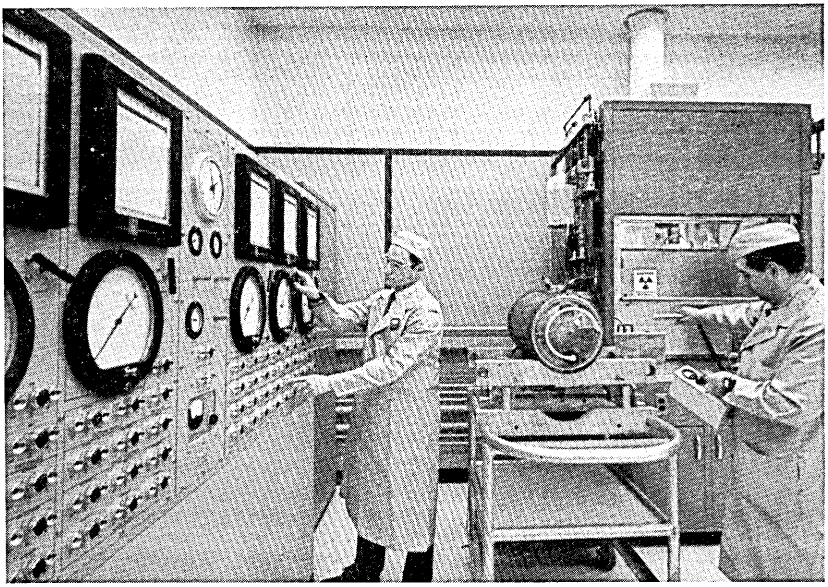

Fig. 6 — Isotope test facilities.

automatic balancing features. For example, in testing capacitors, the operator inserts a section of a punched card, punched with the type of test to be performed, apparatus code, and test limits, in the data transmitter. A smaller card section with the operator's identification and the test set identification number is also inserted in the data transmitter. The capacitor to be tested has a tag attached in the form of a small section of a punched card, punched with the serial number and the apparatus code. This card is inserted in a second data transmitting section after the capacitor has been connected to the test terminals. Next, the operator pushes a button which causes the bridge to balance itself rapidly and show the result on the dials. At this point the operator pushes a button on the transmitting panel which transmits the information on the three card sections, plus the reading of the test set, to a data center, where a receiver connected to a punched card punch receives the information and creates a card punched with the complete information transmitted, plus the time the data were received. In the data center the data card is compared to a standard card punched with the test limits and an indication whether the capacitor met requirements or not on that particular test. Upon completion of all the tests on an item of apparatus, the data from the individual cards are collected on a master card which is used for verification that the apparatus item has gone through all of the process steps and has met all requirements. A computer is available in the data center for making calculations where needed and performing the more complicated verification operations. A diagram of the flow of information from the test sets to the data center and processing of the data cards is shown in Fig. 7.

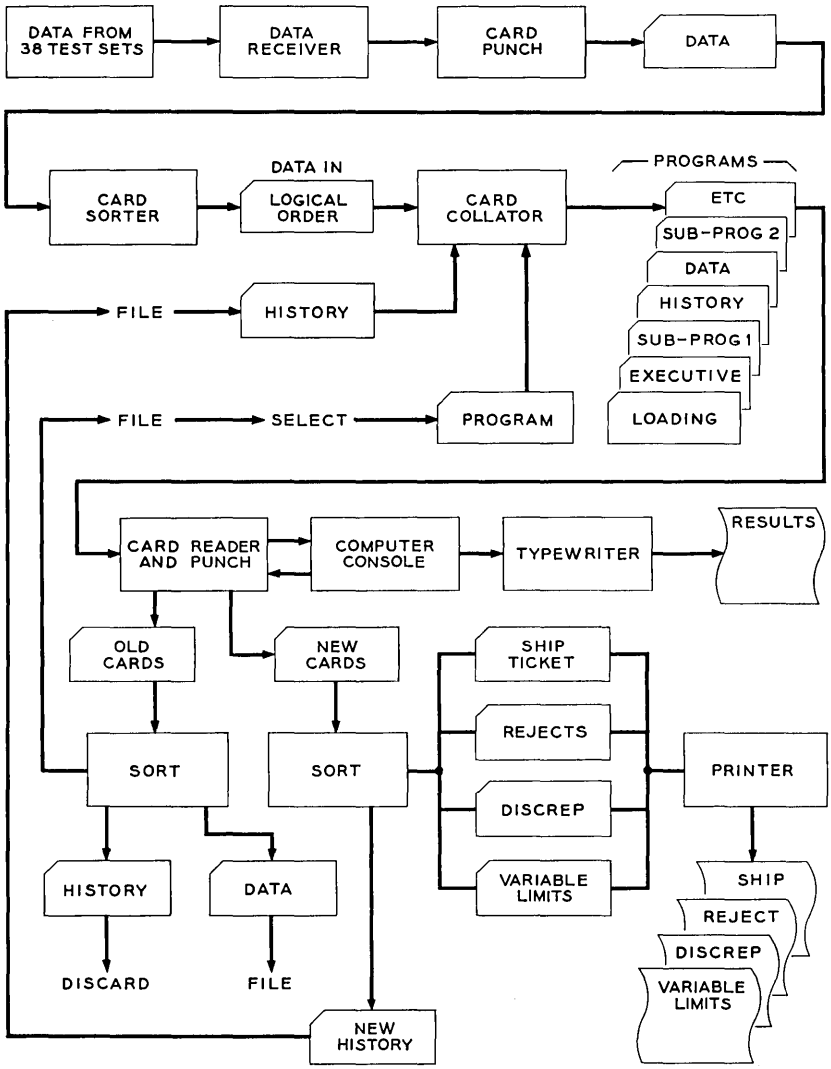


Fig. 7 — Flow of information from test set to data center, and processing of data cards.

A digital voltmeter method is used for measuring the insulation resistance of capacitors, since this method lends itself well to the required conditions of the test and is adaptable to read-out and transmittal of information to the data center. The insulation resistance measurements must, to be consistent, be measured at a predetermined time after application of the voltage, which must also be held precisely at the desired value.

Maxwell-type bridges capable of accuracies of ±0.02 per cent are used for inductance and effective resistance measurements. This accuracy of measurements is obtained by limiting the range of the bridge and by careful selection of components and their over-all assembly in the bridge. Since only a limited number of frequencies in the 20-kc to 2-mc range were required, it was possible to use the "difference frequency" from fixed crystal heterodyne oscillators, which are simple and quite stable. The detectors used to indicate bridge balances are selective to the test frequency to eliminate errors from harmonics in the oscillator output.

Measurements of resistance on resistors are made by passing a known current from an exceptionally well-regulated current supply through the resistor and then measuring the voltage drop across it with a digital voltmeter. This accomplishes resistance measurements to within ±0.01 per cent with a simple arrangement for transmittal of the resistance readings to the data center. A standard cell is used as reference in the voltmeter, and Zener diodes serve this purpose in the current supply.

For measuring the transmission characteristics of networks, filters, amplifiers, and completed repeaters, automatic transmission sets covering the 50-kc to 2-mc range are used. These sets are programmed to test at a certain number of frequencies over the desired transmission band. The results are sent in to the data center and recorded, and are also typed out on an automatic typewriter connected to the set. The programming of the set can be changed as required to perform tests at any frequency desired within the range of the test set. The test set, shown in Fig. 8, is housed in three floor cabinets, one containing the heterodyne oscillator and associated power supplies, the second the measuring circuit, and the third the indicating and readout equipment.

Phase and loss test sets capable of outstanding accuracy for measurements on networks, amplifiers, and repeater units outside the transmission band, at frequencies up to 30 mc, are constructed using a number of standard purchased units. These units, the majority of which are of German make, have performed very satisfactorily

For adjusting filter and other network circuits, visual return-loss

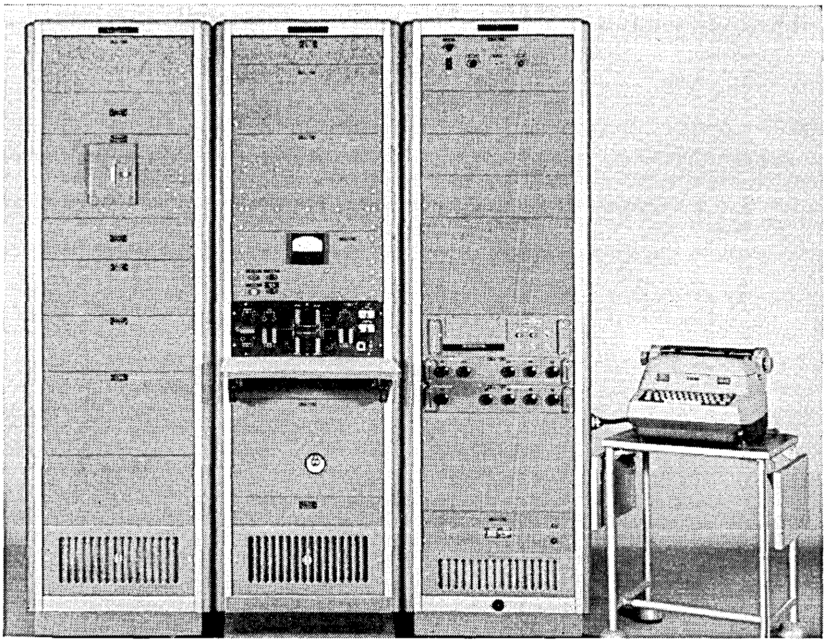

Fig. 8 — Auto-balance transmission measuring test set SID-100799, group 1 (front view).

sets have been provided. On these sets the transmission characteristics with frequency for the apparatus under test are displayed on a 17-inch picture tube.

Practically all test sets are provided with automatic readout, which requires a 150-conductor cable connection to the data center. The cables, which are run in the floor ducts mentioned earlier, are terminated in plug-in sockets under the test sets on the benches or the floor, depending on the type of test set.

## VIII. JOB LEVELS AND PERSONNEL

Assignments among the people performing work directly on the repeater have, as at Hillside, been divided into nine different job levels, depending upon the requirement on skill and tour of duties. The lowest level includes assignments such as helper and materials handler, whereas the highest level entails duties which are much more complicated, such as those of the layout operator, whose assignments include operations requiring a long training period and a high degree of skill, and also include some instruction and work assignment duties. At Clark the greater portion of the population is in the four lower grades, with a peak in the third level. This is quite different from Hillside and can be accounted for by a greater breakdown of operations at Clark. The considerably higher production rate of individual components at Clark permits full-time occupancy for one person on just a few operations.

The key personnel — such as engineers, supervisors, and a number of the skilled trades and layout operators — were obtained by transfer from Hillside or Kearny. Other personnel were hired locally, usually within the first three grades. As they acquired skill, they were upgraded into higher grades and trained for the new assignment. The training program used for operators at Clark is similar to the one employed at Hillside.

In establishing the job grades, the requirements and the description of the assignments to be covered were recorded. Based on this and the general knowledge of elementary operations and their "value," the jobs were classified within the nine assignments mentioned. General judgment was used, and the levels and grades were discussed among several supervisors in order to establish a grade which was as realistic as could be obtained.

In hiring personnel and evaluating them, they were interviewed by supervision, in most cases at several levels, and also given standard tests devised for screening applicants for Western Electric employment. In general, the selection has been good and there have been very few cases where employees unsuitable to the assignment have been hired. There did not seem to be any serious objections to the specific work rules applying at Clark with respect to clothing, environment, and other items. As at Hillside, there seemed to be a genuine interest in the over-all project and its success, or what we might call "team spirit."

Communication between operators and supervision in different areas is extremely important. The larger the work force and operation, the more difficult is the task of maintaining these lines of communication. It is believed that the Clark organization of between 500 and 600 people is approaching the maximum which could be safely, from a quality standpoint, and efficiently utilized at one location on a complicated project of this type.

## IX. PROCUREMENT AND TESTING OF RAW MATERIAL AND PARTS

Raw material and parts are purchased according to KS specifications and drawings. Ninety-one suppliers are involved, covering approximately 200 different items of raw material and 1,125 different parts. The raw material includes items from metal bars and wire to plastic material and solvents. The parts are practically all of the metal, molded, and ceramic types.

Most of the raw material specifications are written around the A.S.T.M. standards, but nevertheless a good percentage of the material has failed to meet these general specifications and cannot be used in the product. This applies specifically to metal rods and sheet metal, which were purchased in smaller lots from jobbers. The philosophy of 100 per cent testing, as used at Hillside, is followed. This has paid off in many cases, because individual items in lots of material were frequently found to be entirely different from the rest. A special laboratory is set up at Clark for this testing purpose. It is equipped with facilities for chemical analysis and physical tests on material, including tensile, Rockwell, and microscopic examination.

In a number of cases it was necessary, in conjunction with the supplier, to develop materials to meet repeater specifications. For example, Teflon rod was purchased from two suppliers who did their utmost to produce rod to meet specifications. The main reasons for rejections were minute inclusions of foreign material, probably carbon, and cracking of rod materials during a bend test. To obtain satisfactory material, it was necessary to work with the suppliers and make changes in their processing technique to produce this material in reasonable lengths, free from imperfections. This development work enabled the supplier, in many cases, to place a higher-quality product on the market. This also was the situation on the ceramic items which, although they are parts, were mainly considered as raw materials.

Another unusual material is the singly-oriented polystyrene film for capacitors. As far as we have been able to determine, there is only one supplier in the country for this type of material. This supplier has a small shop with only one other employee. A considerable number of trial lots of this material were made by him and he, too, had to devise and learn a number of new tricks and precautions based on Western Electric's tests before he could produce a satisfactory product.

Of the approximately 200 different types of raw material, over 6,000 samples were tested during the first year, which amounted to over 25,000 different determinations. A large number of these were chemical tests which required considerable time to perform and evaluate.

One difficulty which was encountered was caused by the general lack of knowledge and understanding of our needs for unusual quality. In discussing specifications and drawings with suppliers, there was often misinterpretation of requirements and lack of understanding of the difficulties involved. This resulted, in many cases, in too low a bid and inability to deliver satisfactory parts on time. When additional lots of parts were to be ordered, new suppliers were involved, who had to be indoctrinated and developed to produce the required quality of parts. Although this resulted in considerable engineering effort, it did generally produce parts at lower cost of equal and, in some cases, better quality. On critical parts, where the efforts to produce them were extensive, and where the production of the parts would take up a considerable portion of the capacity of the supplier's facilities, dual sourcing was arranged wherever possible. Also taken into consideration was the possibility of human or natural interference with the flow of material. For example, on the beryllium copper housing and end covers for the repeater enclosure, a second source was developed which is about to produce after nearly a year of effort.

Where the suppliers are located some distance from the Clark shop, the Western Electric supplies inspection organization is called upon to do the inspection at the source, to ascertain that the quality is maintained at the desired level. This arrangement involved training of supplies inspection personnel in different fields to realize new types and levels of quality.

In some cases the suppliers were not able to produce to our original specifications even after considerable assistance. In these instances, detailed analysis of their abilities and present-day manufacturing techniques was necessary before changes in the requirements were undertaken to make it possible to produce parts. This, in general, resulted in changes and tighter requirements on associated parts.

## X. MANUFACTURING EXPERIENCE AT CLARK

### 10.1 *Paper Capacitors*

High-voltage capacitors which must be capable of operating at potentials up to 6600 volts dc are wound with eight layers of 1-mil thick paper between aluminum foil. Proper alignment and tension of the large number of papers and foil did initially present problems, which have been greatly reduced as improvements in winding machine design and winding methods were made and operator skill increased. Some unusual difficulties were discovered after cycling and the six-month life test on the early lots of these capacitors. It was found that the weld between the foil and the flag terminals had ruptured, which caused variation in the impedance of the capacitor. The weld rupture apparently was caused by mechanical forces, including expansion and contraction with temperature and vibration, during the temperature cycling and life testing processes. The difficulty seemed to be connected mainly with insufficient flexibility of the internal leads from the capacitor units and insecure wedging of the capacitor units within the can. The problem was solved by increasing the flexibility of leads, improving mounting of the capacitor units, and changing the welding cycle to improve the weld.

Another difficulty was indication of denser metallic particles within the capacitor assembly on X-ray examination. In a number of cases this was found to be inclusions in the steel of the can caused by brazing alloy splashed during the assembly of mounting lugs. To avoid unnecessary rejection, the cans are X-rayed before assembly. Where these inclusions are found, a notation is made in the record so that in the final X-ray of the completed unit inclusions which are not harmful can be disregarded. The selection of paper, winding technique, and impregnation followed the earlier Hillside pattern.

The low-voltage paper capacitors use 0.3-mil thick paper in three and four layers between the foil. The low-voltage capacitors are also manufactured in a manner similar to that used at Hillside. However, one difficulty which was experienced might be worth mentioning. Some of these capacitors have a combination enclosure consisting of a ceramic cup and a metallic cup. The metallic cups were made from steel rods by turning. It was found that the steel, although it met all test requirements, had minute inclusions in it which were dissolved during the chemical cleaning and plating processes, producing a porous condition. This did not in many cases show up before the leak test of the completely assembled capacitor. The difficulty was overcome by a change to a cup drawn from sheet steel.

During impregnation, special precautions had to be taken to assure that the oil level in the capacitor was of the proper height. If the capacitor cooled down too rapidly, the excess oil would not have an opportunity to escape before the final sealing, causing the pressure to build up during cycling to a point where it would rupture the enclosure. By providing an infrared heating lamp over the capacitor in the sealing operation, the temperature is maintained and the desired oil level is obtained.

Based on the experience at Hillside and further study and work on causes for rejects, the over-all yield has been improved to the point where it exceeds that at Hillside. A general picture of the yield is shown in Fig. 9.

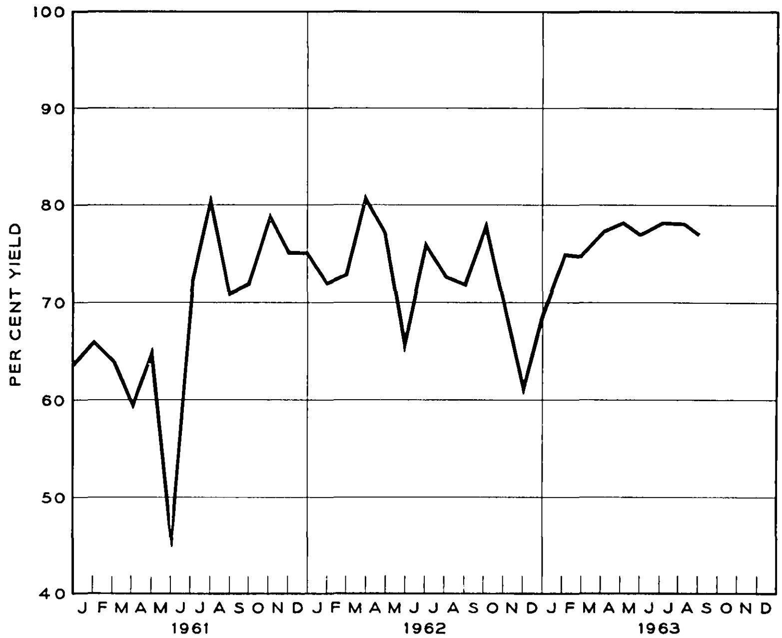


Fig. 9 — Paper capacitor yield.

10.2 *Polystyrene Capacitors*

This is a new type of capacitor used for the first time in Bell System repeaters. A singly-oriented polystyrene film is used. Since this film has a very high insulation resistance and easily becomes statically charged, it has a tendency to pick up dust and foreign particles during winding. It was necessary to enclose the spools on the winding machines with Plexiglas covers and to perform the winding in an area of 35 to 40 per cent humidity. The wound capacitor unit is heat treated to shrink or coalesce the polystyrene film around the foil to exclude air pockets and produce a homogeneous unit. The capacitor units are then mounted in metal cans having ceramic button insulators at one end. No air drying or special treatment is given the capacitor units during mounting.

After manufacturing these capacitors for nearly a year, using the original lot of polystyrene film, difficulties with cracks in the film were encountered when the leads were soldered on the units. Several changes were made in the soldering technique and some in the winding processes to avoid undue strains in specific areas. However, this did not entirely solve the difficulty, since it apparently became inherent in the polystyrene film after storage for a period of time. A new supply of film solved the difficulty, and presently the supply is being held to a maximum storage interval of six months. In reviewing the manufacture of this type of capacitor, a most important aspect seems to be the supply of good polystyrene film. A graph of the inspection yield of polystyrene capacitors is shown in Fig. 10.

10.3 *Mica Capacitors*

In designing the mica capacitors for the SD repeater, greater margin was provided between the silvered areas and the edge of the mica laminations than for the flexible repeater. This has made possible a sizable increase in yield, as has a change in design to omit cementing operations.

The silk screen method is still being used for application of the silver coating to the laminations. However, in place of the hand method, the machine described earlier is used. With this tooling, greater accuracy of size and location and fewer blemishes and other similar defects of the coated areas have been obtained. This also applies to the firing method, in which the silver is fused to the mica. It was found that minute particles in the firing furnace from carbonized silver paste vehicle and lint from operators' clothing and other sources would settle down on the coated laminations before the coating had dried. By predrying

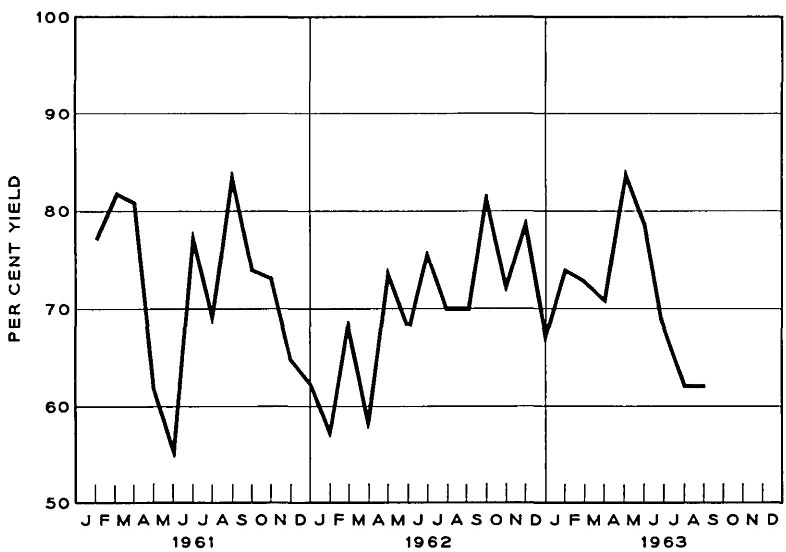


Fig. 10 — Polystyrene capacitor yield.

the laminations under infrared lamps before they enter the tunnel furnace, and providing better exhaust of the smoke from the vehicle, rejects for this cause have been reduced considerably.

Cracking of mica during the crimping of terminals has also been reduced by improvements in method and, to some extent, terminal design. Approximately half of the mica laminations are actually used in repeaters. Fig. 11 is a graph of the yield that has been obtained.

### 10.4 *Inductors*

All inductors are machine wound, a variation from the flexible repeater procedure, where the majority were hand wound. The winding time per unit has been decreased considerably for inductors with such strict requirements. Most types are wound in an hour or less. The change to polyurethane-insulated wire has made it easier to strip and tin without necking down the wire. A change in the other direction is the extensive use of Litz wire having up to 90 strands of No. 40 wire. However, it has not presented any unusual problems from the standpoint of cleaning and soldering. The Litz wire is used mainly in the coils for directional filters where a high and uniform $Q$ value is important. To obtain the desired uniformity, all wire needed for foreseeable projects was manu-

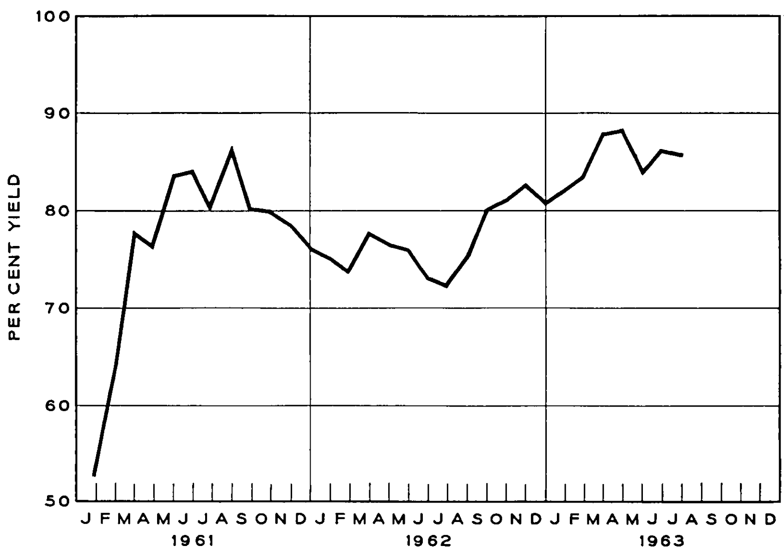


Fig. 11 — Mica capacitor yield.

factured at one time. This is important, since the type of equalizer used in the cable system is determined by the directional filter characteristics which, in turn, depend to a great extent on the $Q$ value of the inductors.

As far as winding is concerned, there were, in general, no unusual problems that required extensive development work to solve. One exception to this was the progressive duolateral winding of some of the filter coils. Here the adjustment of tension, speed of the machine, play in the machine, and several other factors required considerable cut-and-try effort and development before a satisfactory winding could be produced.

When we speak about inductors, we may separate them according to the winding type: (1) single layer, (2) double layers in parallel, (3) progressive duolateral, (4) straight duolateral, and (5) toroidal with Permalloy dust cores. A number of the solenoid inductors are adjustable over an average range of $\pm 1$ per cent by means of carbonyl iron cores. Difficulty in cementing the cores into the threaded carrier was resolved by applying the cement to the bottom of the carrier and then inserting the core. The most tedious coil to wind is a toroidal coil, where Mylar tape insulation has to be applied under the winding and between layers of the winding. This particular coil requires close to a full day for winding, although it is small and requires relatively few turns.

Practically all of the solenoid coils are wound on Mycalex cores which are held to close dimensional tolerances. The majority of the coils therefore require adjusting only by the adjustable core, since the number of turns per inch is also held to close limits. Fig. 12 shows the yield obtained on the inductors in general.

### 10.5 *Transformers*

The six transformers used in the repeater have ferrite cores which are manufactured at Hawthorne. Two of the transformers have Mycalex winding forms and the remaining four have diallyl phthalate forms. The secondary winding is wound on an inner spool and the primary on an outer spool in single layers. Some difficulty was experienced in obtaining the desired uniformity of winding and placing the shields between the windings properly to obtain the required direct and distributed capacitance values, which are important to meet the desired transmission characteristic. Cracking of the ferrite cores was also experienced. This was connected with the process of cementing the core sections and the winding form to the core. By changing the cementing technique, undue stress in the cores from the shrinking of the cement while drying was avoided and the difficulty cured.

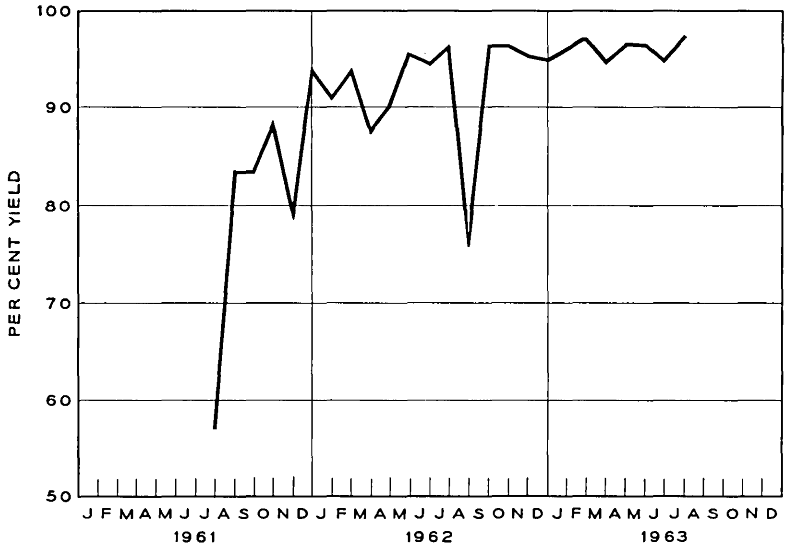


Fig. 12 — Inductor and transformer yield.

### 10.6 *Resistors*

Two types of wire-wound resistors are made at Clark, one using straight resistance wire, the other mandrellated wire made at Buffalo. Both types are wound on Mycalex spools which have gold-plated nickel pigtail leads. The ends of these leads at the spool winding area had to be flattened and notched to produce a fork-like terminal to hold the resistance wire. Originally this was incorporated in the lead wires before molding into the Mycalex spools. However, difficulty with closed slots and dirt in the slots from the molding operations caused considerable trouble. To overcome this, a special tool was developed for flattening the leads and producing the notch after molding of the spools. No unusual difficulties in brazing the resistance wire, such as experienced at Hillside, were encountered. This could be accounted for by the knowledge gained on facilities, materials, and operators' skill from Hillside. The yield on resistors is now running above 90 per cent, as shown in Fig. 13.

### 10.7 *Composition Resistors*

The composition-type resistors are purchased to specifications which stipulate special precautions on an otherwise standard product. Purchased resistors are then subjected to a selecting and screening process, followed by a six-month life test. Special precautions are taken with some of these test procedures to avoid secondary effects caused by a change in moisture content, which affects the resistance values considerably. In the low-temperature cycling test, where the resistors are brought down to $-100°F$, the humidity of the air in the test chamber was reduced to less than $\frac{1}{10}$ of 1 per cent. Four different resistance values are used, from 11,000 to 500,000 ohms. The yield, surprisingly enough, varied considerably among codes and lots of resistors. Over-all, approximately 28 per cent of the resistors purchased end up in repeaters.

### 10.8 *Enamel Resistors*

The two codes of vitreous enameled resistors used in the heater circuit and heater protection circuit are purchased. The manufacture of these resistors required special facilities, including air-conditioned space, at the supplier's plant. Considerable change in his methods and procedures was also necessary.

### 10.9 *Networks, Filters, Amplifiers, and Repeater Units*

From the standpoint of manufacture, the mechanical assembly of networks (shown in Fig. 14), amplifiers (shown in Fig. 15), and repeater

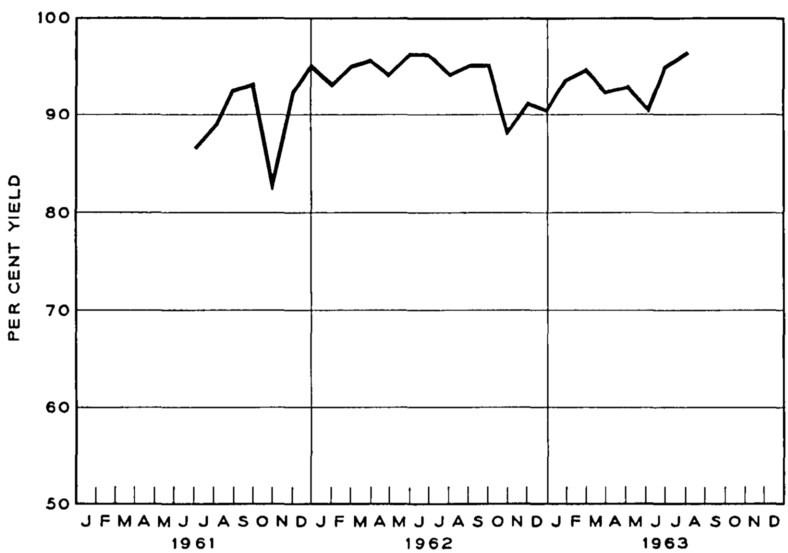


Fig. 13 — Precision resistor yield.

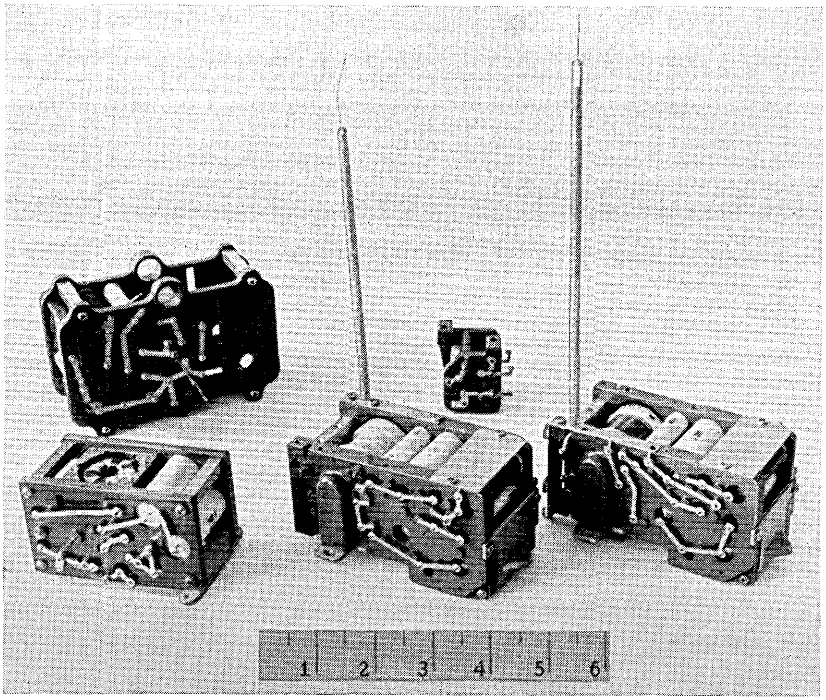


Fig. 14 — Networks.

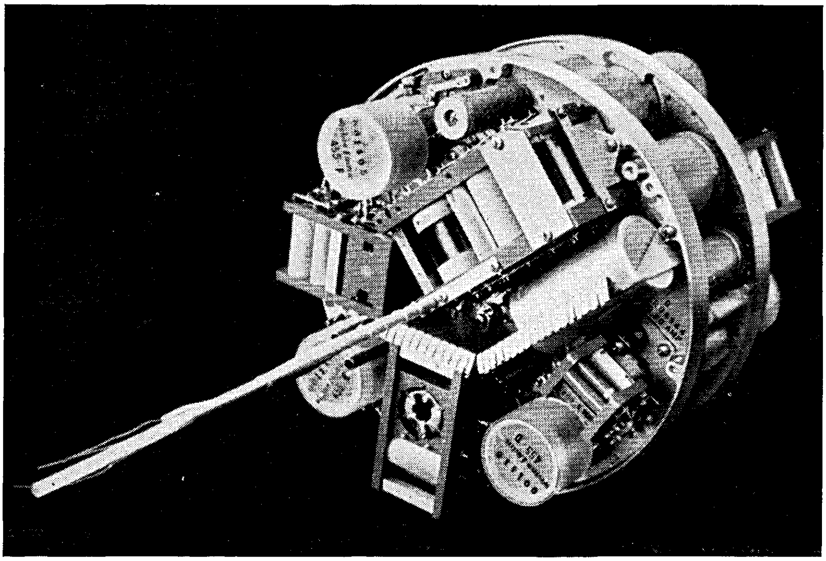

Fig. 15 — Amplifier.

units is fairly straightforward. However, from time to time difficulties with minor imperfections in the aluminum castings and molded parts involved have plagued the production.

Establishment of realistic electrical test limits at the start of production would have been a great advantage if this could have been done. Although the well controlled mechanical assembly and use of wiring strips defined parasitics quite well, small deviations from anticipated values occurred and were difficult to explain and trace.

An innovation worth mentioning in connection with the assembly of these units is the soldering technique developed for connecting wiring strips to the apparatus leads. Preformed rosin-core solder rings and a carbon electrode for heating are used. The solder rings are placed around the leads on top of the straps. A metal electrode is placed on the strap to be soldered, and a current is passed through the carbon electrode and the solder ring to the strap. A timing device limits the heating to a safe value.

### 10.10 *Repeater Closure*

After assembly of the repeater unit, it is tested for gas tightness, using a helium mass spectrograph leak detector, and then vacuum dried approximately 100 hours while heated to 130°F. This is considered to be the start of closure operations.

After vacuum drying, the repeater unit is covered with an epoxy coating to provide the necessary electric insulation between it and the outer housing which surrounds it. The housing is at ground potential, while the repeater unit is at cable potential. The coating is about $\frac{5}{32}$ inch thick and covers the repeater unit completely. The epoxy, a mica-filled compound, is carefully mixed immediately before use and degassed in a bell jar under vacuum. In applying the coating, small epoxy areas or lands are first cast on each end of the unit. These lands are used to locate the final mold, which completely surrounds the repeater unit. Each end requires approximately 24 hours for the epoxy to cure. The mold consists of two cast-aluminum half cylinders which are locked together around the repeater unit and have attached to them end covers matching the repeater unit shape. The end covers rest on the epoxy lands and line up the rest of the mold with respect to these lands. In filling the mold, the epoxy compound is poured into an injection cylinder, the lower part of which is connected to the bottom of the mold by means of a flexible hose. Air pressure is then applied to the cylinder above the epoxy compound, which is forced into the mold from the bottom. Since a considerable amount of heat is developed in the compound from the curing, which starts as soon as the compound is mixed, the injection cylinder is water cooled to limit the temperature and slow down the curing. Two transparent plastic tubes are provided on top of the mold as risers for the compound, which shrinks to some extent as it cures. To eliminate voids in the coating, a slight air pressure is applied through the risers on the epoxy in the mold. This will permit the epoxy to flow slowly as it cures from the bottom up. To favor curing from the bottom up, the mold is heated by a warm air heater placed externally at the bottom. Any voids that appear after the casting process are filled in, using a tinker's dam.

After epoxy coating, the repeater unit is inserted in the outer beryllium copper cylinder, where it is held in place by Fiberglas springs resembling venetian blind slats. These springs serve as additional electrical insulation and at the same time as a cushion against shocks to which the repeater may be subjected during laying operations, such as hitting the sea bottom. A hydraulic jack is used to push the repeater unit into the outer cylinder. The cylinder is then placed in the assembly machine, Fig. 16, where it is held in place in the center of the machine while two end covers with the required seals in them are held in the fixture just outside the cylinder and lined up with the bore in the end of the cylinder. While the end covers are held at some distance from the cylinder, the leads are spliced together, and the joint is over-molded with polyethylene to insulate it and X-rayed. The X-ray, which is taken in two planes, determines the concentricity of the polyethylene insulation and ascertains whether it is free from foreign particles or voids.

After making all connections to the repeater unit and shielding and taping the leads, the leads are coiled up inside the end of the cylinder while the cover is being pushed in place. Coiling of the lead is done automatically in the assembling machine while the cover is pushed in place. As the heavy circular-disk Fiberglas spring attached to the end cover of the repeater locates the repeater unit in an axial direction inside the cylinder, a certain amount of pressure is applied to the repeater unit from the end covers. The covers are secured with steel clamps, which are bolted to the cylinder using the threaded holes in the periphery of the cylinder. The repeater is then removed from the assembly machine and is ready for welding the end covers in place.

After the repeater is trued up on one of the turntables on the welding machine, the milling head is swung out over the repeater and the surface of the edges of the cover and cylinder lips is milled off to remove the fine layer of beryllium oxide which forms fairly rapidly on beryllium copper. Next, the milling head is swung out of the way, the welding head is moved in place over the repeater, and the starting button is pushed.

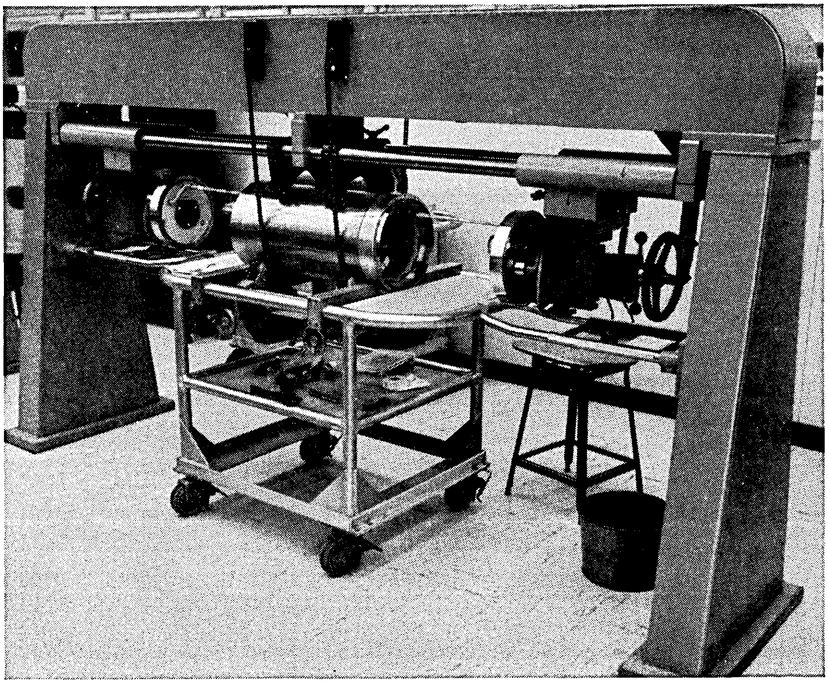

Fig. 16 — Repeater assembly machine.

This starts the turntable, turns on the argon shielding, and starts the arc by means of a high-frequency discharge between the electrode and the repeater. The arc is played on the lips of the cover and cylinder and melts both to form them into a rounded bead over the area while they are being rotated. An ac voltage of about 14 volts and a current of approximately 270 amperes is used, and the repeater is rotated at $\frac{1}{3}$ rpm.

To ascertain that the weld is of sufficient depth, an ultrasonic test is performed in a water bath at a number of points around the circumference (see Fig. 17). The required minimum is $\frac{1}{16}$ inch, but the welds usually run close to twice this.

The repeater is now ready for a high-pressure helium leak test, during which it is subjected to helium at a pressure of 11,600 pounds per square inch on the outside, while the inside is evacuated and then connected to a mass spectrograph leak detector. Before the repeater is placed inside the large steel test vessels, it is surrounded by a "dead man." This consists of an aluminum cylinder in two halves placed on the outside of the repeater cylinder and blocks at each end, which are hollowed out to fit

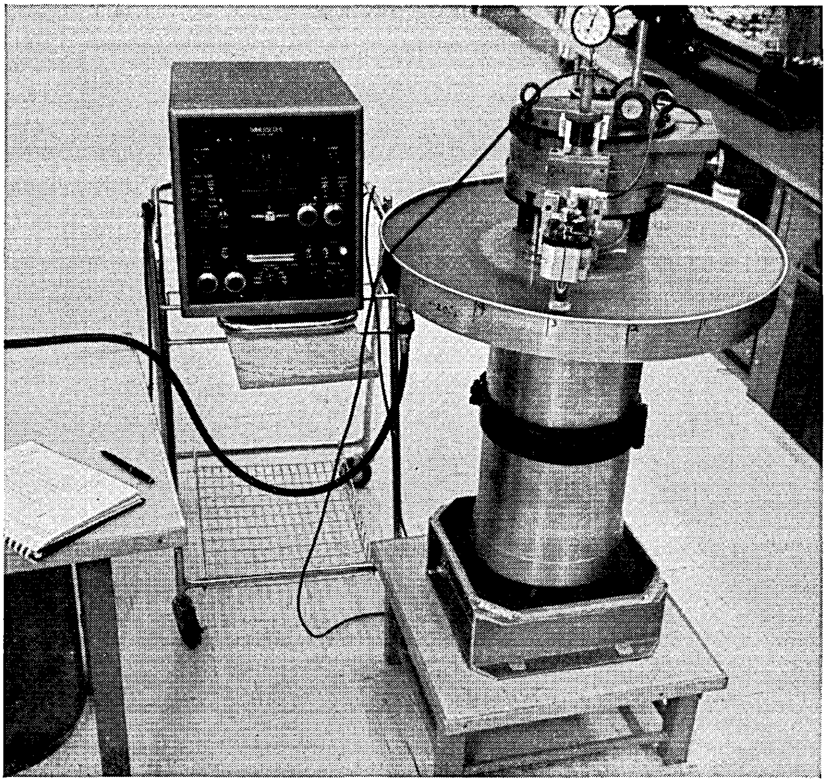

Fig. 17 — Ultrasonic test of weld.

closely over the covers and seals. This reduces the free volume in the test chamber and thus keeps the total amount of energy stored in the compressed helium to a minimum for the sake of safety. The pressure on the repeater in the vessel is increased gradually to the test pressure, held there for close to an hour, and then decreased over a period of about an hour to avoid damage to the polyethylene leads. Before inserting the repeater in the test vessel, the polyethylene-insulated pigtail leads are wrapped with polyethylene tape to avoid penetration of helium into the insulation, as this may produce minute blisters as the pressure is reduced.

The helium gas is reused; only a small amount is exhausted for each test. From the regular gas cylinder, two larger storage vessels are filled at a pressure of 2,000 psi. From here, the gas is pumped into a smaller high-pressure storage vessel at 13,000 psi, from which the gas is controlled through a console and slowly bled into the test cylinders until the desired pressure is obtained. During this operation, helium is pumped into the storage vessel to maintain pressure. When pressure is released, the gas is first bled back to the 2,000-psi storage vessels and below this pressure into a low-pressure storage tank, where it is held at approximately 100 pounds pressure.

When a repeater has passed the high-pressure helium test, the tubulation which connects the leak detector to the inside of the repeater is still open and must be closed. This is done by pinch-welding while the inside of the repeater is filled with dry nitrogen to a pressure of approximately 2 pounds. To ascertain that the pinch-weld is satisfactory, a test using a radioactive isotope is performed. A small cylinder is placed over the tubulation and held in place by a heavy fixture. The cylinder is filled with an isotope solution on which pressure is applied to bring it up to 11,600 pounds per square inch. This pressure is maintained for six hours; then the isotope solution is drained off and the tubulation and the cylinder thoroughly washed. Any penetration of the isotope solution would be detected by a high count on a measuring instrument. This whole process, which has a fairly involved filling and washing cycle, is done semiautomatically. Valves are opened and closed automatically, permitting wash water, air, and the isotope solution to be moved in and out of the small test chamber as required to perform the test.

Electrical tests are performed on the repeater before welding and after the complete leak test to ascertain that it meets requirements. The last operations are forming and annealing of the pigtail leads, mounting of the end cones, and painting. After this the repeater or equalizer is ready for packing and shipping.

Included in the closure operations is manufacture of the seals for the repeater unit and the repeater. The seals use polyethylene for insulation and permit electrical connections to the inside of the repeater or equalizer circuit. In the case of the repeater a seal against sea pressure is provided. The repeater unit seal is a barrier to water vapor. In molding the seals the metal outer housing and center conductor, which have a layer of oxide applied chemically to assist bonding them, are held in place in a mold, and polyethylene is injected to fill the spacing between, and bond to, these metal parts.

The molding of satisfactory seals has been the most difficult operation on the whole project to master and control. There are still unknown factors which are difficult to control and evaluate.

The main difficulty is obtaining a good bond between the polyethylene and metal and at the same time attaining the required electrical characteristics. Nearly a year was required to bring this process under reasonable control. Numerous small changes were made during this period to improve the design. They consisted mainly of controlling the bonding areas by restricting bonding to the outer shell to certain limited areas to avoid internal stress in the polyethylene. Also, a period of rest in the order of four to ten days was required for the seal after molding, to permit relaxation of stresses in the polyethylene.

## XI. VERIFICATION OF COMPLETED REPEATER

As in the case of the flexible repeater, the rigid repeater is verified before shipment to ascertain that every operation has been performed and all requirements have been met. This includes every raw material item, piece part, and subassembly.

All electrical test results except simple go or no-go tests are punched on cards. The results of the go or no-go tests and mechanical inspection are entered manually on the punched card section attached to the apparatus by the inspector performing the test. This inspector also verifies that prior operations have been performed satisfactorily as indicated by the entries on the card section. When an apparatus item is completed, inspection visually verifies from the card section that all operations have been performed and accepted. A final-acceptance punched card, indicating that all operations have been completed, is originated and forwarded to the data center for verification of the electrical requirements before releasing the apparatus for use in the product.

In the data center the test data cards are sorted by group code, serial number, and operation number, to put them into logical order. The test data cards and unit history cards are now collated by group code and serial number. Next, the data and history cards are collated with computer program cards by group code. Finally, the combined cards are placed in an IBM 1620 computer where the data cards are read and the limits checked, as called for by the program card, and a punched output of verified test data is produced. Any errors in the data cards or in the processing of them are detected by the computer and a listing is automatically typed. Before proceeding with the verification, the items listed are corrected. After removal from the computer, the punched cards are run through a printer, where the components are listed as satisfactory to ship or to be rejected, depending on which is to apply.

All data pertaining to the assembly of a repeater are compiled in two data books — one covering mechanical items and the other electrical information. The data are entered by hand in these books by the individual operators and inspectors. All component apparatus assembled into a repeater is listed in the mechanical data book and identified by code and serial number. Pertinent electrical test data, which are compiled on punched cards, are printed or typed on a sheet which becomes part of the data book. These two books are jointly associated with the repeater assembly until completion of the repeater, at which time the books are merged into one repeater data book for a specific repeater. This data book is verified by Western Electric inspection representatives and then pertinent data (primarily electrical) are check-verified by the customer's representative before the repeater is accepted and released for shipment.

For each repeater and its components there are about 3,750 separate electrical tests involving 38 test sets of 20 different types, in addition to all other tests and inspections. Approximately 3,000 punched cards, punched with up to 40 items and with up to 40 written-in items, are required, along with approximately 17,200 entries in the data books.

## XII. PACKING

In preparing for shipping, the open end of each of the end cones on the completed repeater is closed with a Lucite cover. An impactograph to register any shock to which the repeater may be subjected during handling and shipping is mounted on one cover. On the other cover is mounted a min.-max. temperature indicator which will show whether the repeater has been subjected to temperatures in excess of 120°F or below 0°F during storage and transport. Next, the repeater, which weighs around 500 pounds, is mounted on a $5 \times 2\frac{1}{2}$-foot flat between two rigid foam plastic housings which fit over the ends of the repeater and are held together with the repeater between them by four $\frac{3}{4}$-inch steel tie rods. In case of excess shock, the foam plastic will crush and reduce the shock on the repeater. The housings, in turn, are bolted to the flat and a wooden cover is placed over the assembly and strapped to the flat. The cover has a sliding door at each end for reading the impactograph and temperature indicator. The packing arrangement, which is reusable, is identical for both repeaters and equalizers and is designed for handling by a fork lift truck. It is also relatively inexpensive, which is of particular advantage in cases where it would be impractical to return it for reuse.

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# Electron Tubes for the SD Submarine Cable System

By V. L. HOLDAWAY, W. VAN HASTE and E. J. WALSH

(Manuscript received April 16, 1964)

*Three new codes of electron tubes of the high reliability that is required for submarine cable service have been developed for use in the type SD systems. The basic philosophy was much the same as that which proved successful in designing tubes for the earlier cable systems. However, in order to meet the one-megacycle bandwidth requirement of the new system, it was necessary to extend such amplifier tube design considerations as transconductance, cathode current density and interelectrode spacing. The emphasis in this paper is on designing for reliability, since the amplifier tube is electronically quite conventional. In the field of protective devices, the new gas-filled cold cathode tubes also offer conservative and reliable applications of established design techniques.*

## I. INTRODUCTION

Three codes of electron tubes have been designed and developed specifically for use in the SD submarine cable system: the 455A-F, 456A, and 458A. The 455A, B, C, D, E, and F are pentode-type amplifier tubes manufactured as one type and subsequently designated for the six amplifier sockets to obtain optimum repeater performance. The 456A is a gas-filled cold cathode tube used as a power bypass device to (1) protect the heaters of the amplifier tubes, and the low-voltage components in parallel with them, from transient high-voltage surges on the cable and (2) to provide a continuous path for the cable current in case of an open heater in any of the amplifier tubes. The 458A signal path protector is a high-speed gas-filled cold cathode tube used at both the input and output of the repeater to protect the transmission path from voltage surges.

For a period of approximately two years engineers of the Western Electric Company were resident at Bell Telephone Laboratories to participate in the final development stages of the tubes. As a result of this endeavor the final tube designs and processing schedules represent the combined thinking of both the development and manufacturing organizations.

## II. RELIABILITY CONSIDERATIONS

### 2.1 *Objectives*

Reliability requirements for electron tubes for use in submarine cable systems were formulated for the SB (flexible repeater) system[1] and have not been materially changed for the new broader-band system. Lifting cables for the purpose of changing faulty repeaters will always be an expensive operation. Revenue loss during the out-of-service period increases with bandwidth because of the additional voice channels.

The reliability objective for the tubes may be stated in several ways. Loosely, one hears "no tube failures in twenty years." Actually, the objective adopted is that the probability of system failure due to a tube failure shall not exceed 50 per cent for a twenty-year service period for a 3000-mile system. This objective corresponds to a mean time between system failures of twenty-nine years.

The amplifier tubes (455A-F) are probably limiting with respect to reliability, because they have closer interelement spacings, tight requirements on stability, and are operating continuously, as compared to the gas tubes (456A and 458A), which are on standby duty. Because of this and the large number of repeaters required for a long system, the amplifier includes two parallel strings of three tubes each with the circuit so arranged (see Fig. 5, Section 3.4.1) that the most probable kinds of tube failure will cause a system failure only if both strings are involved. Such defects would be permanent open circuits or short circuits between tube elements. There is no protection against plate shorts in the amplifier output stages, and it is also recognized that a single noisy tube could make the system unsatisfactory for commercial service.

The objective stated above corresponds to a tube failure rate of 0.08 per cent* for twenty years for defects not minimized by circuit redundancy. A failure rate of 2.4 per cent* is the corresponding value where circuit redundancy is provided. In the reliability analysis, it has been assumed that the deterioration due to decreasing thermionic emission would be negligible. This assumption is justified in Section 3.4.2, *Thermionic Life.*

* See Appendix for details.

### 2.2 *Background and Prospects*

The reliability objective and the prospects for adequate stability for the 455A-F tubes for twenty years were based largely on the experience gained from the 175HQ tube used in the SB system where, to date, no tube failures have occurred during more than 80 million tube-hours of sea-bottom operation. In 1955, when development work was started on 455A-F tubes, 18 of the 175HQ tubes had been in sea-bottom service in the Havana-Key West system for about five years with no failures and no significant change in tube performance. Some 50 175HQ tubes of essentially the final design had been life-tested for lengths of time up to about sixteen years at various operating conditions. The results indicated that the transconductance would decrease less than 1 per cent per year at the operating conditions adopted for cable use. Additional life tests on 4800 tubes[1] showed that a 5000-hour aging period was sufficient to cull out substandard tubes and allow selection of those tubes most likely to meet the reliability objective. A 5000-hour aging-in and screening period was therefore adopted for the 455A-F tubes.

Since no gas tubes were used in the Havana-Key West system, no field data were available. However, considerable life testing had been done on the gas tube subsequently used in the first transatlantic system.

This background offered promise that the development of a higher transconductance vacuum tube and suitable gas tubes was feasible, with the stated reliability as a reasonable objective. However, it was evident that unproven materials, processes, and design features should be avoided where possible. Also, the basic philosophy which had been used in the fabrication and selection of 175HQ tubes was adopted for the new tubes. Every significant deviation from the "expected" by an individual or a batch is viewed with suspicion. If the cause can be found and understood, the cloud of suspicion may be removed; otherwise, the affected tubes must not be used. The methods of implementing this philosophy are described in a later section.

## III. THE 455A-F AMPLIFIER TUBES

### 3.1 *Design Considerations*

The 455A-F electron tubes are pentodes of the indirectly heated cathode type using fine-pitch frame-type grids. With the emphasis on reliability and reliance on proved techniques, most of the design features are conventional, some perhaps even old-fashioned. Since optimizing pentode performance characteristics by geometry is an established art, the emphasis of this article is on designing for reliability.

Because of the excellent performance of the 175HQ tube it was used as the datum point for designing the new tube. The most important parameters and operating conditions for the 175HQ and the 455A-F tubes are compared in Table I. This comparison provides a basis for explaining the design considerations involved in the development of the 455A-F tubes.

#### 3.1.1 *Cathode Temperature*

The most important operating factor affecting the thermionic life of the cathode is the cathode temperature. It was decided at the outset that, in spite of the higher current density required, the cathode temperature for the 455A-F tubes would be no higher than that of the 175HQ. Use of a special cathode alloy and improved processing and storage techniques for tube parts made this possible.

#### 3.1.2 *Cathode Current Density and Transconductance*

The higher cathode current density of 10 $ma/cm^2$ is necessary in the 455A-F tube to achieve the higher transconductance. Life tests on 175HQ tubes which had run about fourteen years at a cathode temperature of 710°C showed no significant difference between tubes operated at 0.2 $ma/cm^2$ and those operated at 2.8 $ma/cm^2$. These and other similar results indicated that 10 $ma/cm^2$ was a reasonable operating level. The higher transconductance also requires an improved cathode alloy which develops less interface resistance than the nickel used in the 175HQ tubes.

#### 3.1.3 *Grid-to-Cathode Spacing*

The 0.0055-inch grid-cathode spacing of the 455A-F is also necessary to achieve the higher transconductance. This is perhaps where the great-

TABLE I — COMPARISON OF PARAMETERS AND OPERATING CONDITIONS

| | 175HQ | 455A-F |
|---|---|---|
| Cathode temperature (true) | 670°C | 670°C |
| Cathode current density | 0.7 $ma/cm^2$ | 10 $ma/cm^2$ |
| Grid-cathode spacing | 0.024 in. | 0.0055 in. |
| Maximum element voltage | 51 v | 45 v |
| Transconductance | 1000 $\mu$mhos | 6000 $\mu$mhos |

est extrapolation from the 175HQ (0.024-inch spacing) is involved. Spacings of only 0.0025-inch are successfully employed in several telephone tubes for readily accessible land systems. For the less accessible submarine cable tubes, it was felt that the greater care in fabrication and inspection which is necessary to minimize particles can economically be justified. This would make the 0.0055-inch spacing feasible, even with the high level of reliability required.

#### 3.1.4 *Maximum Element Voltage*

Although there was no indication that the maximum element voltage of 51 volts was high enough to affect the life of the 175HQ tube, it was found possible to operate the 455A-F at 45 volts maximum, which was considered desirable.

### 3.2 *Structural Features*

#### 3.2.1 *Interelectrode Spacings and Foreign Particles*

The design of the tube was strongly influenced by the "particle problem." The reduction in grid-cathode spacing is a serious factor because of the risk of failure due to a particle of foreign matter becoming lodged in this critical area. A conducting particle can cause a short circuit or it can cause noise. A nonconducting particle can cause noise, particularly after it has been subjected for some time to the deposition of the normal vaporization products from the cathode. Noise is particularly serious, since the parallel-path redundancy feature of the amplifier circuit actually increases the risk of trouble due to noisy tubes, because there are twice as many tubes in positions followed by substantial amplification.

The tubes have been designed to minimize particle generation, are fabricated in extremely clean areas using the highest practicable degree of housekeeping measures, and employ selection criteria designed to minimize the hazards due to particle contamination.

#### 3.2.2 *Tube Mount Assembly*

A phantom drawing of the based tube is shown in Fig. 1. The glass envelope, the ceramic base, and the braided gold-plated beryllium copper flexible leads are essentially the same as those used in the earlier cable tubes. The stem of the glass envelope is made from a molded glass dish into which are sealed eight pre-beaded two piece nickel-dumet leads

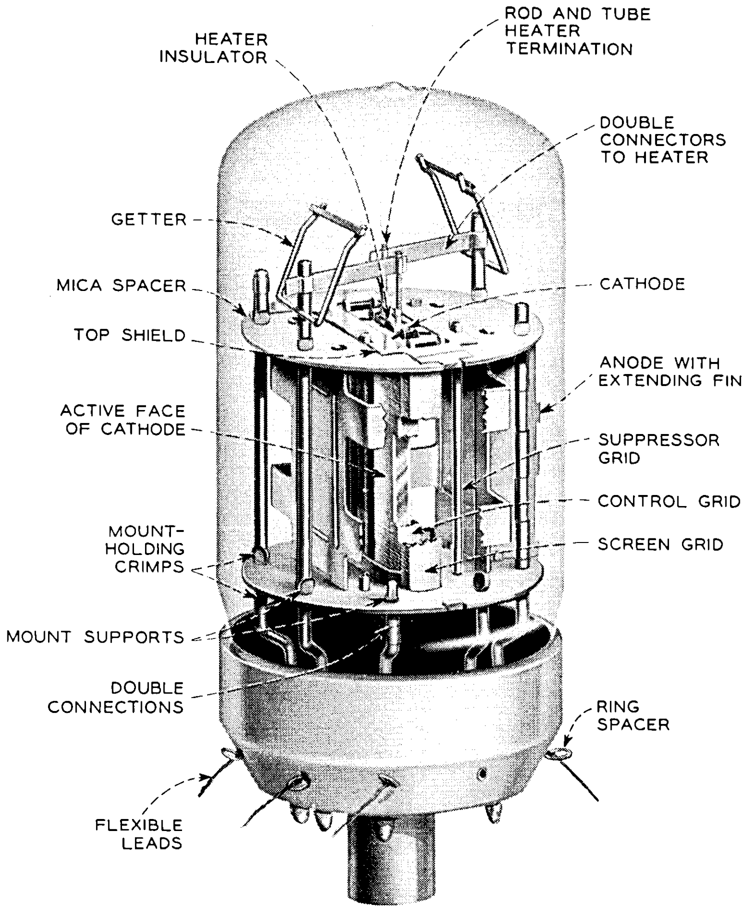


Fig. 1 — Structural details of the 455A-F electron tube.

whose inner nickel portions form the supports for the element assembly. The entire mount is supported from the stem leads. It was so designed to eliminate the mica insulator to bulb contact present in the earlier tube, with its resultant production of small mica particles.

The element "cage" assembly consists of the molybdenum anode, the oxide-coated cathode sleeve, frame-type control and screen grids, four rods that act as a suppressor grid, and two end shields. All of these are held together in proper relationship by two magnesium oxide-coated mica insulators. The "cage" assembly slides over the support leads, which are then crimped to position the cage. The coated heater and insulator assembly slides into the cathode sleeve from the top. The attachment of the heater connectors and getters completes the mount. The judicious placement of standoffs, tabs and lead crimps creates a truss-like structure that permits the tube to withstand a 500-g, 2-msec shock in any direction without damage. (This is ten times the predicted maximum shock to which the tube might be subjected in cable laying.)

In a repeater the based tube is supported on rubber cushions in a methacrylate housing as shown in Fig. 2. The flexible leads pass through the housing to form circuit connections and to provide for relative motion between the circuit and the tube. The small rings that pass through the flexible leads control the length of lead in the various regions.

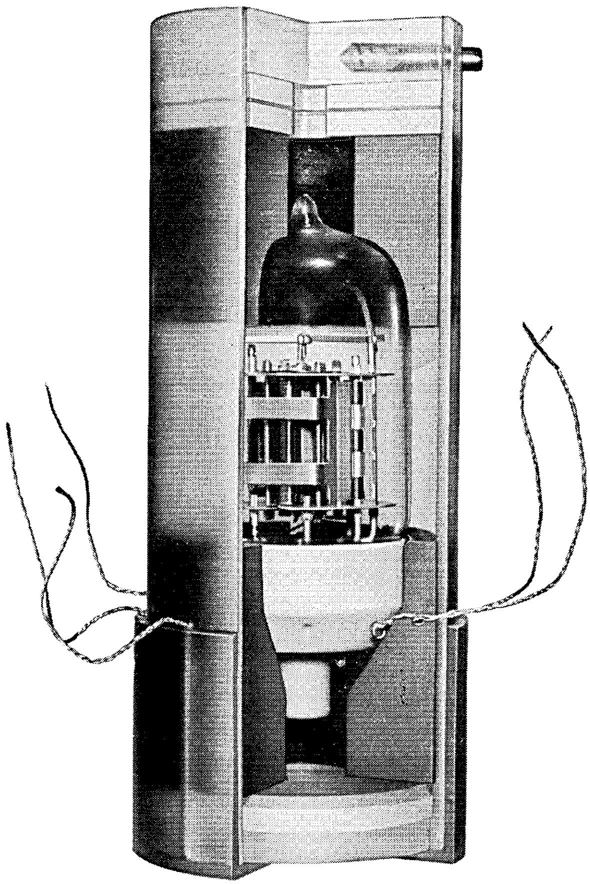

Fig. 2 — 455A-F tube cushioned in a methacrylate housing.

### 3.2.3 *Lead Welding and Crimping*

Again referring to the particle problem, a hazardous condition is created by splattering from the spot welds made during mount fabrication. Particles of 0.005 inch can be seen quite readily when viewed under a microscope on a flat surface. They are, however, extremely difficult to detect in a mount structure. This problem has been minimized by designing the tube so that the number of spot weld positions is roughly one-third those in the early flexible repeater tube. The tube design is such, however, that even with the reduction in the number of welds, every active tube element is redundantly connected so that should a single weld fail, the tube would still function.

Another design feature to minimize particle contamination is the use of crimped leads to support the mount structure. The older submarine cable tubes used metal eyelets crimped to the micas and welded to the stem leads as the mount supporting arrangement. Experience had shown that eyelets so used provided excellent structural support but, in a close-spaced tube, had the disadvantages of increasing the weld splash problem, generating mica particles, and catching and retaining all kinds of particulate matter and concealing it until late in the tube processing.

### 3.2.4 *The Anode*

The anode is a one-piece detail with a side fin. An earlier design, utilizing a two-piece plate with no side fin, optimized the interelectrode capacitances and provided sufficient mount ruggedness in the direction parallel to the grid plane, but was somewhat weak in the transverse direction. Ruggedness for tubes intended for the quiescent environment of the ocean floor may seem incongruous but is needed to protect against shocks during cable handling and laying. The anode structure, as can be seen in Fig. 1, has had all nonfunctional portions eliminated to provide the most open structure possible. This was done to permit microscopic examination of the cathode surface and the critical 0.0055-inch grid-to-cathode region to insure that no foreign matter has been entrapped.

### 3.2.5 *The Grids*

The control grid and screen grid are both made with fine tungsten wire wound at high tension on frames blanked and formed from sheet molybdenum (see Fig. 3). The frames are made in two sections, lapped to very precise dimensions, and paired to close tolerances. After the wires are wound on the paired frames, a single furnace operation brazes the frame

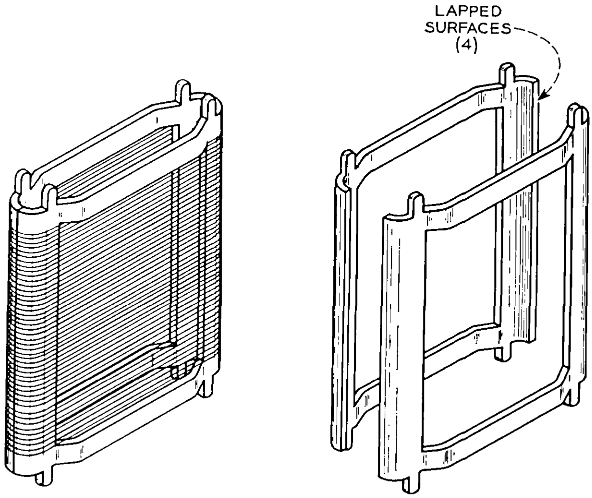


Fig. 3 — Wound grid and a pair of grid frames for the 455A-F tube.

sections together, brazes the fine wire to the frame and causes molten gold to cover the fine wire. While other types of frame grid construction were available,[2,3] this type, patterned after the original frame grid,[4] was selected because of fewer welds, lower grid mass, and the elimination of frame embrittlement.

### 3.2.6 *The Heater*

Heater reliability is of major concern, as this element is probably the most susceptible to catastrophic failure in that tungsten is subject to possible recrystallization and embrittlement. The heater in the 455A-F tube is a coiled tungsten wire formed into a precisely dimensioned M-shaped heater, spray coated with alumina, and slipped into a formed alumina block. Details of the heater and connectors are shown in Fig. 4. Connection to the tungsten heater is made in a manner similar to that which proved successful for the 175HQ tubes[1] with a single modification, namely, the crimping of the nickel sleeves to obtain a more intimate heater-to-connector contact. The 1090°C heater temperature is consistent with the conservative approach to design and operation.

To insure a large supply of uniform quality material, a procurement program was worked out with the supplier, the Westinghouse Electric Company. Special ingots of tungsten were made specifically for this use. The ingots were reduced to the wire form and wound onto many small spools, each one related by code marking to each other and to the original ingot. The spools were sampled in a statistical manner by making heaters and running regular and accelerated life tests on them. The accelerated tests included higher temperature operation as well as ON and OFF cycling. Use of a spool of wire was contingent upon obtaining no failures on these tests.

The insulator block shown in Fig. 4 is novel[5] and worthy of discussion. It is essentially a four-bore alumina block with the wall broken through between the two center holes, giving this opening a dumbbell shape. This permits the heater in its final M shape to be inserted into the block from one end. In addition to permitting an easier assembly operation, the dumbbell insulator makes it possible to insert a coated heater that has been fired. Use of a coated heater minimizes the transfer of tungsten to the insulator walls and insures high insulation resistance between the heater and cathode.

### 3.2.7 *The Cathode*

3.2.7.1 *Study of Cathode Materials.* There was evidence that impurities in commercial cathode nickel could, in time, cause performance degrada-

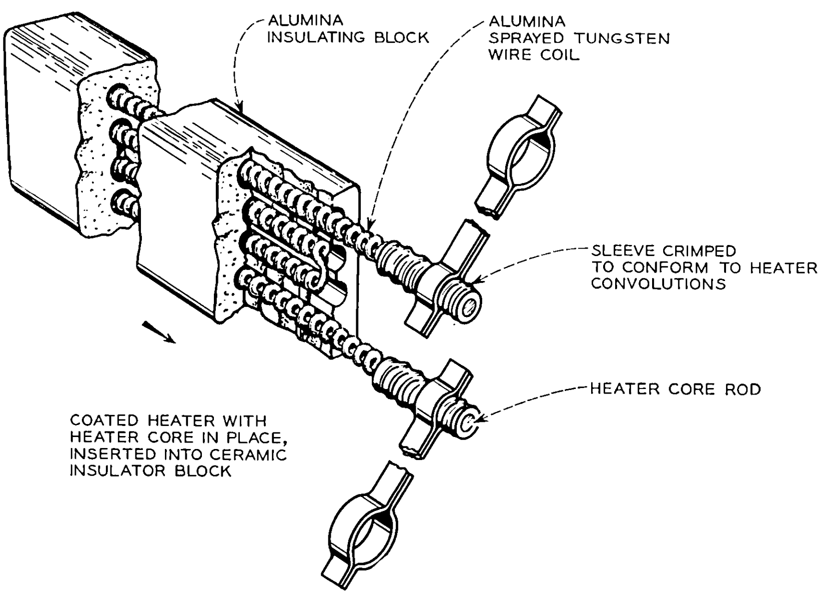


Fig. 4 — Heater and insulator assembly, and heater connector arrangement for 455A-F tube.

tion either through sublimation with consequent leakage between elements or with the development of cathode interface impedance. A survey showed that there was no source of supply for cathode nickels of the purity needed for the newer long-life high-transconductance tubes with their more stringent requirements.

Accordingly, a development program was undertaken to (1) provide special materials for the tube development work and (2) establish means for procuring production quantities in cooperation with the Western Electric Company. The first part of this program made available small billets of high-purity nickel and nickel with various additives[6] in which no single impurity exceeded 0.005 per cent by weight. Studies of the fundamental properties of these materials and a comprehensive evaluation of their suitability for use in long-life electron tubes were conducted.[7,8]

3.2.7.2 *Cathode Fabrication.* The cathodes are made of rectangular tubing with the emissive coating on the two broad surfaces. Initially they were fabricated from two channel-shaped pieces of nickel joined together by a diffusion welding process using sapphire tooling to avoid contamination of the nickel.

Approximately 700 tubes were fabricated and put on life test, using as a test vehicle a modification of the Western Electric 435A electron tube. This pentode was used because its close electrode spacing and high transconductance would accentuate the effects being studied. The tests included nine different cathode melts run at nine different operating conditions. Throughout the development program complete analytical tests were made at various points to insure the cleanliness and purity of the cathodes.

The making of cathodes from sheet material had provided ultra-pure sleeves for all of the cathode program. The fabrication method had been developed to an extent that would permit its use in production, and some 230 tubes of preliminary and refined designs for the 455 A-F amplifier tube were on life test. Since there were some undesirable aspects to the welded cathode, a program to produce seamless cathode sleeves from raw material supplied by Bell Laboratories was worked out with the Superior Tube Company of Norristown, Pennsylvania. Special measures were applied at their plant to insure that no contaminants were picked up and that each individual cathode sleeve was identified with respect to its starting billet. Analytical tests were applied to insure the purity of the material at critical points in the production. No changes could be observed from the original data. Tubes made with the new seamless cathode sleeves were put on life tests along with suitable control lots.

3.2.7.3 *Choice of Cathode Material.* As the development neared completion, a pilot production run of 300 tubes was made using the final design with all fabrication techniques and parts processing oriented toward a scaled-up production run. The life data from the cathode programs had, by this time, indicated two melts with superior characteristics for long life. These were (1) a single-additive, nickel plus 2.0 per cent tungsten, and (2) a double-additive, nickel plus 2.0 per cent tungsten plus 0.02 per cent magnesium. Because ample supplies of these two kinds of cathode materials had been stockpiled, it was possible to delay the final choice until production was ready to start, thus accumulating more evidence to support the final decision. The melt ultimately chosen for production was the double-additive, since the immediate effectiveness of the magnesium as a reducing agent permits a relatively short age-in period. The tungsten, with its slower diffusion and reaction rates, would not by itself make available tubes of adequate uniformity with 5000 hours of aging.

### 3.3 *Processing and Cleaning Controls*

A basic principle of reliability is that while inspections are important they are usually after-the-fact, and hence reliability must be built into the product. This is done by meticulous workmanship and by a system of multiple checking on parts and processing.

The system that was evolved recognized that it is virtually impossible at the time of tube fabrication to predict what specific information would be important when the tube is to be evaluated 5000 hours later, or if the tube is on life test, perhaps years later. Each tube was given a unique serial number, and all records were arranged so that from the serial number it would be possible to:

(a) trace every item in the tube back to its raw material lot,
(b) know who treated each part at every step in the tube fabrication,
(c) know when each part was treated, and
(d) know how each part was treated.

This was accomplished by tying together with proper records:

(a) the tube serial number,
(b) a serial number on the cathode, (duplicated on the plate)
(c) a serial number on the control grid,
(d) a serial number on the screen grid,
(e) lot numbers on each group of parts, and
(f) lot numbers on all material batches.

The record keeping consumed a large number of man-hours, even though maximum use was made of modern machine aids. This detailed information on individual tubes was essential in analyzing anomalies in test results and in rationalizing the acceptability of processes and tubes.

The cleaning procedures used in tube fabrication are of utmost importance in producing long-life, highly reliable tubes. The basic cleaning procedure adopted was that developed at Bell Laboratories.[9] This is:

(a) removal of grease by solvents,

(b) removal of physical contaminants by ultrasonic agitation,

(c) rinse in deionized water in a cascade-type cleaner,

(d) light oxidation to remove residual organic materials,

(e) reduction in hydrogen to outgas parts,

(f) testing for surface contaminants by the water wettability (atomizer) test, and

(g) storage in "atomizer clean" containers with strict limitations on duration of storage, i.e., 96 hours maximum for coated cathodes to ten days maximum for shields.

These basic processes were used wherever applicable at each step in the fabrication. Early contaminant elimination and low carryover was thus achieved. The resulting fabrication and processing procedures consisted of some 350 separate operations, a formidable number under any circumstances. However, the associated test and life data proved beyond question that a uniformly high-quality tube was being turned out on a production basis.

### 3.4 *Electrical Characteristics and Life*

#### 3.4.1 *Operating Characteristics*

The arrangement of the electron tubes in the SD system repeater is shown in the simplified circuit schematic of Fig. 5. In the amplifier, stages A, B, C and D, E, F comprise the two parallel amplification paths mentioned earlier in this article. Table II lists the operating voltages and principal electrical characteristics of the 455A-F tubes for input and output conditions of amplifier operation. Grid noise is important in stages A and D, and significant in B and E, while output capability is most important in stages C and F. The typical equivalent grid noise figure is 825 ohms compared to the theoretical value of 750 ohms.

A family of plate current versus plate voltage curves for a typical tube over the approximate region of operation is shown in Fig. 6. While the curves have the general appearance of a pentode family, the sharp breaks at the knee region are more characteristic of a tetrode. Actually, the tube is a cross between the two since the suppressor grid consists of only four rods and there is considerable dependence on space charge for suppres-

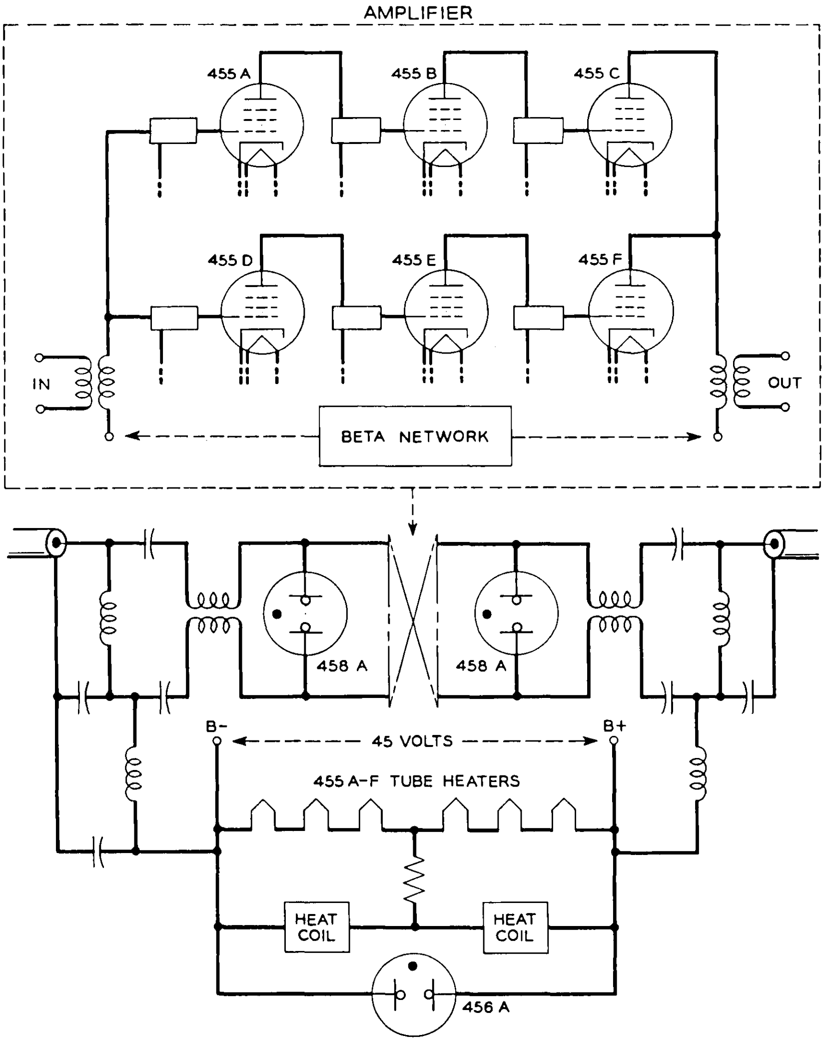


Fig. 5 — Functional location of the electron tubes in the SD submarine cable system repeater.

sion of secondary electron exchange in the screen grid to plate region. The sharp breaks of the curves as the plate voltage is varied are due to the movement of the virtual cathode between the screen grid and the plate with the attendant changes in potential distribution from one which follows the three-halves power to one in which there is complete

TABLE II — AVERAGE OPERATING ELECTRICAL CHARACTERISTICS FOR THE 455A-F TUBE

| | Input Stages A,B,D,E | Output Stages C,F |
|---|---|---|
| Heater current | 305 | 305 ma |
| Heater voltage | 7.55 | 7.55 v |
| Control-grid voltage | +3.6 | 0 v |
| Cathode resistor | 600 | 450 ohms |
| Plate voltage | 37 | 45 v |
| Screen-grid voltage | 30 | 45 v |
| Plate current | 7.2 | 6.9 ma |
| Screen-grid current | 1.3 | 1.4 ma |
| Transconductance | 7,000 | 5,900 μmhos |
| Plate resistance | 60,000 | 80,000 ohms |
| Equivalent grid noise | 825 | — ohms |
| Power output* | — | 50 mw |
| Second harmonic F/2F† | — | 34 db |
| Third harmonic F/3F† | — | 65 db |
| Interelectrode capacitances, measured cold in a methacrylate housing | | |
| input capacitance | | 15.7 pf |
| output capacitance | | 7.2 pf |
| control grid to plate capacitance | | 0.075 pf |

* Measured into 3200 ohms load resistance with grid drive ($e_g$) adjusted for maximum power with no observable distortion.
† Measured into 3200 ohms load resistance with grid drive $e_g$ = 0.1 volt rms.

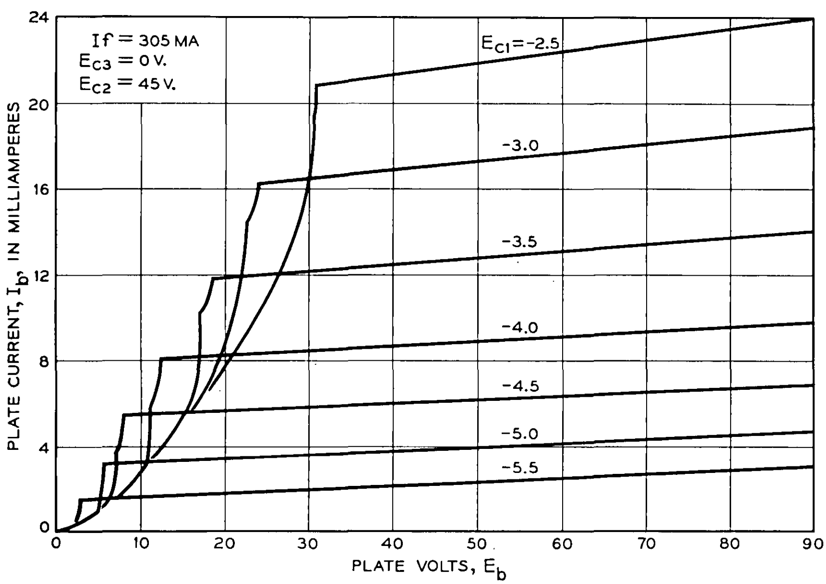


Fig. 6 — Plate current-plate voltage characteristics for the 455A-F electron tube.

transmission of current to the plate. The double shoulders in the curves are attributable to lack of perfect symmetry.

### 3.4.2 *Thermionic Life*

The thermionic performance of tubes during life is of major importance to a cable system. In the discussion of reliability, it was assumed that deterioration due to decreasing thermionic emission would be negligible. This was based largely on the performance of 175HQ tubes in SB cable systems and backed up by the life data accumulated on development models of 455A-F tubes. During the development program many tubes, representing a variety of structural features, many different cathode melts and several sets of operating conditions, chiefly cathode temperatures, were put on life test.

Curve (a) of Fig. 7 shows the life pattern for the oldest test of development model 455A-F tubes. This is for a representative group of tubes with cathodes of grade 220 nickel operating at 700°C.* Transconductance has been normalized to the median value at the 5000-hour test. Per cent of this reference transconductance is plotted versus total aging time in hours and years. Median values and ranges are shown at the various test points. The decrease in transconductance with time is attributable to the development of cathode interface impedance which, at the latest test point, had a median value of about six ohms.

Life performance of a group of tubes using cathodes with the tungsten and magnesium additives (final type) are shown in curve (b). At nearly 40,000 hours life the median transconductance exceeds the 5000-hour reference value by about one per cent. There was no measurable interface impedance in these tubes at the latest test. Again the cathode operating temperature was 700°C. Comparative tests subsequently showed 670°C to give results comparable to those at 700°. Consequently, in the interest of conservative operation, the lower temperature was selected for the final design.

Curve (c) in Fig. 7 is for tubes typical of Western Electric Company production operating at 670°C. While the total age is shorter for these tubes, it is gratifying to note that the trend is following closely the pattern set by the development tubes at comparable age.

The activity data of Fig. 8 present an indication of future trend in transconductance for the same groups shown in Fig. 7. Here are plotted the changes in transconductance (per cent $\Delta G_m$) which accompany a 20 per cent decrease in tube heater current. It is noted that the activity picture is favorable for development and production tubes. The wider

* All cathode temperatures referred to in this paper are "true" temperatures.

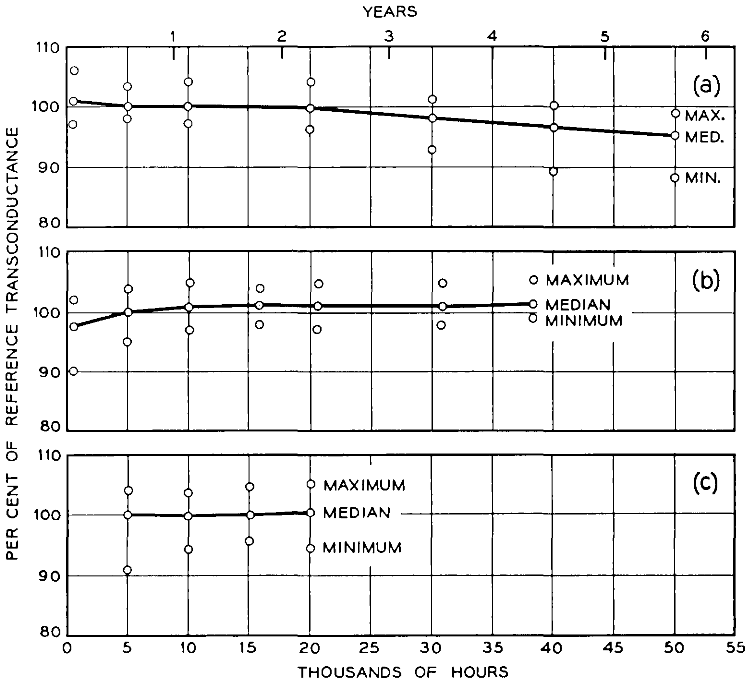


Fig. 7 — Transconductance as a function of life for 455A-F tubes.

spread for the Western Electric product is consistent with the larger sample on test. From the stability exhibited in curves (b) and (c) of Figs. 7 and 8 it appears that the extrapolation to the higher current density, the use of the special cathode alloy and operation at 670°C are all justified.

### 3.5 *Tube Production*

Production of tubes has been underway for nearly four years at the Allentown Works of the Western Electric Company. The philosophy of building reliability into the tubes was mentioned above, and it was pointed out that only tested and proved materials would be used. This was successful during the development and has been carried over into production. All fully certified parts and materials are given lot numbers, certain piece parts are individually numbered and each tube is given a unique serial number. To expedite the handling of product a "kit" system was adopted with six tubes in a kit. Six sets of parts and the records pertinent to them are given to an assembly operator. At the completion of the assembly, the operator passes on six tube mounts

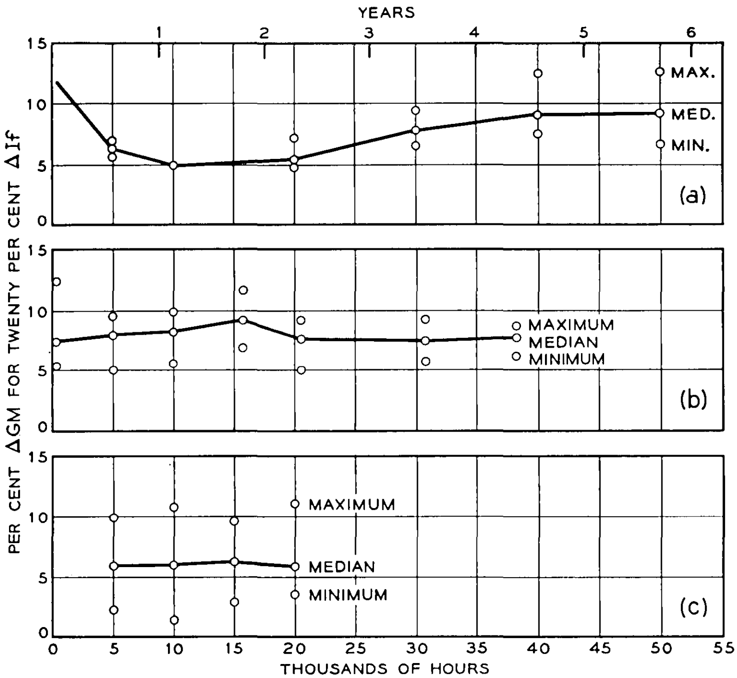


Fig. 8 — Cathode activity as a function of life for 455A-F tubes.

(assemblies) and the pertinent papers. Some operations, for example pumping, can handle two or more kits at a time. The kit system also permits examination of data for "batch effects." As the name implies, these are deviations or trends in data that can be studied in related groups of tubes as well as in individuals.

In the course of fabrication all tubes are given ten inspections, six of which include thorough searches for particles. Also, at specific times within the 5000 hours of aging the general electrical characteristics are tested five times. Supplementary tests are also made of special electrical parameters such as power output, modulation, equivalent grid noise, etc.

## 3.6 *Tube Selection Procedure*

### 3.6.1 *Review by Committee*

The selection of tubes for sea-bottom service goes beyond the mere matching of test data against limits. There are certain attributes or second-order responses of a tube to which it is difficult to assign numbers.

These attributes are assessed by the selection committee much as if the candidate were a person. Before a tube is submitted to the committee, the processing and inspection records are checked for consistency and completeness.

The selection committee reviews all of the data in detail, studying trends and minor variations occurring within the limits of acceptability. As examples: the age-in characteristics are compared to the characteristics at the 5000 hours acceptance point. The residual gas test and plate current age-in curves are reviewed. The departure of any data from the normal pattern is critically analyzed, and only those tubes which have exhibited normal behavior are accepted for sea-bottom use.

### 3.6.2 *Grouping for Repeater Use*

The tubes accepted for sea bottom are permanently grouped by sixes for use in an individual repeater. This grouping has no relation to the "kit" of six used for production control. The grouping takes into account the sum of the heater voltages at a fixed current, the slope of the plate current aging-in curve, and the products of the transconductances for the tubes in each of the two amplification paths (tubes $A \times B \times C$ compared to tubes $D \times E \times F$). Tubes with low noise figure are assigned to input stages while tubes of high power output are used in output stages.

As a final check on the static characteristics and on the grouping of the tubes, they are given an electrical test in a circuit simulating the dc circuit of the amplifier, energized at rated cable current. Individual tube plate and screen grid currents are measured in this circuit, and then a comparison is made between tube performance in the working circuit and in the tube testing equipment. The tubes are now ready for shipment to the repeater assembly factory, where they are immediately restested in an amplifier simulating circuit identical to the one at the tube manufacturing plant. With satisfactory agreement between these two tests, the group of tubes is acceptable for assembly into a repeater.

## IV. THE GAS-FILLED PROTECTIVE TUBES

### 4.1 *Circuit Function*

In those portions of the cable system operating at more than about 1500 volts to ground, a fault resulting in the grounding of the center conductor produces severe electrical transients. These transients propagate through several repeaters to either side of the fault before being attenuated to a safe level. If no protection were provided, damage to repeater components would be probable, and repeater failure would be possible.

Two types of gas tubes were developed to provide the desired protection. Both types are electrically symmetrical diodes, designed to conduct current in either direction, and both are of the cold cathode variety, requiring no power in the standby condition. Cutaway views of the two tubes are shown in Fig. 9.

### 4.2 *The 456A Power Bypass Gas Tube*

#### 4.2.1 *Operating Requirements*

The 456A tube is bridged across the six series-connected amplifier tube heaters as shown in Fig. 5 and has two functions: (1) in the event of a fault on the cable causing an abnormal current to flow through the repeater, the tube will fire and conduct the current, preventing damage to the tube heaters and to other parallel low-voltage components; (2) if an amplifier tube heater opens, the rising voltage will fire the gas tube, holding the heater circuit voltage at a safe level. The cable voltage is then

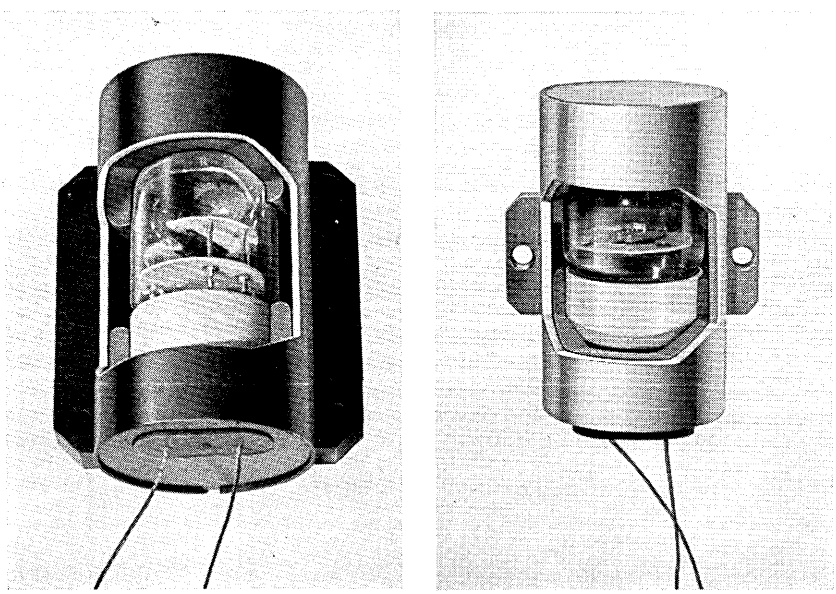

Fig. 9 — 456A (left) and 458A (right) electron tubes cushioned in aluminum housings.

turned down and the procedure carried out for energizing the heat coil, which in turn melts the fusible link to bypass the defective heater.[10] By means of a center-tap connection, only half of the amplifier tubes (ABC or DEF) will be turned off. The minimum firing voltage of the gas tube is set slightly above the voltage required by the heater circuit for this operation so that the tube does not refire. Should a heater in the second string subsequently fail, the gas tube will again fire and maintain dc continuity during trouble location tests.

For surge protection service, the tube is designed to pass a charge of 0.6 coulomb at a peak current of 75 amperes in either direction. This provides a reasonable margin for the maximum reverse surge which would occur in a near-shore repeater with a fault on the shore side, and for the maximum forward surge which would occur at the one-half voltage to ground point with a fault on the seaward side of that repeater. For a system of maximum length, the charge passed in either case is approximately 0.5 coulomb (the charge stored in a 100-mf capacitor at 5 kv). The magnitude of the peak current in the heater curcuit is less than 50 amperes under either condition and well within the capability of the tube.

The tube has a nominal breakdown voltage of 190 volts, and being located inside the power separation filters where the rate of rise of the transient voltage is relatively slow, the voltage rises only a few tens of volts above breakdown before the tube fires. Glow conduction is established within five microseconds at a tube voltage drop of about 70 volts. In less than one-half millisecond the cathode is heated sufficiently by ion bombardment to cause a transition to arc conduction, giving a tube voltage drop of about 11 volts. In this mode, as an ionically heated cathode device, the tube can conduct the large surge transient or the normal cable current as required. The power dissipation in the tube at normal cable current is approximately 5 watts. Tube life in this condition is more than 1000 hours, providing ample margin over the 100 hours estimated maximum time required to locate a cable fault. As a surge protection device the tube can conduct more than 50 maximum-energy surges without going out of firing voltage limits.

The fundamental characteristics and ratings are given in Table III.

#### 4.2.2 *Design Details*

The detailed design of the working parts of the 456A is shown in Fig. 10. The two cathanodes are each mounted on three leads which are in turn strengthened, and made to move as a unit under shock, by means of the ceramic baffle. The baffle also prevents the arc discharge

TABLE III — 456A COLD CATHODE, GAS-FILLED ELECTRON TUBE

| | |
|---|---|
| Maximum Ratings | |
| Average cathode current | 450 ma |
| Surge cathode current | 75 a |
| Coulombic charge | 0.6 coulomb |
| Starts (firings) | 100 max. |
| Surges | 50 max. |
| Shelf life | 20 years min. |
| Conducting life at 450 ma | 100 hr min. |
| Ambient temperature | −10 to +50°C |
| Shock — 5 msec | 50 g |
| Electrical Data | |
| Breakdown (firing) voltage | 160 v min.<br>230 v max. |
| Breakdown time — to glow | 20 μsec max. |
| Transition time — to arc | 500 μsec max. |
| Sustaining voltage — glow | 70 v |
| Sustaining voltage — arc | 11 v |

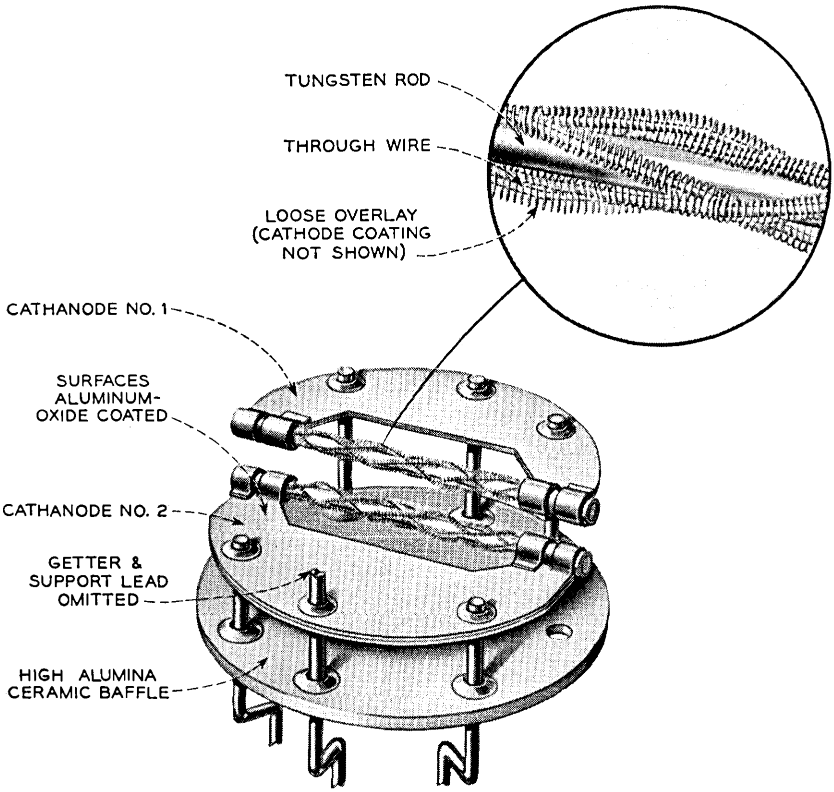


Fig. 10 — Structural features of the 456A tube.

from forming on the dumet seals. Each cathanode is formed from two identical "C" shaped molybdenum plates which clamp the active tungsten cathode.

The cathode is a composite structure made up of a 0.030-inch tungsten rod over which are braided six strands of 0.0045-inch tungsten wire, each strand carrying a loose over-winding of 0.001-inch tungsten wire. The crossed structure of braided wire and over-winding is filled with the emissive oxides of barium and strontium, providing small emission zones that have a loose thermal coupling with the rod. In establishing conduction, any one of these zones will be heated by ion bombardment, at a fraction of normal cable current, to a temperature sufficient for thermionic emission and operation as an ionically heated cathode. The zones are sufficiently short, however, that the heat energy resulting from high-current surges is conducted to the rod at the crossover points, preventing major damage to the finer wires.

The width and thickness of the molybdenum "C" plates are so proportioned that during the pumping process each part of the cathanode structure comes to the proper processing temperature simultaneously when heated by high-frequency induction. The two cathanodes are spaced approximately 0.100 inch apart and the gas filling is 18 torr of reagent-grade argon. A barium getter (not shown) is used to aid clean-up of impurity gases. The tube has a priming of one microcurie of radium bromide to insure fast breakdown in a dark environment.

### 4.3 *The 458A Signal Path Protective Tube*

#### 4.3.1 *Operating Requirements*

The 458A tube is bridged across the transmission path at both the input and output of the repeater, just inside of the power separation filters (see Fig. 5). The most severe voltage surge the tube is required to handle is that caused by a short-circuit fault in the adjacent cable section. In the higher-voltage portions of the system this surge voltage may rise to a value of more than four kv in approximately one $\mu$sec. Since it is desirable to limit the voltage on many of the transmission path components to less than 1500 v, a very fast tube is required. The signal path tube is designed to fire in from 0.2 to 0.3 $\mu$sec on a 4 kv per $\mu$sec transient, limiting the surge to the transmission path to a maximum of 1200 v.

The charge shunted by the gas tube is a substantial portion of the charge stored in the high-voltage capacitors of the repeater, and may be as much as 1.5 millicoulombs. The discharge is oscillatory in nature and lasts about 10 $\mu$sec. The peak current through the tube on the first swing may be as high as 1200 a. These high currents are carried by the tube in the metallic arc mode of conduction at a tube drop in the order of 15 v.

The ability of the tube to pass such surges is tested in a circuit equivalent to that in a repeater. The size of the capacitors is doubled, however, to insure an adequate testing margin. In this test each tube is surged ten times in each direction with a total integrated charge of 4.5 millicoulombs and a peak current of 1800 a. The tube is conservatively rated to pass 50 maximum cable surges.

In use in the cable the tube is not required to carry continuous current. There is a secondary use of the tube in the power supply for equipment protection in which approximately 2 ma dc is conducted until the trouble is corrected. For this use the tube is given a 5-ma average current rating.

The fundamental ratings and characteristics are given in Table IV.

#### 4.3.2 *Mechanical Features*

The structural details of the 458A are shown in Fig. 11. The two identical cathanodes are mounted on a high-alumina ceramic disk, one on either side, with their support tabs at 90°. The cathanodes face each other through an aperture in the support disk.

Each cathanode is a square nickel cup with integral mounting tabs. The facing surfaces are coated with a thin layer of emissive oxides of barium and strontium, activated during tube processing by means of a high-frequency discharge to develop super-emissive cold cathodes. The "nutmeg grater" shaped perforations perform two functions: (1) the

TABLE — IV — 458A COLD CATHODE, GAS-FILLED ELECTRON TUBE

| | |
|---|---|
| Maximum ratings | |
| average cathode current | 5 ma |
| surge cathode current | 1500 a |
| coulombic charge | 1.5 millicoulombs |
| surges | 50 max. |
| shelf life | 20 years (min.) |
| conducting life at 5 ma | 200 hours (min.) |
| ambient temperature | $-10$ to $+50$°C |
| shock — 5 msec | 50 g |
| Electrical data | |
| breakdown voltage | 60 v |
| sustaining voltage — 5 ma | 50 v |
| breakdown time — 500 v | 5 μsec max. |
| breakdown time — 4 kv/μsec | 0.7 μsec max. |

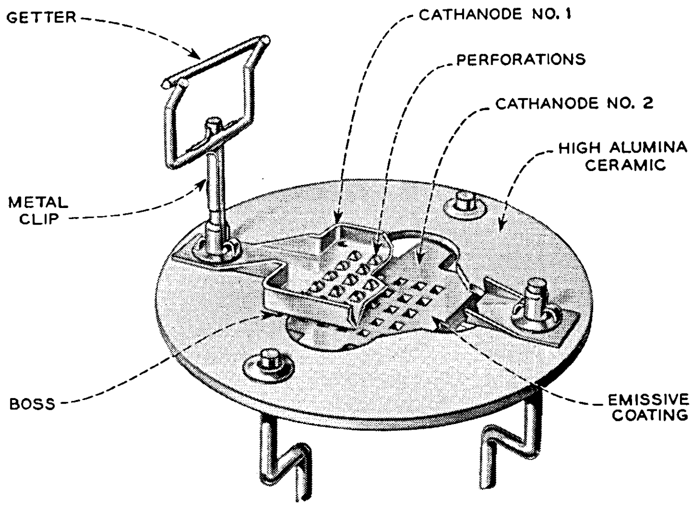


Fig. 11 — Structural features of the 458A tube.

hollow cathode effect of the small depressions increases the emission efficiency and life; (2) they allow a visual observation of the glow over the cathode surface to determine the uniformity of emission and cathode coverage. A small boss is provided at each corner of the cathanode to limit and position the contact area on the ceramic disk. This provides a leakage path of greater than 1000 megohms between the elements, even after the sputtering of the cathode material due to high-current arcs. The barium getter is the same as that used in the 456A tube.

The gas filling in the 458A tube is 1 per cent argon and 99 per cent neon at 60 torr pressure. The plane-parallel electrode geometry at a 0.030-inch spacing gives a nominal breakdown voltage of 60 v and a sustaining voltage at 5 ma of 50 v. One microcurie of radium bromide is used as a priming to insure sufficient initial ionization for high-speed operation in the absence of light.

### 4.4 *General Considerations*

In the design of the two gas-filled tubes the glassware, stem, bulb, and basing follow the pattern of the 455A-F amplifier tube. Both gas tubes are mounted between rubber cushions in aluminum housings (See Fig. 9). The housing for the power bypass tube has a black anodized finish and is secured to the power separation filter chassis, which it uses as a heat sink. This insures a bulb temperature of less than 130°C when carrying full cable current. The signal path tube has no heat problem and is in a bright housing. This tube and lead-out braid, however, require insulation from the housing for 6-kv operation.

In addition to the basic twenty-year standby life requirement, the tubes must also not reduce the system reliability through their own failure. Shorting of the elements has been made virtually impossible by generous spacings, rugged structural design and the multiple securement of parts. Both types can withstand some five times the shock levels expected in the present cable systems. The tubes operate on the high-pressure side of the Paschen minimum, and gas leak-in cannot reduce the firing voltages to unsafe values.

Raw material control through strict specifications, adequate testing procedures, and lot prove-in follow the pattern of the amplifier tube. Similarly, the parts production, handling, processing and cleaning, quality tests and inspections have also followed approved procedures.

The tubes are carried through a comprehensive aging and operating procedure simulating operating conditions in the cable. Elaborate testing schedules evaluate the performance at each stage in the processing, giving the detailed behavior of each tube. The tests include high-energy surge tests at or above maximum ratings and a two-hour thermal pulse at 125°C to evaluate over-all cleanliness. The tubes are checked for stability over a minimum period of three months and for operation in the dark to insure adequate radium priming. The power bypass tube is given a 30-day test in the dark at 4°C with cable voltage applied.

## V. CONCLUSION

When electron tubes were first used in deep-sea repeaters for the SB systems, it was recognized that the undertaking was ambitious and perhaps even audacious. The faith exhibited in proceeding with this application of electron tubes appears well justified with more than 80 million amplifier tube hours of operation on sea-bottom with no failures. Strict attention to details of processing, fabrication, aging, testing, and selection constitute the background for this achievement. By modification and extension of this formula, it is expected that a similar record will be achieved for the electron tubes in the SD systems.

The development of the three codes of tubes for use in the SD system was a project staffed by many members of Bell Laboratories, who contributed a variety of knowledge and skills. No attempt will be made to single out individuals for special mention. It was a team effort.

## APPENDIX

### *Discussion of Reliability*

The reliability objective for the electron tubes of the SD system was stated as: "The probability of system failure due to a tube failure shall not exceed 50 per cent for a twenty-year service period for a 3000-mile system."

The probability of no system failures

$$P_{f(0)} = e^{-\lambda}$$

where $\lambda$ is the expected number of tube failures for the period. For a 50 per cent probability $e^{-\lambda} = 0.5$ and $\lambda = 0.69$.

The mean time between system failures is $20/\lambda$ or twenty-nine years.

For a 3000-mile system with a twenty-mile repeater spacing there will be 150 repeaters. For defects not minimized by circuit redundancy, there are six tubes per repeater. Then, for a twenty-year period

$$\lambda = (150 \times 6 \times 20)/T$$

where $T$ is the mean time (in years) between random failures. For $\lambda = 0.69$, $T = 26{,}100$ years.

If 0.69 failure is experienced among the 900 tubes for a twenty-year period, this corresponds to a failure rate of $0.69/900 = 0.00077$ or 0.08 per cent for the twenty years, or to $4.4 \times 10^{-9}$ failure per tube per hour (4.4 fits).

For the defects which, because of redundancy, would cause failure only if both circuits were affected:

$$\lambda = 150[(3 \times 20/T)^2] = 0.69 \text{ (approximately)}$$

and

$$T = 885 \text{ years mean time between failures.}$$

Since with redundancy the required tube life is about $\frac{1}{30}$th that required without it, the corresponding failure rate would be 2.4 per cent and the number of fits 132.

This analysis has assumed that no "wear-out" mechanism is involved in the twenty-year service period. While mechanisms such as depletion of cathode coating or reducing agents are known, the rates are such that they have no significant effect in this period.

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# Cable Power Facility

By J. D. BISHOP and S. MOTTEL

(Manuscript received March 19, 1964)

*Submarine cable system power supplies must be designed to provide an uninterrupted flow of precisely controlled, transient-free operating power for a time interval equal to the service life of the cable system. Heavy reliance on redundancy along with conservative application of semiconductor and magnetic circuit elements form the basis for the circuit design. The equipment design emphasizes the techniques required to withstand high voltages, provide ease of maintenance and insure personnel safety.*

*Saturable reactors operated in the constrained mode serve as the basic power control element. AC power for the saturable reactors is obtained from a transistor inverter fed from a continuously floated storage battery. Metering-type magnetic amplifiers are used to isolate the regulation, metering and alarm circuits from the high-voltage output. Transistor amplifiers and temperature-compensated silicon reference diodes complete the regulating loop.*

## I. INTRODUCTION

The power supplies for the SD submarine cable system[1] must be designed to provide an uninterrupted flow of precisely controlled, transient-free operating power if the long life and stable transmission characteristics inherent in the submerged repeater design are to be obtained. Ideally, the power system should be capable of providing this power without interruption for the life of the cable system. Equally important is the need for reliable automatic alarm and shutdown circuits. These signal the presence of abnormal cable currents and voltages and turn down the power if hazardous levels are reached, whether the cause of the trouble is within or external to the power plant.

## II. DESIGN REQUIREMENTS

Fig. 1 illustrates the basic power feeding arrangement used. Nominal current and voltage for a 3600-nautical mile (nm) system are shown.

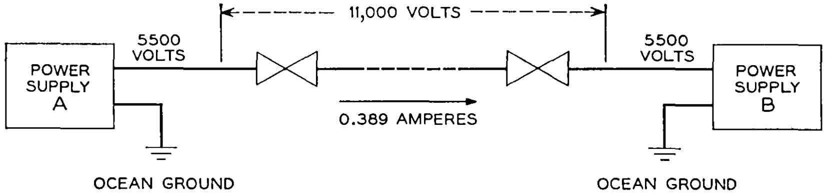


Fig. 1 — Basic power feed arrangement.

Power is normally applied from both ends to minimize the applied voltage stress. For systems shorter than 1800 nm, power may be applied optionally from both ends or one end only.

Complete electrical design requirements are given in Table I. These values apply for supplying power at one end of the cable.

Table I — Electrical Design Requirements

| | |
|---|---|
| Normal voltage | 5500 v |
| Normal current | 0.389 a |
| Ripple | 1 v rms maximum |
| Noise | −120 dbm maximum (0.1 mc–1.1 mc) referred to transmission input |
| Normal accuracy of current control | ±0.4% absolute |
| Load current regulation | |
| 1000-v change | 1.0% |
| Rectifier failure | −0.5% |
| Output resistance above 6500 v | 2500 ohms |

External alarms:

Power plant output

| Minor alarm | Major alarm |
|---|---|
| current ±2% | current ±5% |
| voltage ±5% | voltage ±10% |

Rectifier output

| Minor alarm | Major alarm |
|---|---|
| current −5% | current +5% |
| less than 500 v | more than 7500 v |

Protective shutdowns:

Rectifier

5% over-current
over 7500 v

Plant

over 9000 v

III. DESIGN PHILOSOPHY

Redundancy was considered the key to achieving the required degree of reliability. To fully exploit this approach, three basic principles were felt to be essential: minimum interdependence of one functional element upon another, use of static components only, and minimization of the number of components which could not be made redundant directly connected to the power plant output. Fig. 2 illustrates the basic power system. Two identical power plants are used, independent of each other except for the sharing of the ac input power source and cable terminating equipment.

Power for the battery charging rectifiers is normally obtained from commercial sources. When commercial power failure occurs, these rectifiers are fed from the emergency power system of the station. The batteries are normally maintained on continuous charge with their outputs fed directly to the inverters. The inverters are designed to operate over the normal battery voltage range without end-cell switching or other voltage adjustment means.

Regulation of the cable current is done by the high-voltage rectifiers. These, along with their associated inverters, are designed to have full

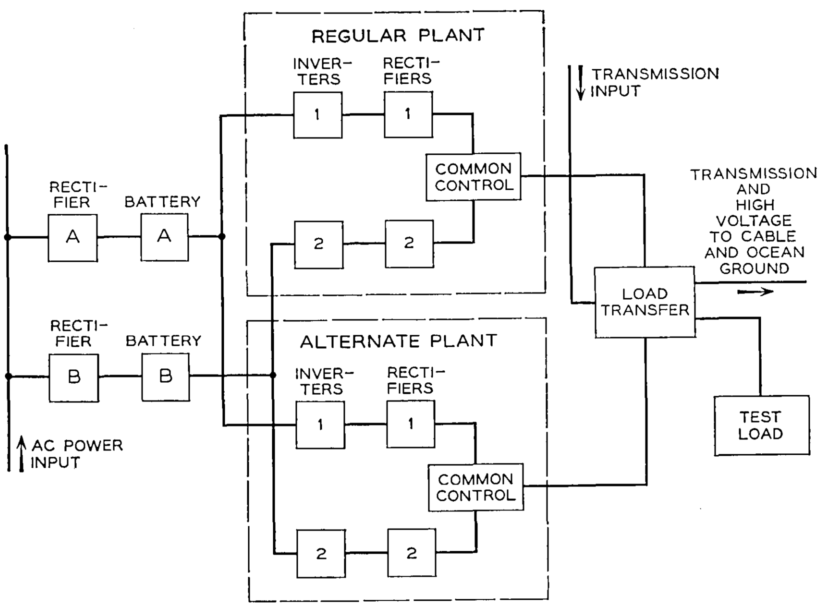


Fig. 2 — Power system functional block diagram.

load capability. In normal operation they are connected in series and adjusted to share the load equally. If the output of one of the rectifiers fails, the remaining rectifier assumes the cable load. When this occurs, it is normal practice to transfer the power feed to the standby power plant. The load transfer is designed to permit such a transfer without disturbance of the cable current.

An adjustable test load is provided to permit testing of both individual rectifiers or a complete power plant. A precision calibrating circuit is included as an integral part of the test load to permit periodic calibration of the cable current meters.

## IV. EQUIPMENT DESIGN OBJECTIVES

The equipment design objectives were as follows:

(a) to provide an equipment arrangement capable of withstanding the high voltages present without dielectric breakdowns or corona for extremely long service periods,

(b) to give easy access to apparatus for repair or maintenance operations

(c) to guarantee personnel safety and proper operation of the plant by design features,

(d) to provide mechanical integrity to withstand 3-g shock loads due to atomic blasts when installed in hardened sites,

(e) to require a minimum of installation effort, and

(f) to provide a distinctive, pleasant appearance.

## V. GENERAL DESCRIPTION

### 5.1 *Equipment Design*

The power plant is composed of a number of seven-foot-high cabinets, the exact number and arrangement being a function of the specific application. Among the considerations involved are the length of cable being powered, the type of installation (hardened or nonhardened), and the degree of redundancy desired. An arrangement of cabinets for a regular supply is shown in Fig. 3. An alternate power plant does not include a load transfer. A test load cabinet is furnished with each regular supply.

The power plant equipment cabinets are 7 feet high, with split rear doors. Two widths are available. The cabinets are of welded aluminum construction. A different type of cabinet is used for the test load and is available with wheels or for direct mounting to the floor. A number of slide-mounted equipment units of a generally similar mechanical configuration are incorporated in the cabinets. Typical units are shown in Fig. 4.

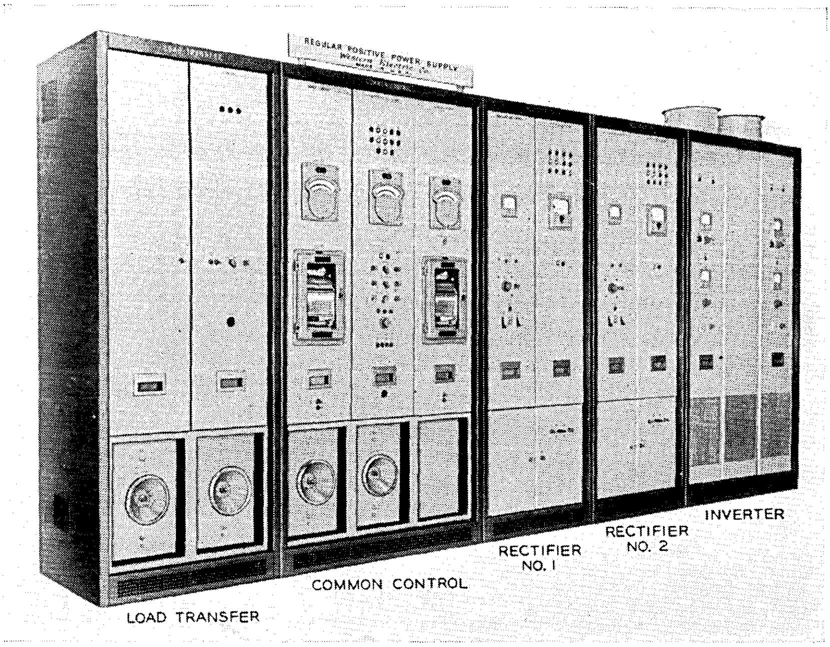


Fig. 3 — Terminal plant — regular power supply.

### 5.2 *High-Voltage Rectifier Circuit Design*

A series-connected saturable reactor,[2] operated well into the constrained mode, is used as the main power-control element in the rectifiers. This device electrically approximates an ideal current source by virtue of its ability to maintain an output current whose magnitude is proportional to the control current but is virtually independent of supply and load voltage variations. When appropriately designed with a control circuit having a long time constant, it behaves as a current source under dynamic as well as static operating conditions.[3]

Fig. 5 shows the circuit schematically with typical wave shapes. The rectangular wave shape of the load current is independent of supply and load voltage wave shapes in the linear operating range, as shown. Typical saturable reactors used in this system exhibit only a 2 per cent change in load current for a 25 per cent change in supply voltage and a load voltage change equivalent to 6500 v.

The principal reasons for the use of the saturable reactor were:

(1) it is inherently a current source, requiring only a nominal amount

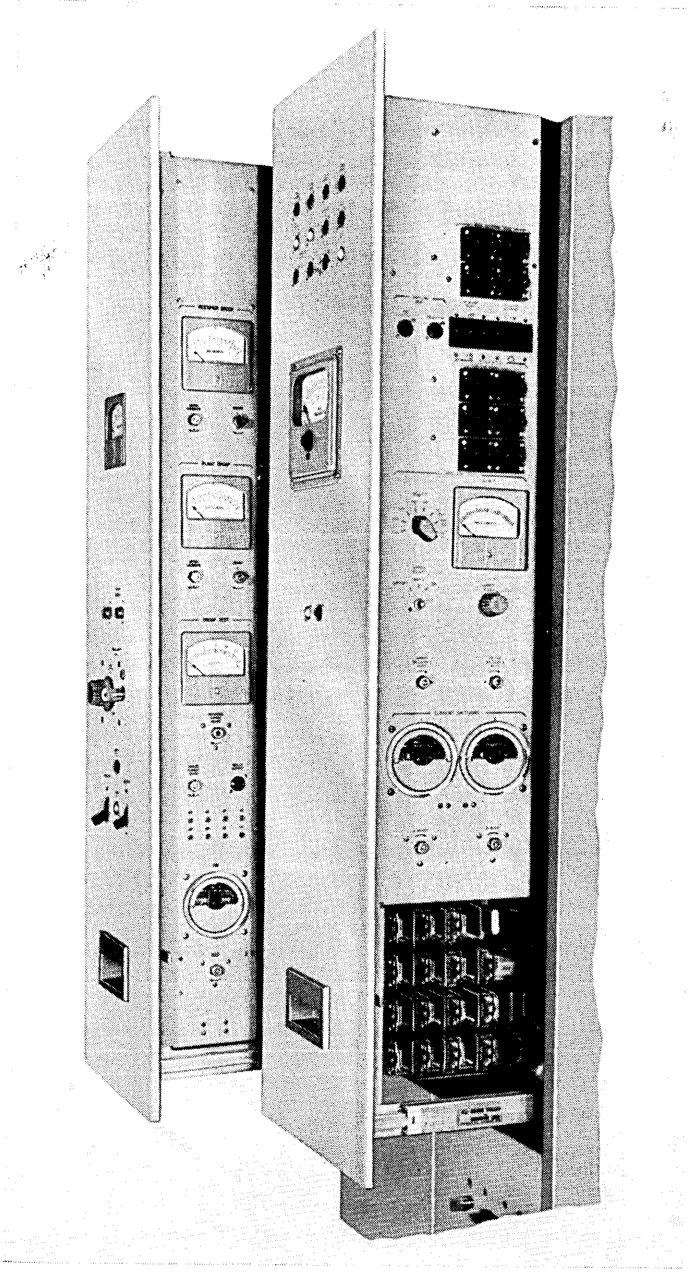

Fig. 4 — Typical slide-mounted units.

of over-all regulating circuit loop gain to meet both static and dynamic performance requirements;

(2) the rectangular load current wave shape is ideal for rectification, giving a small percentage output ripple;

(3) a long control circuit time constant prevents sudden and rapid change in the rectifier output, providing ample time for detection and turndown of a runaway rectifier before significant changes in cable current can occur; and

(4) insensitivity to supply voltage variations permits use of an unregulated ac power source.

The practical problems associated with designing a saturable reactor circuit for operation at these power levels virtually rule out the use of commercial power frequencies. A 60-cycle design would be impracticably large in volume and weight. The attractiveness of the saturable reactor

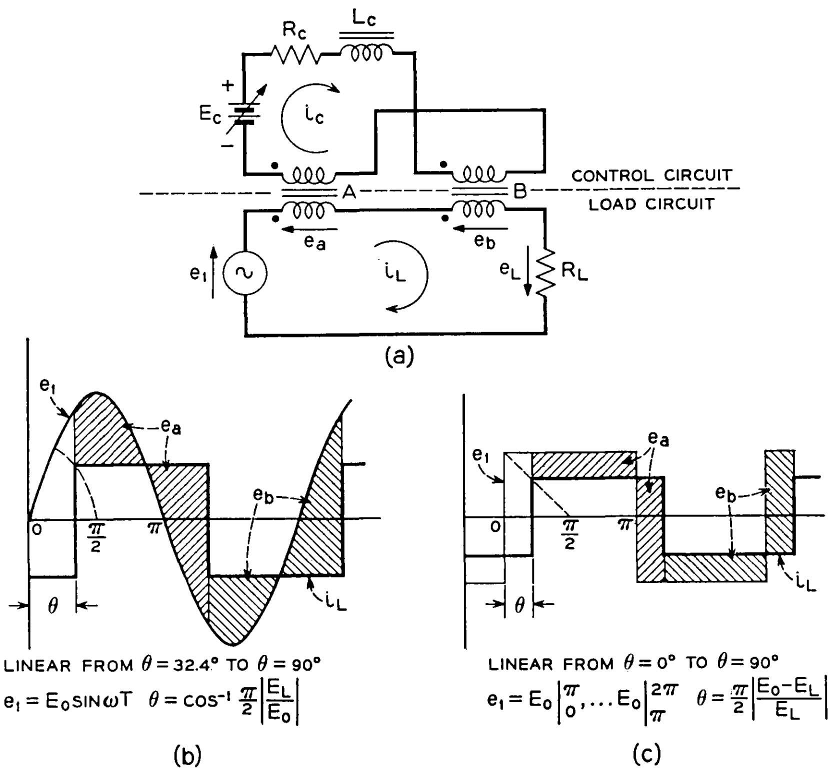


Fig. 5 — Saturable reactor regulator circuit: (a) schematic, (b) waveforms with sinusoidal excitation, (c) waveforms with square-wave excitation.

approach, however, was sufficiently great to justify the use of higher supply frequencies.

Since a reliable source of ac operating power is essential to fulfillment of the design objectives, careful consideration must be given to its selection. The availability of power transistors having collector dissipation ratings of 250 watts makes possible static inverter designs capable of meeting the power requirements for this system. These inverters, in their simplest form, generate rectangular output voltage wave shapes (although sinusoidal outputs can be obtained by appropriate techniques). Saturable reactors as used here are inherently insensitive to supply voltage wave shape, within broad limitations, and a single design can be made to give satisfactory performance with either wave shape. The rectangular wave shape offers the advantage of the widest possible linear operating range for a given reactor, as may be seen by reference to Fig. 5, permitting the most economical design for a given set of requirements. Where operation with both wave shapes is required, this economy cannot be obtained.

Proven schemes for generation of reliable ac power based on the use of rotating machines are widely used. Because of the availability of reliable 400-cycle rotating machines and the broad experience gained with this frequency in military systems, a decision to use nominal 400-cycle power was made (although even higher frequencies would have been more suitable from a size standpoint).

The advantages of the static inverter, including freedom from routine maintenance, make it the preferred ac power source for this system. Although a suitable proven design did not exist at the outset of this project, the availability of rotating machines as a back-up approach permitted ample time to prove in an inverter design. This was accomplished, and static inverters are used at all terminal installations.

To obtain the full potential of saturable reactor regulation, it is necessary to connect the outputs of the rectifiers in series. This stems largely from the desire to maintain a constant cable current under all operating conditions. If the rectifier outputs were connected in parallel, for example, loss of output from one of the rectifiers would require a sudden increase in the output current of the remaining rectifier if a significant dip in cable current were to be avoided. The relatively long time constant of the saturable reactor circuit precludes rapid adjustment of rectifier output current. A second disadvantage would be the need for a greatly increased regulator loop gain in order to provide the required gross changes in control current without a significant change in cable current. While this approach represents a departure from past practices, it is not entirely without precedents. A dual of this method may be found in the parallel operation of voltage sources in the commercial power industry. This arrangement permits addition or removal of supplementary sources without significant disturbance to the load.

Fig. 6 shows the basic interconnections within a plant. Shunt diodes are connected across the output of each rectifier. Under normal operating conditions these diodes are reverse biased and conduct a negligible current. If the output current of a rectifier should fail, its voltage will drop to zero and attempt to reverse polarity as a result of current flow from the remaining rectifier. The shunt diode, becoming forward biased, provides an alternate path for the current, permitting the remaining rectifier to supply the load. Only two rectifiers are shown in the illustration, but the technique can be extended to any number of series-connected rectifiers.

To insure stable load voltage sharing between rectifiers, two steps must be taken. The first is a reduction of the nearly infinite rectifier output resistance to a finite stable value. The second is provision of a highly stable regulating circuit.

While any desired amount of rectifier output resistance could have been obtained by a combination of both current and voltage feedback, the complexity of this approach was felt to be excessive when contrasted with the simplicity of an equivalent physical resistance connected across the output. To limit the change in cable current to less than 0.5 per cent following failure of a rectifier, this resistance must have a value of 1.5 megohms. The less than 3-watt power consumption is insignificant.

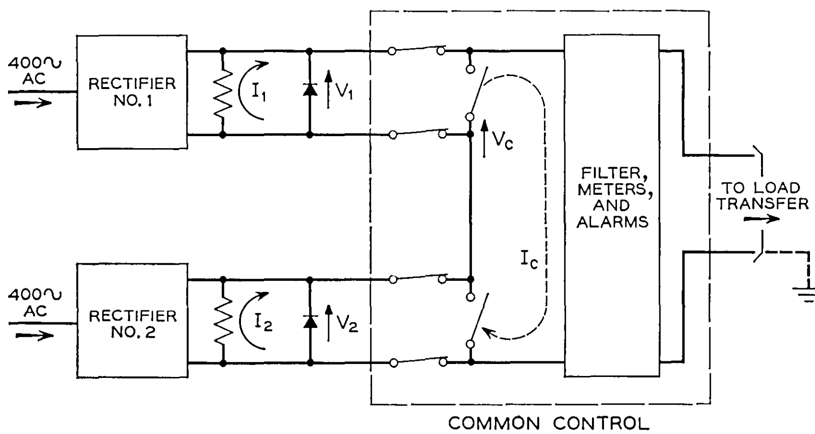


Fig. 6 — Power plant interconnections.

If the drift in voltage between two rectifiers is to be held to less than 75 volts for long periods of time, the drift in rectifier output current must be held to less than about 0.025 per cent for equivalent periods of time. Achievement of this high level of stability requires careful regulator circuit design. The availability of temperature-compensated silicon reference diodes and matched transistors permitted meeting this requirement with direct-coupled transistor amplifier circuits.

No special precautions were found necessary other than compliance with accepted feedback stability criteria to insure freedom from oscillation and hunting. The rectifiers are designed to be stable for both open- and short-circuit conditions.

### 5.3 *Common Control Circuit*

By virtue of its relationship to the over-all system, the common control is one of the more critical parts of the system. Either terminal-to-terminal short circuits of shunt-connected apparatus or a grounding failure of apparatus connected to the high-voltage conductor will result in immediate loss of cable power. Great care was therefore taken to minimize the likelihood of such failures. This was done largely by keeping the number of such components to a minimum and by paying special attention to the design and manufacture of these components to insure the highest possible quality.

While an open-circuit failure of series-connected components will also result in immediate loss of cable power, series-connected components are limited to magnetic amplifiers and filter inductors. With suitable design and manufacture the probability of an open-circuit failure in these can be made virtually zero.

## VI. DETAILED DESCRIPTION

### 6.1 *Inverter*

The design of the inverter was based on the use of 250-watt silicon power transistors developed by Westinghouse Electric Corporation.

The inverter is designed to operate from a 42 to 52-vdc source. Two outputs are provided. The main output, rated at 4.5 kva, is unregulated and supplies power to the saturable reactor in the rectifier. A second output, rated at 0.3 kva, supplies regulated operating power to the rectifier feedback amplifier and the metering magnetic amplifiers in both the rectifier and common control. The regulated output voltage is held statically to within ±1 per cent for combined input voltage and load current changes. No special speed of response requirements was necessary, however, because of the type of regulating circuit used in the rectifier.

Special attention was given to the design of the main power stage to insure reliable operation with the saturable reactor load. The inverter must perform satisfactorily with a load current whose magnitude and phase angle describe the region bounded by 0 to full-load current and 0 to unity power factor. For example, a rectifier delivering rated current into a short circuit will draw full-load kva at nearly 0 power factor from the inverter.

With the exception of the oscillator, each inverter stage is of the bridge configuration. The oscillator uses a center-tap circuit to permit simple application of series *LC* timing.

Provision is included in the oscillator circuit for frequency synchronization of all inverters in a power plant. The synchronizing circuit is loosely coupled, so that faults on the synchronizing bus will result only in loss of synchronization. Synchronization is provided to eliminate possible beat frequency interference between the combined outputs of the rectifiers in a plant.

### 6.1.1 *Reliability*

Conservative transistor operation was considered essential in obtaining reliable inverter performance. To achieve this, not only must the average and peak transistor power dissipation be held within conservative limits, but also the locus of the product of instantaneous collector current and voltage must be maintained within the reliable operating region for the transistors used.

The peak collector power dissipation of the transistors has been held to less than their rated average power dissipation. With the exception of the power stage, average collector power dissipation has been held far below ratings. The heat sinks provided are capable of maintaining collector junction temperatures below 100°C under all operating conditions.

Economic considerations required that the transistors in the power stage be operated much closer to their ratings, in order that the total number of devices be held within reasonable limits. The power stage design permits failure of up to one transistor in each of the four circuit legs before catastrophic inverter failure becomes imminent. This is accomplished by the use of 8 parallel-connected individually-fused transistors in each leg of the power stage. The fuses are of the fast acting current limiting type. Sufficient overload current capacity is available in

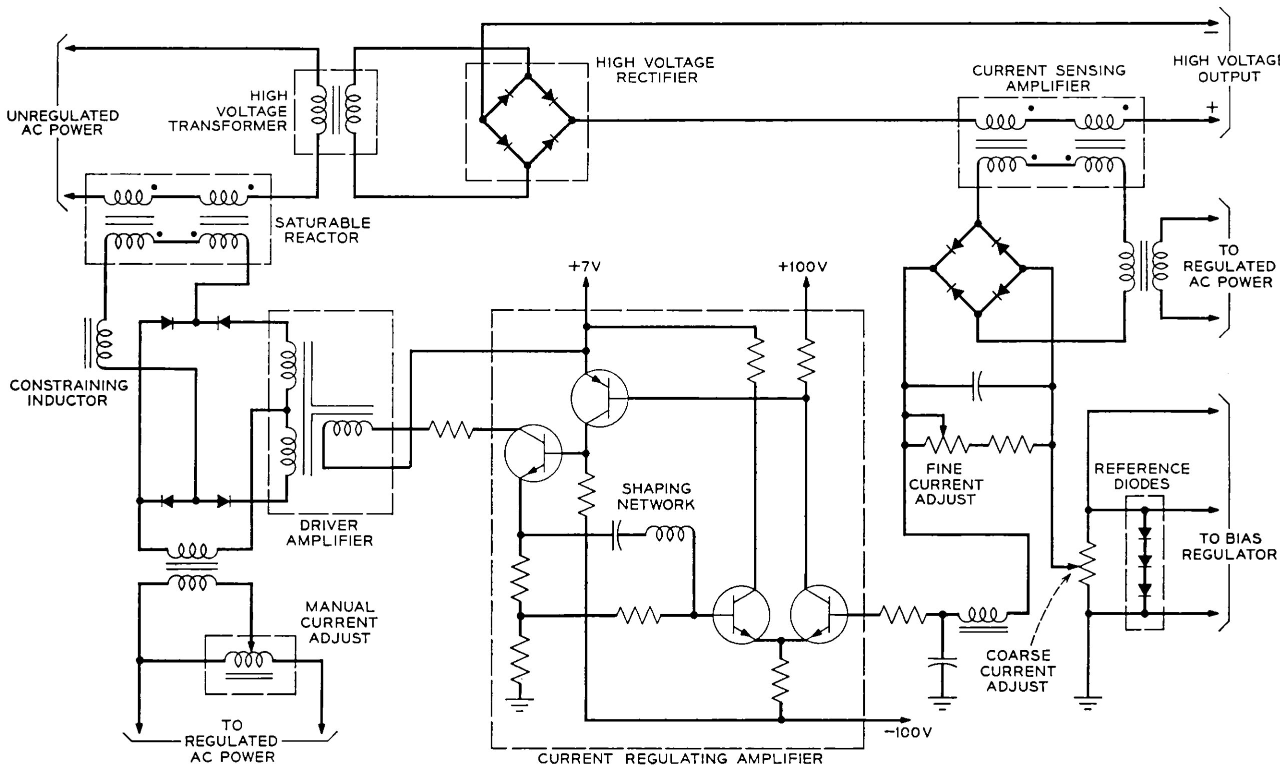


Fig. 7 — Current regulating feedback circuit.

the circuit to blow a fuse following a transistor failure without serious overload of the remaining transistors. The circuit has been designed to operate at rated load for at least 8 hours with only 7 transistors per leg.

An automatic fuse failure alarm is provided to signal the presence of a blown fuse. A manually operated metering circuit is provided to permit in-service measurement of individual transistor currents, permitting detection of low-gain or open-circuited transistors.

### 6.2 *Rectifier*

It was shown earlier that output failure of one of the rectifiers—resulting from a terminal-to-terminal short circuit, for example—while undesirable, does not result in loss of cable power. Grounding failures within the rectifier directly connected to the high-voltage power plant output conductor will result in immediate loss of cable power. As in the common control, it again becomes important to minimize the likelihood of grounding failures.

Metering-type magnetic amplifiers, which functionally exhibit at dc all the attributes of a high-quality ac current transformer, are used to isolate the metering, regulating and alarm circuits from the high-voltage part of the circuit. This approach offers the dual advantage of materially reducing the number of components directly subjected to high voltage and permits use of conventional devices and circuit techniques for metering, regulation and alarms. Only those components which by their basic function must be connected to the high-voltage conductor are so connected.

#### 6.2.1 *Current Regulation*

The current regulating circuit is shown in Fig. 7. Negative feedback is provided around the 3-stage transistor amplifier to reduce the effects of unit-to-unit variations in transistor parameters and to provide a convenient point for applying the shaping network required to insure adequate gain and phase stability margins for the regulation system.

A reference voltage of about 20 v obtained from temperature-compensated silicon diodes is required to obtain the required regulator dc stability. Bias current for the reference diodes is obtained from a single-stage transistor regulator.

The output of the transistor amplifier controls a self-saturating magnetic amplifier (driver amplifier) which in turn drives the main regulating saturable reactor.

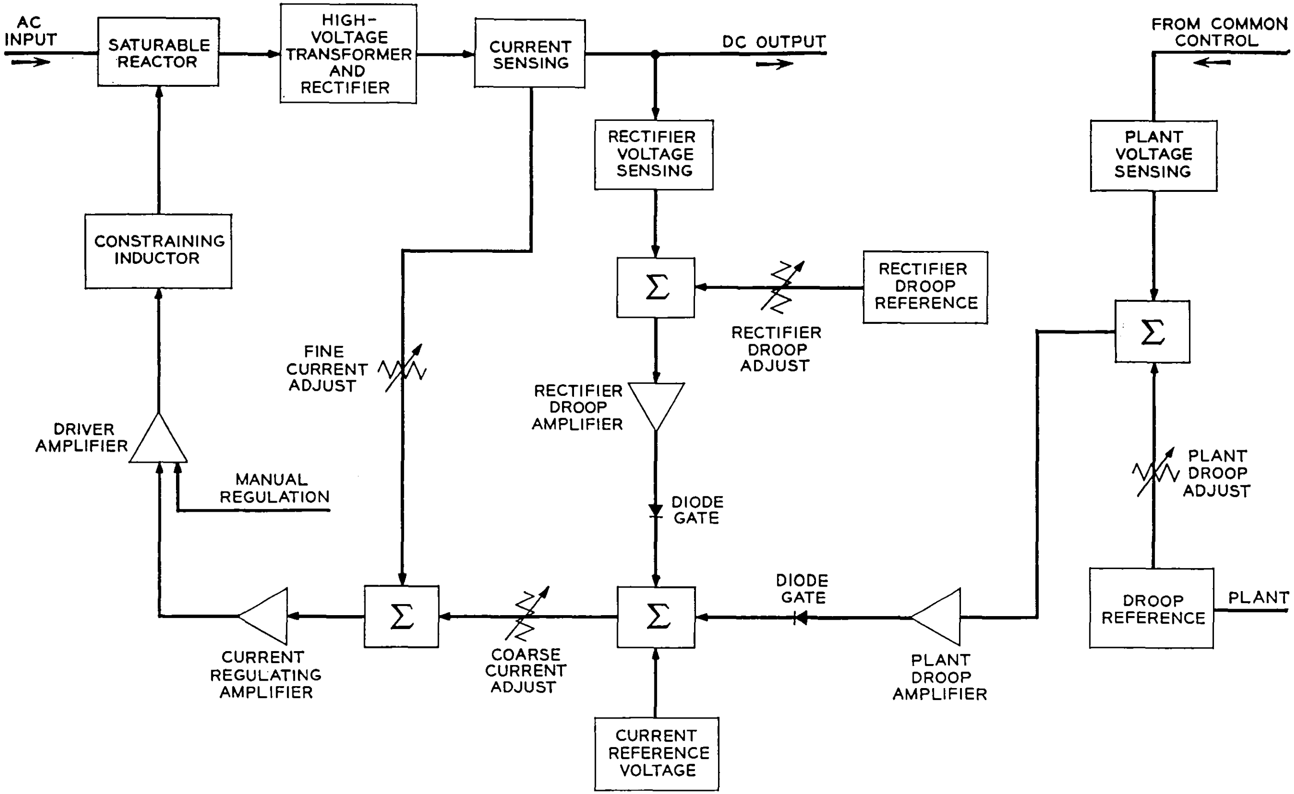


Fig. 8 — Rectifier feedback regulator functional block diagram.

### 6.2.2 *Current Droop*

Voltage limitations in the repeater power separation filter capacitors make it preferable, when the applied cable voltage exceeds 6500 volts (as might occur with abnormally high earth potentials), to reduce cable current rather than allow further voltage increase. A transition from current to voltage regulation is obtained by the addition of a second feedback path to the regulator, responsive to plant output voltage. This feedback path is coupled into the first path at the current regulator reference. The circuit is so designed that in the current droop region the magnitude of the reference voltage is reduced in direct proportion to the increase in output voltage. Since the current regulator acts to maintain the rectifier output current accurately proportional to the magnitude of its reference (voltage), effective control of current is possible.

The gain of the droop circuit is adjusted to produce a 100 per cent reduction in cable current for a 1000-v increase in cable voltage (normally from 6500 to 7500 v). A 3-stage single-ended transistor feedback amplifier provides the controlled gain and power required to modulate the current regulator reference voltage. A functional block diagram of the over-all rectifier feedback regulating circuit is shown in Fig. 8.

Two separate droop circuits are provided with each rectifier. The first, as described above, responds to plant output voltage. The second, functioning in a similar manner, responds to rectifier output voltage and serves as back-up protection. It is normally adjusted to act at the same voltage as the plant droop circuit. Since the voltage of an individual rectifier is normally about one-half the plant voltage, the rectifier droop circuit will function only if one of the plant droop circuits fails.

### 6.2.3 *Droop Circuit Test*

Under normal circumstances, the occurrence of large earth potentials is infrequent, but it is important that the droop circuits function properly when required. Confidence in these circuits can be obtained if an in-service test can be performed. To be meaningful, this test should involve as much of the droop circuit as possible.

A second control winding (test winding) is provided on each of the metering magnetic amplifiers. The output of these amplifiers is proportional to their net control ampere turns. By passing a dc current through the test winding, it is possible to either increase or decrease the amplifier output while in no way affecting normal system output.

The input and output of each droop amplifier is metered during test. The input meter indicates either the plant or rectifier voltage; the output meter indicates the voltage difference between the droop amplifier output and the current regulator reference voltage. This voltage indicates the amount of margin existing before droop action takes place. By adjustment of the test winding current, this margin can be brought to zero. The indication on the input meter then corresponds to the voltage at which droop will occur.

Selector switches are provided to permit application of an adjustable current to each of the test windings. Normal droop action of the circuit is inhibited during test.

Fig. 9 illustrates the voltage-current characteristic of a power plant when the effects of the current droop circuit are included.

6.2.4 *Manual Regulation*

The main regulating saturable reactor is sufficiently stable over time intervals of 10–15 minutes to permit usable rectifier operation on a manually controlled basis. This provides a back-up operating mode. Operation in this mode involves only the driver magnetic amplifier and a continually adjustable autotransformer, the latter serving as the manual current adjust control. In this mode of operation, control current is removed from the driver magnetic amplifier. It then behaves purely as a passive element, delivering a dc output voltage proportional to input voltage obtained from the manual current adjust control. Input

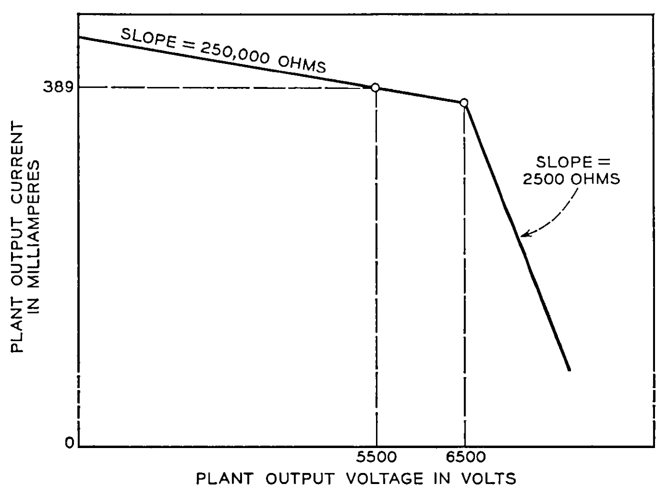


Fig. 9 — Power plant voltage-current characteristic curve.

power for the driver amplifier is taken from the regulated ac output of the inverter.

### 6.2.5 *Rectifier Alarms and Shutdown Circuits*

To meet the over-all design objectives, the rectifiers must provide automatic alarm and shutdown protection when abnormal currents or voltages exist. These abnormal conditions can occur as a result of malfunction of a rectifier, operator error, excessive earth potentials or faults on the cable system.

Two classes of alarms are provided. Those designated "minor" imply the presence of an abnormal but tolerable current or voltage. Those designated "major" imply the presence of hazardous current or voltage and require shutdown of the offender.

Two independent sensing circuits feeding separate, permanently adjusted, meter-type relays provide the current alarms. Each relay responds to both high- and low-current conditions. When the high-current contact on either relay makes, shutdown as well as an alarm indication takes place. Shutdown is produced by release of the main ac input contactor. A second fast-acting electronic shutdown circuit, fed along with one of the meter relays from one of the sensing magnetic amplifiers, is provided. This circuit produces shutdown by interrupting the dc input to the inverter oscillator. Power flow from the inverter ceases within about 15 msec after the shutdown level is reached. The shutdown circuits are all adjusted to operate at the same current. The electronic circuit, being faster, operates first. The relays provide back-up protection.

A single sensing circuit feeding both an adjustable contact indicating meter relay and a fast-acting electronic circuit is provided for the voltage alarm. Shutdown is accomplished in the same manner as for the current alarms, with both circuits adjusted to operate at the same voltage. The meter relay serves also as the rectifier output voltmeter.

While great care has been taken in the design of the rectifier and inverter, a malfunction is likely to result in abnormal output. Where low current occurs, the shunt diode automatically bypasses the output. When high output occurs, the alarms will provide immediate warning, and if the output is over 5 per cent above normal will result in immediate shutdown. When sudden failure of the feedback regulator occurs, resulting in maximum output, the long (0.3-second) time constant of the main saturable reactor control circuit provides ample time for detection and shutdown before the current can climb appreciably above the shutdown level.

Alarm lamps are provided for each specific alarm function. These lamp indications persist for any alarm that signals the office alarm. An approximately 2-second time delay is provided on all minor alarms. If the alarm comes in and clears before the delay has elapsed, the alarm clears automatically and no office alarm is transmitted.

#### 6.2.6 *Alarm Testing Circuits*

Under normal conditions, the frequency of alarm indications is very low. It is important, however, as with the droop circuits, that these circuits function properly when abnormal conditions occur. Additional positions are provided on the magnetic amplifier test selector switches to permit in-service testing of these circuits. Where the function to be tested includes shutdown, shutdown is inhibited. All other aspects of the alarm and shutdown circuits are unaffected by the inhibiting action. Through application of the test signal to the magnetic amplifier, confidence in the integrity of the alarm circuits is maintained, since the complete alarm path is tested. Inhibiting involves bridging of normally closed relay contacts.

The design of the alarm test circuit does not permit accurate adjustment of the alarm operating points, but rather is intended solely as a functional check. The design of the meter-type relays insures that they will hold their calibration over long periods of time. Accurate calibration of these relays is possible by taking the equipment out of service and operating it with the test load. Fig. 10 shows the test circuit used.

#### 6.2.7 *Spark Gap*

A protective spark gap is connected across the dc output of the rectifier to limit the maximum instantaneous voltage which can be developed. This is done to protect components in the rectifier against damage resulting from excessively high voltage. A resistor and a current sensing relay are connected in series with the spark gap. Operation of this relay results in rectifier shutdown. The resistance is provided to limit the peak current in the protector circuit.

### 6.3 *Common Control*

The basic functions of the common control are:

(1) connect and disconnect means for the individual rectifiers in a plant,

(2) voltage and cable current metering,

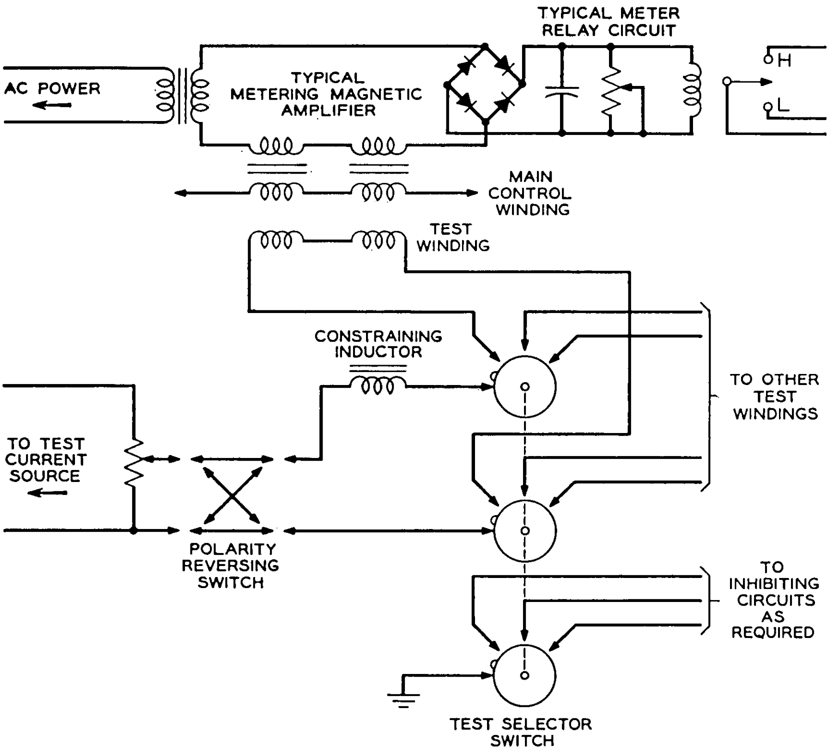


Fig. 10 — Magnetic amplifier test circuit.

(3) monitoring of cable voltage and cable current by means of alarms,
(4) final power supply output ripple filtering, and
(5) means for surge voltage limiting.

As in the rectifier, metering magnetic amplifiers are used to isolate the alarm circuits from the high voltage circuit. Since one side of the plant output is at ground potential, indicating voltmeters are operated directly with high-resistance multipliers.

A suppressed-zero meter (300 to 450 ma), operating from a metering magnetic amplifier having exceptional stability, is used for precision cable current metering. The magnetic amplifier is connected in the high-voltage conductor at the output of the common control. AC power for these magnetic amplifiers is selectable by means of a selector switch so that power can be obtained from any of the rectifiers.

Since none of these alarms results in shutdown, their failure results only in loss of alarm capability. Alarm failure resulting from loss of ac

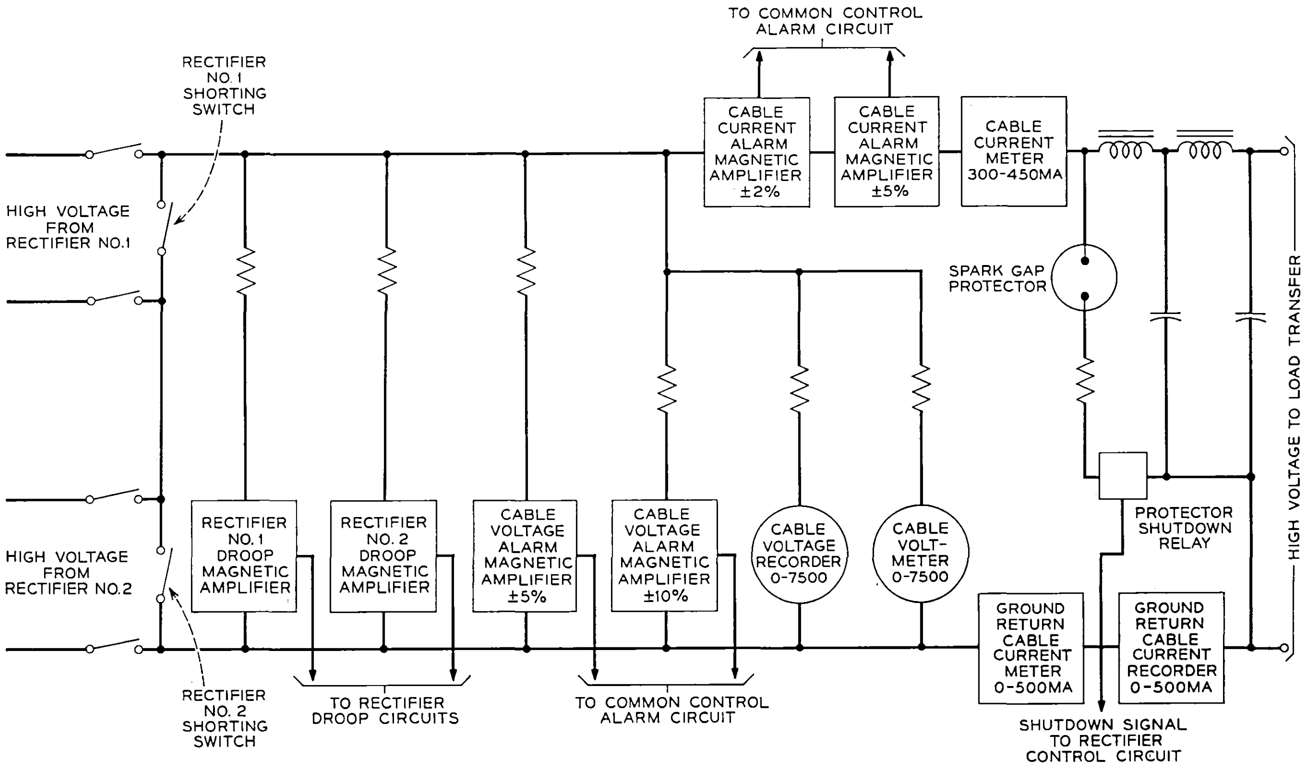


Fig. 11 — Common control functional circuit.

power produces immediate transmission of low-limit major alarms to the office alarm system.

An alarm test circuit similar to that used with the rectifiers is provided for in-service testing of all alarms. Fig. 11 illustrates the common control functional circuit.

### 6.3.1 *Surge Voltage Protection*

The series connection of the rectifiers results in an asymptotic open-circuit voltage greater than 15,000 v. Application of such a voltage to filter capacitors within both the power plant and the repeaters will severely shorten their life. Because of the constant-current nature of the power plant, such voltages are possible following an open-circuit cable break. The rate of rise of voltage can be as high as 120 v per msec depending on the location of the break. This rate of rise is too fast to control by direct overvoltage sensing and turndown circuits. Instead, a spark gap, designed for fast triggering and capable of carrying the full plant output current indefinitely, is used for surge voltage protection.

A current limiting resistance and current sensing relay is included in the spark gap circuit to limit the magnitude of the surge current and to produce shutdown of the power plant.

### 6.4 *Load Transfer*

The purpose of the load transfer is to permit transfer of power from the working power plant to the standby power plant without interruption or disturbance of the cable current. Fig. 12 illustrates the circuit used. The transfer operation consists of energizing the standby plant through the connected path (A) into the test load; then simultaneously adjusting the standby plant and test load until the current and voltage equal that of the working plant; then closing the presently open contacts (B) and opening the formerly closed contacts (A). It may be seen at this point that the former working plant is now feeding the test load and the standby plant is now feeding the cable.

Alarm transfer relays synchronized with the high-voltage contacts connect the office alarm to the working plant.

### 6.5 *Test Load*

The test load is designed to dissipate the full power output of either an individual rectifier or a complete plant. Load voltage is adjustable to permit operation at any voltage from 0 to 7500 v. This flexibility is

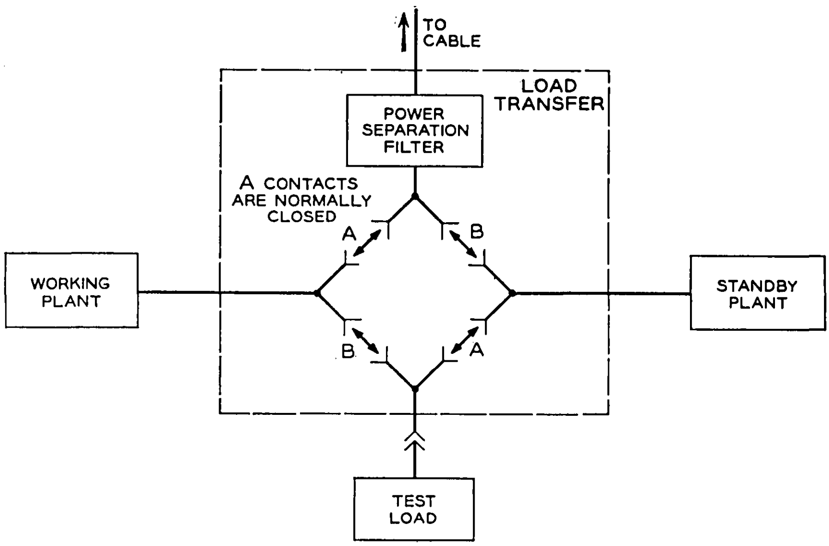


Fig. 12 — Load transfer circuit.

required to accommodate all possible lengths of cable systems. Meters accurate to 0.25 per cent are provided for current and voltage measurement.

6.5.1 *Ripple Measurement*

An attenuator is provided to permit rectifier or plant output ripple voltage to be measured at a safe potential with respect to ground.

6.5.2 *Precision Current Meter Calibrator*

Two sets of shunts and standard cells are provided to permit an accurate calibration of the power plant cable current meters. The shunts have a resistance which gives a voltage equal to the nominal standard cell voltage at 0.389 ampere of current. The voltage drop across the shunt is compared to the voltage of the standard cell by means of a sensitive galvanometer. Switches are provided to permit comparison of the voltage drop across each shunt to the voltage of each standard cell and permit cross comparison of calibrating circuit elements to reveal a drift or aging in any of these elements.

## VII. DETAILED EQUIPMENT DESCRIPTION

### 7.1 *Appearance*

In the equipment development the aim was to design a distinctive, pleasant-appearing, and functional set of equipment. A distinctive blue color was selected for the exterior of the cabinets and the rear doors. Light gray panels are used for ease of legibility, readability and maintainability. Panels which are adjacent to one another have rounded edge contours to minimize the effects of assembly tolerances. An effort was made to provide an up-dated appearance for components such as meters recorders, etc. The number of cables, conduits and other appurtenances to the equipment bay tops is minimized in order to achieve a clean, uncluttered look.

### 7.2 *Voltage Isolation, Personnel Protection and Key Interlock System*

Hazardous voltages over 600 volts within the power supply are isolated so that access to components with these potentials is restricted when the equipment is energized. These voltages are isolated in locked units or in locked compartments. Fig. 13 demonstrates the isolation within the equipments. The high- and low-voltage sections within the cabinets are defined by vertical or horizontal partitions. The tops of the cabinets are enclosed with sheet-metal covers. The foregoing is generally applicable to all equipment cabinets except the inverter cabinet, which has no potentials above 600 volts and is therefore unlocked.

Operating procedures designed to minimize any interruptions to service or injury or damage to equipment were developed to allow access to high-voltage portions of the equipment only when the potentials had been removed. Each step in the procedure requires the operation of a key or number of keys wherein the key is released, captured or exchanged.

The key interlocks are used to control the operation of switches, the opening of doors, the operation of variable autotransformers, the operation of the patch panels, the operation of patching facilities for testing, etc.

### 7.3 *Maintenance*

A number of maintenance features have been included. The major feature is the provision of regular and alternate power supplies which are in either the working or standby condition. This permits testing and main-

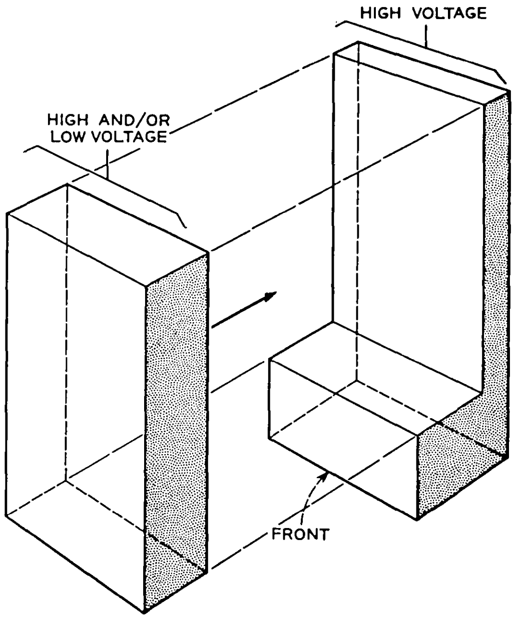


Fig. 13 — Voltage isolation in equipment.

taining the standby plant without concern, since there is no effect on the submarine cable system.

Recording ammeters and voltmeters monitor the output voltage and current of the regular and alternate power supplies. These recorders serve as an invaluable aid in maintenance procedures in the event of an unscheduled shutdown of the power supply. Alarm lamps and indicators have been furnished to assist trouble shooting or adjustment. Test jacks have been provided for in-service checks of low-potential circuits. A major maintenance tool is the test load.

Human engineering principles have been applied wherever possible in the location of controls, meters, switches, etc.

Equipment units on pull-out ball bearing slides are used for better packaging and also to improve maintenance access. Units with only low-voltage circuitry have an interior secondary control area for controls and apparatus required for maintenance adjustments. These are exposed when the slide unit is extended. A typical arrangement is shown in Fig. 4. Indicators of system performance are front panel mounted and are visible at all times. This approach eliminates the vast clutter of instrumentation controls, switches, etc. which might otherwise appear on the front of the equipment panels, and has simplified maintenance and training.

### 7.4 *Corona and Dielectric Tests*

For system reliability the power plant must withstand corona and dielectric voltage test requirements. Portions of the equipment must pass 19,000-vac or vdc dielectric test requirements and 10,000-vdc corona tests. Workmanship items which include elimination of sharp projections, loose strands of wire and the achievement of smooth, round solder joints are important in passing these dielectric and corona requirements. Ceramic standoff insulators required baked silicone varnish surface treatments to pass corona requirements.

### 7.5 *Apparatus*

#### 7.5.1 *Patch Panels*

Since the power plant includes redundant rectifiers and provision for regular and alternate supplies, it was necessary to incorporate a suitable disconnect and voltage isolation means whose mechanical operation could be visually verified. The term "patch panel" has been applied to this piece of equipment, which is seen in Fig. 3 in the lower part of the common control cabinet.

The patch panel is essentially a mechanically operated jumper cable. When a handwheel is turned clockwise, specially designed male and female molded high-voltage cable assemblies are connected. The patch panels are locked in the connected and in the disconnected position by means of key interlocks.

#### 7.5.2 *Vacuum Relays*

Vacuum relays are used as shorting switches and control relays. Their operation is associated with the operation of the key interlock system. Vacuum relays were selected rather than mechanical switches because of their superior voltage breakdown characteristics and small size. Relays are normally used in pairs with paralleled contacts. The relays are designed to fail-safe in the event that the coil power is lost.

#### 7.5.3 *Semiconductor Devices*

Semiconductor devices have been extensively employed in the equipment. No tubes, other than gas tubes which will be described later, have been used. In the high-voltage portion of the rectifiers, encapsulated silicon diode sticks with capabilities far in excess of operating conditions have been specified. The diode-encapsulated sticks are mounted using ceramic standoffs to further improve their voltage capability to ground.

#### 7.5.4 *Gas Tubes*

In order to further assure personnel safety and plant reliability, gas tubes have been used which are counterparts of the gas tubes used in the submarine cable repeaters. These gas tubes protect power supply high-voltage meters and recorders if their ground side opens. The tubes will fire and clamp the instruments to ground. Another gas tube, which can carry full cable current, is shunted around the current recorder and the direct-reading ground current return meter to protect against an open in the meter shunts.

### 7.6 *Hardening*

For protection of communications facilities, most submarine cable terminal stations are installed at hardened sites. In order to achieve a minimum usage of floor space for the power supply, a design with the equipment cabinets arranged in two rows, facing each other, was developed as shown in Fig. 14. The equipments are placed on a platform mounted on rubber shock mounts.

## VIII. SPECIAL EQUIPMENT

### 8.1 *Ground Supply*

The ground supply bay is primarily designed to act as a ground and transmission termination for a cable system powered from one end. A power separation filter is included to permit insertion and removal of transmission circuits. The ground supply bay can be connected to a second ground supply bay to serve as the through connection at an intermediate point on the submarine cable system. It is also possible, on an emergency basis, to patch in a high-voltage power plant to the ground supply to power a part of a submarine cable system.

### 8.2 *Shipboard Power Plant*

During the laying and repair operation in the submarine cable system it is necessary to provide power to the cable from both land and ship or possibly from one source alone. For these situations a shipboard power

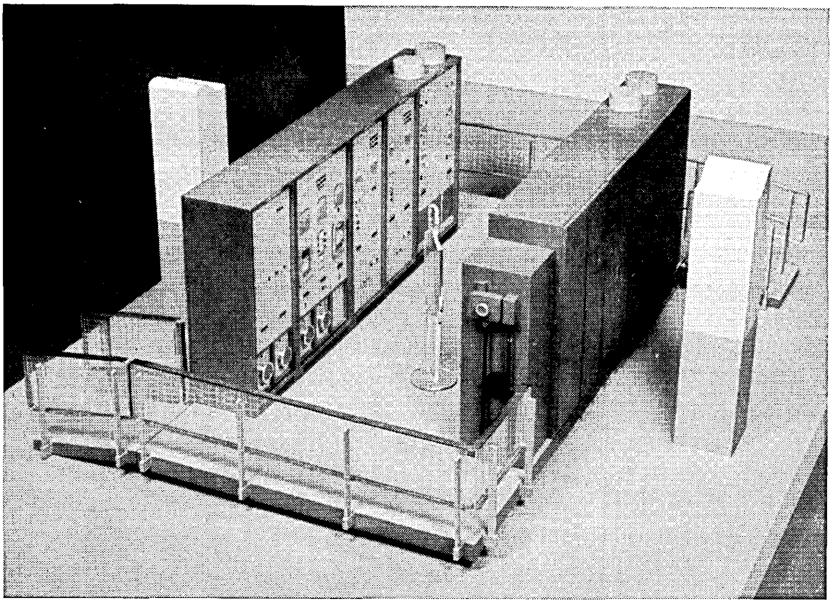

Fig. 14 — Hardened site installation.

supply has been designed and is installed on C. S. *Long Lines*. The shipboard power supply is available for cable laying operations and powering the cable stored on a ship. It is also possible during cable laying operations to power from the shore end and apply a ground to the cable aboard the ship. The shipboard power supply is designed to operate on 400-cycle ac power supplied by a pair of motor alternators. Its design includes several options permitting use with existing foreign or domestic submarine cable systems.

### 8.3 *Power Plant for Short Cable Systems*

A small power plant similar in design to one of the main power plants has been developed to supply operating power for distances less than 300 nm with double-end power feed or 150 nm with single-end power feed. The major differences are the use of only a single two-rectifier power plant, 1200 cycles ac power, and elimination of key interlocks.

## IX. ELECTRICAL NOISE

Some difficulty has been found with electrical noise interference, both from sources within and external to the power plant equipment. This problem was aggravated by the presence of three distinctly different grounds (ocean, office and cable outer conductor) which must be common at signal frequencies but isolated at dc. A satisfactory solution was found after on-site investigations and involved minor equipment wiring changes and the addition of capacitors at appropriate points in the circuit.

## X. ACKNOWLEDGMENTS

A development of this complexity obviously required the work of many individuals in order to bring the project to successful completion. Special credit goes to Mr. B. H. Hamilton, who formulated the basic approach followed and supervised the circuit design; to Mr. V. B. Boros, who contributed to the concept and was responsible for a portion of the circuit design; to Mr. R. R. Gay, who supervised the equipment design; and to Mr. D. E. Trucksess, who managed the over-all project. Credit should also be given to Mr. A. D. Hasley's magnetic apparatus development group for the successful design of a large number of reliable high-performance magnetic components.

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# A Cable Laying Facility

By R. D. EHRBAR

(Manuscript received March 2, 1964)

*In order fully to utilize new broadband submarine cable systems it has been necessary to consider new techniques for placing the system on the ocean bottom. This article describes the general development plan that resulted in a new cable ship capable of efficiently handling any new system. The article thus serves as an introduction to the remaining articles of this special issue.*

## I. INTRODUCTION

The need for new and more complex submarine cable systems to handle a growing transoceanic communications business produced many new features in the design of cable and repeaters and auxiliary electronic equipment.[1,2,3] It also made necessary new solutions to the problem of placing the cable system on the ocean floor. This task appeared formidable to the early telegraph cable engineers, and many failures preceded the final development of a satisfactory mode of operation. In terms of modern systems their task was simple, since they were interested only in a single-conductor circuit that would remain a low-resistance path well insulated from the sea.

Modern broadband cable systems present a large number of new problems. The cable is now a complex transmission line whose characteristics up to high frequencies must be predictable and stable after the laying process. Repeaters and equalizers requiring large rigid containers are now inserted in the cable at frequent intervals. Both cable and repeaters are expensive and must not be wasted by the lack of precise payout control.

When development of a repeatered telephone system[4] was initiated by the Bell System, it was recognized that the laying of such a system in deep water was a sizable problem. Consequently, effort was concentrated on a flexible repeater that could be handled like cable with only minor modifications to existing cable ships.

At the same time it was realized that this restriction would unduly constrain future developments of broadband systems, and a program was started in 1953 to develop more versatile and more precise techniques and machinery for cable laying that could be integrated into a working cable ship. The objective was a modern cable laying facility that would permit the efficient installation of any type of cable system that might be developed in succeeding years. The many parts of the facility are described in companion articles.[5,6,7] These were developed as an integrated system under a common development plan described below.

As a first step, analytical and simple model work was started on the fundamental mechanics of cable laying and recovery. Some of the questions to be answered were:

(1) What is the configuration of a cable on its way to the sea bottom or during recovery? What are the forces involved?

(2) What is the nature of the ocean bottom environment?

(3) How must the cable be controlled for proper distribution on the bottom?

(4) What are the effects of wind, currents, and wave motion on the laying process?

Many of these questions have not yet been completely answered and are the subject of continuing exploration and study. However, a sufficient background of fundamental knowledge was assembled to guide the development of cable laying techniques and equipment. Some of this work has been reported.[8] Additional information will be published as studies of general interest are completed.

## II. OBJECTIVES AND REQUIREMENTS

The objectives of a perfect cable laying technique can be stated quite simply:

1. The cable should just follow the bottom contour — laying wasteful excess cable must be avoided without increasing the chance of failure during or after laying. Cables suspended above the bottom in areas of varying depth are subject to damage by chafe, abrasion, and man-made hazards.

2. In the trip from shipboard to its place on the bottom no part of the cable or repeaters should be subjected to excessive mechanical deformation or shock. This will insure that the reliability and transmission stability of the system are not affected by the laying process.

With these objectives in mind, analytical work continued. Basic ideas were studied with table-top models and $\frac{1}{4}$-scale working models. Finally the better ideas were converted to full-scale models. At the same time naval architects were brought in as consultants to consider the proposals in the terms of a marine environment and to incorporate them in preliminary arrangements of a new cable ship. Other persons engaged in cable laying were briefed on the new ideas and their comments solicited to take advantage of prior experience.

From these studies came four fundamental requirements to guide the final development:

(1) The cable laying process should be continuous at speeds of 4–8 knots to avoid unpredictable transients and ship control difficulties.

(2) The cable, when under high tension, should be in a straight line and should be handled by machinery that would treat it as gently as possible to eliminate transmission variations and possible damage.

(3) Personnel requirements should be kept to a minimum so that long systems with close-spaced repeaters would not require oversized, highly trained ship crews.

(4) Methods should be safe and simple, avoiding the need for close timing or coordination, since a ship at sea can be a very unstable platform.

## III. NEW DEVELOPMENTS

The exploratory work suggested that the cable ship be considered in terms of two independent functions: (1) high-speed continuous laying of rigid repeater systems, and (2) repair of cable systems of any type or slow-speed laying of a few repeaters. The first function was assigned to the stern of the ship and the second function to the bow.

For stern laying three new developments were needed:

(1) a new cable engine which would hold cable without damage and simultaneously accommodate rigid repeaters without change in speed,

(2) a method to control the cable and repeater during overboarding, and

(3) a system for handling and stowing cable and repeaters in the ship that would permit continuous and essentially unattended payout.

For the functions at the bow, conventional cable engines using large-diameter drums were adaptable. Many new features were desirable, but of most importance was controlled movement of the cable line in the horizontal plane to permit repeaters to be handled without overriding cable on the drum.

Development of methods and equipment to meet these specific needs was undertaken in early 1957. These did not by themselves make a cable handling facility, but had to be integrated into the design of the cable ship. In general, they required large spaces and involved heavy

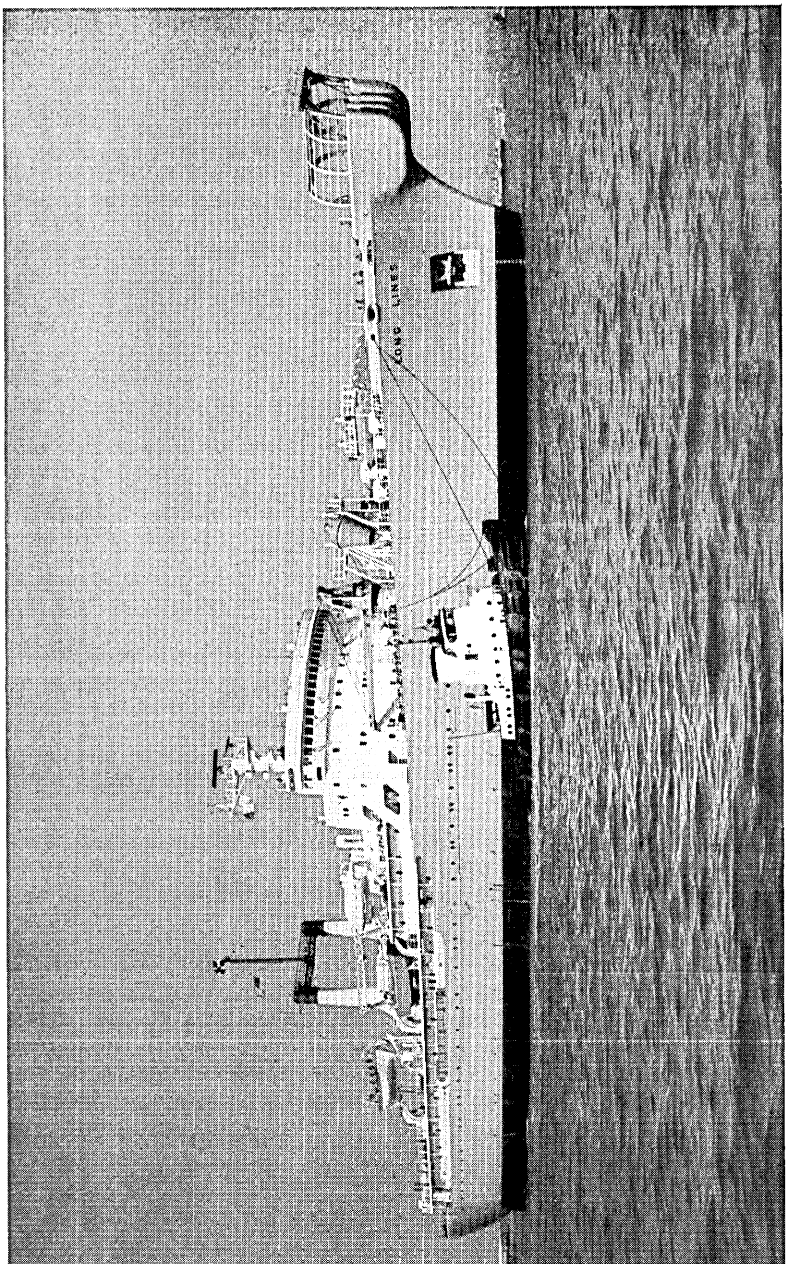


Fig. 1 — C. S. *Long Lines*.

machinery, so provision had to be made in the basic structure and in the spatial arrangements of the ship. It proved to be essential that the development of the laying system and the design of the ship be coordinated under an integrated system concept.

Then the ship with its cable gear had to be put to work in a dynamic sense. This involved operation of the cable gear and the ship by personnel in accordance with requirements dictated by the cable system. To accomplish this most effectively, it was necessary to consider navigation and ship control, control of the laying process, transmission testing and adjustment, cable splicing and loading, communications and many other factors to insure that the cable and repeaters could be placed safely and precisely along the desired route.

## IV. CABLE SHIP *LONG LINES*

The new Bell System cable ship, *Long Lines*, shown in Fig. 1, represents the first example of cable ship design following the basic philosophy of an integrated system design. It was not sufficient that the ship be able to lay the newest system, but was necessary also that its equipment be flexible enough to lay other systems which might follow in the natural evolution of undersea transmission systems. The papers that follow in this special issue describe some of the more important developments and present the story of this new ship. Throughout the descriptions the need for coordination of all the parts should become apparent.

This new cable handling facility has proved, in its first important test of laying a new transatlantic cable, that the thorough development program was successful. Cable and repeaters were payed out continuously at 8 knots with a ship's complement about 25 per cent less than that used on other cable laying ships of comparable size. A facility is available that can be adapted to handle any transoceanic system that might be considered in the next decade. The basic design is such that new features can be added as our knowledge increases and new techniques are developed.

Many organizations and individuals were responsible for the success of this undertaking. During the development the following organizations outside the Bell System were important members of the development team:

Bergen Research and Engineering Company assisted in much of the quarter-scale model design, construction and testing.

Western Gear Corporation was responsible for final design and manufacture of the cable engines.

Gibbs & Cox, Inc. provided the necessary marine background and contributed to many of the design concepts.

The final design and construction of the cable ship was the responsibility of the Long Lines Department of the American Telephone and Telegraph Company. Gibbs & Cox, Inc. acted as its design agent in this undertaking. A contract for construction of the ship was signed with Schlieker Werft, Hamburg, Germany on October 27, 1960. The launching occurred on September 24, 1961, and the ship arrived in the United States on April 13, 1963. It sailed for its first cable laying job on July 23, 1963.

The ship is owned by Transoceanic Cable Ship Company, a wholly owned subsidiary of A.T.&T. Co. It is operated by Isthmian Lines, who handle the cable laying and repair work with the technical assistance of Bell System personnel.

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# Cable and Repeater Handling System

By O. D. GRISMORE

(Manuscript received March 24, 1964)

*This paper describes the development of methods and equipment for handling cable and repeaters in laying submarine cable systems and the application of these developments to C.S. "Long Lines." Both the laying process and the associated operation of assembling the system components in preparation for laying are described.*

## I. INTRODUCTION

The underwater portion of a modern submarine cable system is composed of three basic components; cable, repeaters and equalizers. These are delivered to dockside as individual items, and the handling of these units from this point to the time when they leave the ship on the way to the ocean bottom is the work of the cable and repeater handling system. The planning of arrangements and procedures, and the design of equipment and details to implement the following operations are included in the handling system:

(1) movement from dockside to appropriate stowage positions aboard ship,

(2) connection of components into a transmission system,

(3) cable test during loading,

(4) system test during laying,

(5) preparation of repeaters and equalizers for launching,

(6) control of cable and repeater movement during laying, and

(7) cable jointing for laying and repair.

For the performance of these operations, the following requirements were set for equipment and arrangements:

(1) cable to be handled in a fashion to avoid damage from bending, twist, abrasion and tension;

(2) repeaters stowed and handled to avoid excessive shock and extremes of temperature;

(3) stowage of cable simplified to avoid possibility of cable fouling

and permit easy checking of clearances and provide flexibility in sequence of tanking;

(4) cable and repeaters to be payed out in a steady-state continuous operation at speeds to 8 knots;

(5) minimum manpower requirements during the laying operation.

## II. GENERAL SCHEME OF OPERATION

From a knowledge of the route over which the cable is to be laid, a loading plan is prepared which assigns cable sections, repeaters and equalizers to particular places in the system and particular positions on the ship. The components are then brought aboard ship in the proper order for stowage to permit laying in the correct sequence.

The cable and repeaters, which comprise a shipload, are connected together aboard ship to form a single complete circuit. This may consist of as much as 2000 nautical miles (nm) of cable, 100 repeaters and 10 equalizers if the ship is loaded to design capacity. The circuit thus formed consists of a series of "ocean blocks" 192 nm in length, each containing 10 repeaters. The ocean blocks are connected together through ocean-block equalizers which are adjusted aboard ship just prior to overboarding.

After the shipload of cable and repeaters is assembled into a complete circuit, the ends are connected to the shipboard power supply through power separation filters and the circuit is powered from end to end. Transmission measurements are then made on one block at a time from one equalizer to the next adjacent. Through measurements from end to end of the system are not possible when the cable is aboard ship, because the temperature of the cable in the ship's tanks is much higher than it is at sea bottom, and the excess loss of a complete shipload due to temperature is in the order of 200 db.

Following the shipboard transmission check and upon arrival at the cable ground, the outboard end of the cable is connected to the shore station or to the end of cable previously laid. As soon as the connection is complete, power is turned up on the system, ship-to-shore communication is established and transmission measurements are made. Cable laying is then started, and from this time until the bitter end of the cable is reached there is no interruption in power or signal transmission.

The amount of cable payed out is slightly in excess of the distance traveled over the ground, in order that there be sufficient cable length to fill bottom irregularities, the excess length being known as "slack." To measure the distance over the ground a continuous length of piano wire, called the "taut wire", is payed out. This wire is anchored to the ocean bottom and is payed out under constant tension. The speed of taut wire payout is measured and the cable payout speed adjusted to provide the slack appropriate for the bottom conditions at the point of cable touchdown. Bottom contours are measured by echo sounders, the results of the measurements being plotted on a precision depth recorder. In laying cable over a flat ocean bed or over constant, moderate slopes of less than about 4°, the cable and repeaters are payed out at top speed of 8 knots, weather and sea conditions permitting. Over rough bottom with steep slopes, ship's speed is altered as necessary to get proper coverage of the bottom.[1]

As cable is payed out, the next repeater or equalizer which is to be launched is moved from a stowage position to a launch position, where it is free to move in line with the cable along the working deck, through the cable engine and into the water. At this time a parachute is attached to the repeater body. When in the water, the parachute opens to slow the repeater descent to more nearly match the sinking rate of the cable.

As soon as a repeater is launched the next repeater is prepared for overboarding. The preparation for launching takes about 10 minutes and the time interval between repeaters or between repeaters and equalizers varies from about $\frac{3}{4}$ hour to 5 hours, depending upon cable laying speed.

While laying the system, transmission measurements are being made and communications are being carried on over the cable between ship and shore. The transmission and equalizer adjustment connections to the cable are made at the equalizer, and measurements are made between shore and the next equalizer to be launched. Approximately 3 hours before the equalizer launching a decision is made as to the optimum setting of the equalizer. It is then adjusted by means of the stepping switch. After rechecking the transmission characteristic, the transmission and stepping lead connections are removed, the lead ends are sealed and the equalizer is prepared for launching.

The process of cable laying and repeater and equalizer launching continues section-by-section and block-by-block until the end of the load is reached. The cable end is then joined to the shore end cable or is streamed on the bottom to be picked up later after the ship returns with another load of cable.

## III. CABLE LAYING SYSTEM

The most significant single contribution to improved cable laying was the design and development of the linear cable engine,[2] which made it possible to pay out cable and large, heavy, rigid repeater casings with

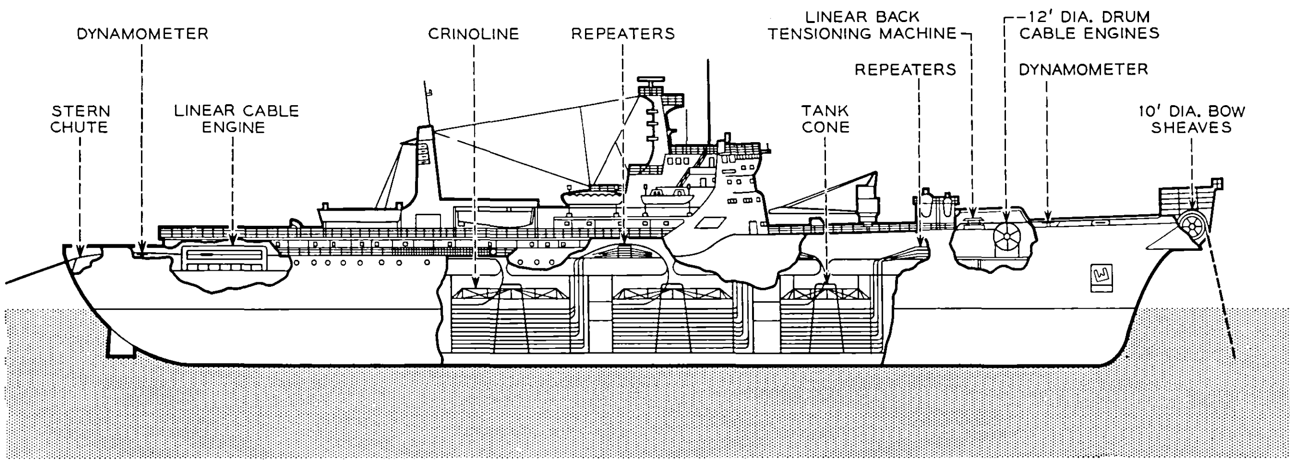


Fig. 1 — General layout of the cable laying system.

equal ease. The cable handling system exploits to the fullest extent the capabilities of the linear cable engine and provides for continuous substantially automatic, payout of cable and repeater.

The general layout of the cable laying system is shown in Fig. 1 and an individual tank arrangement is shown in Fig. 2. Cable is loaded into the cylindrical tanks in a reverse sequence from which it is to be laid. The cable is coiled as shown, in layers called "flakes," around the central core of the tank, which has the form of a truncated cone. There are three main cable tanks along the center line of the ship which hold the cable to be laid. In general, all of the cable in one tank is payed out before transferring to another; the preferred order is tanks 3–2–1. The arrangements are completely flexible, however, and practically any order can be used at a sacrifice in simplicity of stowage.

Cable is payed out from the center of the top of the tank over the smooth faired surface to the cable working deck. It moves aft along this deck to enter the repeater trough and passes through the trough to the cable engine. On passing through the cable engine it reenters the trough, continues over the dynamometer, through the stern overboarding chute and into the water. The guiding principles have been that the moving cable and repeaters travel over faired surfaces, smooth deck areas or through open troughs. Closed guides, rollers and gates are avoided, and it is unnecessary for personnel to handle or guide the moving cable or repeaters at any point in the payout process. Once payout is started the only action required by personnel is to move the repeaters from the stowed to launch position and to dress the following cable on the deck forward of the repeater in the launch position.

In Fig. 2, tank 3 is shown with a repeater in the launch position and the repeater stowage area filled with a complete complement of repeaters. Payout of the cable is aft, and a bight of cable is shown rising through the deck slot just before reaching the working deck. As the bight of cable reaches the working deck the bight is straightened out, the cable is pulled taut, and the repeater is accelerated to payout speed.

## IV. CABLE TANKS

Of the seven cable tanks in the ship only the three main tanks which carry the cable to be laid are of particular interest. The other four are small tanks which hold short lengths of spare and repair cable; cable is not payed out directly from these.

The three main cable tanks are similar, differing only in diameter. Tank 1 forward is 42.5 feet in diameter, with a capacity of 31,000 cu. ft., while tanks 2 and 3 are 55 feet in diameter and have a capacity of

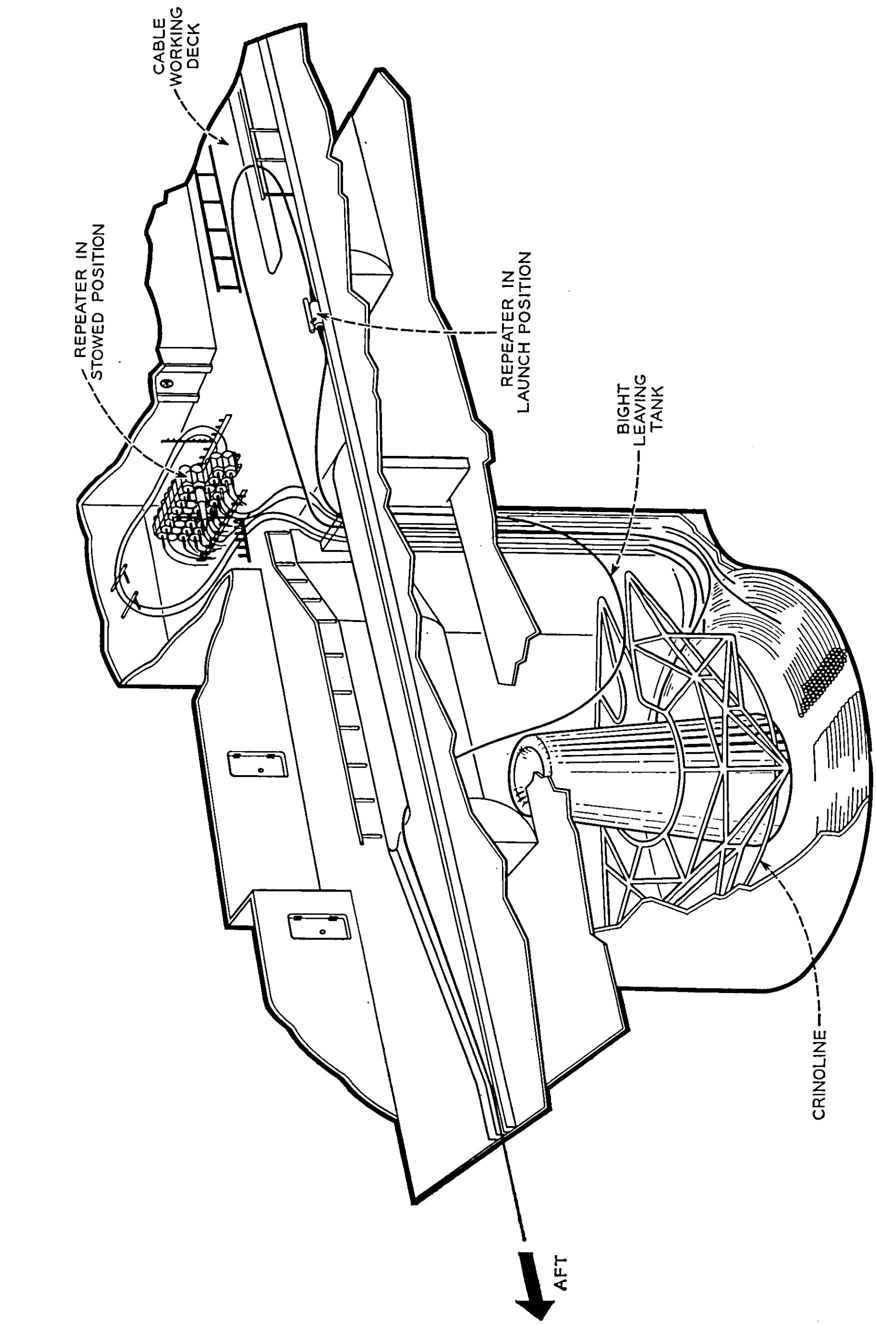


Fig. 2 — Cable and repeater stowage.

54,000 cu. ft. each. The central cones are 15 feet in diameter at the base and taper to 10 feet at the top. The coiling height of 24 feet is the same for all tanks. The total tank capacity is sufficient to contain 2000 nm of $1\frac{1}{4}$-inch diameter deep-sea armorless cable.

The cable tanks differ from previous designs in several respects, all of them pointed toward automating the cable payout. The usual tank opening, consisting of a relatively small round or rectangular central hatch, has been replaced by the long narrow slot shown, extending from the center of the tank forward to the tank wall. This slot permits the cable bights to rise freely from the tanks without danger of twisting or kinking. A nylon net is stretched taut across the entire slot opening a few inches above the deck surface, since it was recognized that an unprotected open slot would be a hazard to personnel. Cable and repeaters move freely under the net during payout. The net also serves to restrain the rising bight of cable as it is pulled out of the tank and into the trough.

The forward wall of the tank has been opened to provide a full-length vertical slot to contain the cables running from the tank to the repeater stowage area. As many as 88 cables are stowed in holders or restrainers mounted in these slots. The slots also contain small elevators or man hoists used for raising and lowering personnel and materials into the tank and as working platforms for personnel placing cables in the cable holders.

The cable holders mounted on the forward wall of the vertical slot are shown in Fig. 3. These are a series of narrow slots deep enough to hold four separate cables and wide enough to accommodate single armored cable (1.88-inch). After the cables are stowed in the holders, the slots are closed with flat strips of rubber which prevent the cable from falling out and control the rate at which the cable leaves the slot. This is particularly important to the cable entering the tank, since if too loosely held it may fall freely and form a kink, and if too heavily restrained it may be bent at too small a radius as it is pulled free. The choice of material as well as its thickness and amount of closure were all critical in a single design to control the several different cables under varying temperature conditions.

The crinoline, seen as the slotted circular pipe framework within the tank in Fig. 2, represents an important development in the automation of bight payout. The purpose of the crinoline is to restrain and control the cable as it moves around the tank during payout at high speeds. The open slot extending from the center ring to the tank wall prevents the cable from running out into the slot during normal payout but permits

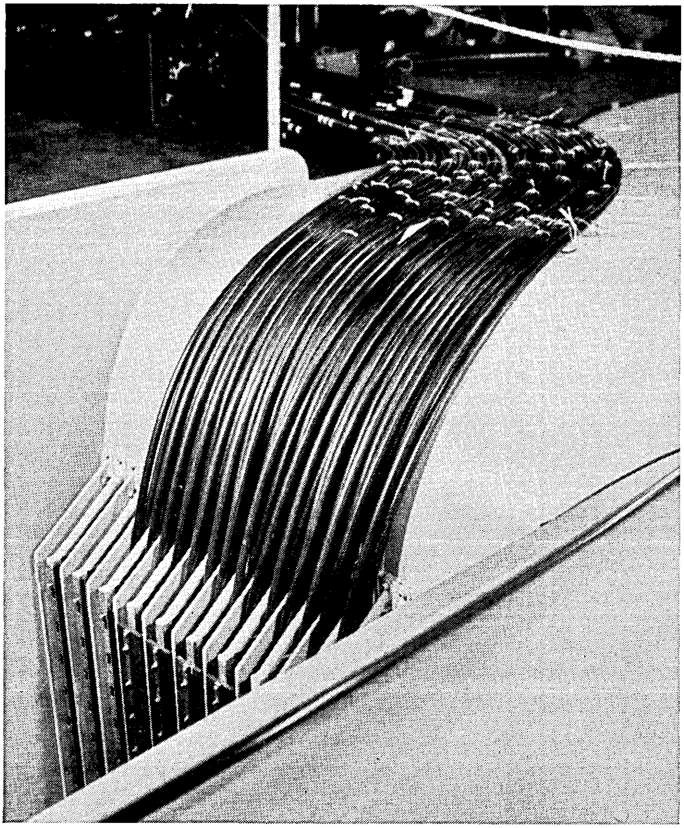

Fig. 3 — Cable holders on forward wall of vertical slot.

the bight to rise freely through the slot to the cable working deck at cable speeds as high as 8 knots. Although the crinoline working height above the top flake is not critical, a height of 6–7 feet gives the best results. Two auxiliary rings, having a diameter (17 feet) equal to the inner ring of the main crinoline, are provided above the main crinoline so that unrestrained cable lengths need not exceed 7–8 feet. The main crinoline and auxiliary rings are positioned at appropriate heights above the top cable flake by means of electrically operated hoists. The hoists are controlled from crinoline control stations at the main deck level. These stations are manned continuously during payout by personnel who can observe the cable action in the tank, adjust the crinoline height as necessary, and report any observed irregularities during the procedure.

V. REPEATER STOWAGE

The repeater stowage areas are located on the port side, forward of the tanks in which the cable is stowed. This position was chosen because it simplified the cable arrangement and the repeater handling process. The repeaters are clamped in individual rack frameworks shown in Fig. 4. These racks, which are demountable, are then bolted one to another and to a deck foundation to form a stack with as many as 44 repeaters arranged 11 wide and 4 high. Since these areas are not air-conditioned, forced-air ventilation for repeater cooling is provided through ducts opening under the repeater stacks. A nearly complete stack of repeaters is shown in Fig. 5.

At the outboard end of the repeater rack foundation a vertical frame is placed to serve as a lateral support for the repeater stack. This also serves as a mounting for power separation filters which terminate the cable and for terminations of transmission and test leads from the transmission testroom. Flexible leads connect the equalizers to measure transmission and to step the equalizer switch to adjust loss during the equalization process.

A station for auxiliary services is located in each of the repeater stowage areas. This provides electrical power, compressed air and fresh water for equipment used in the cable-to-repeater assembly procedure.

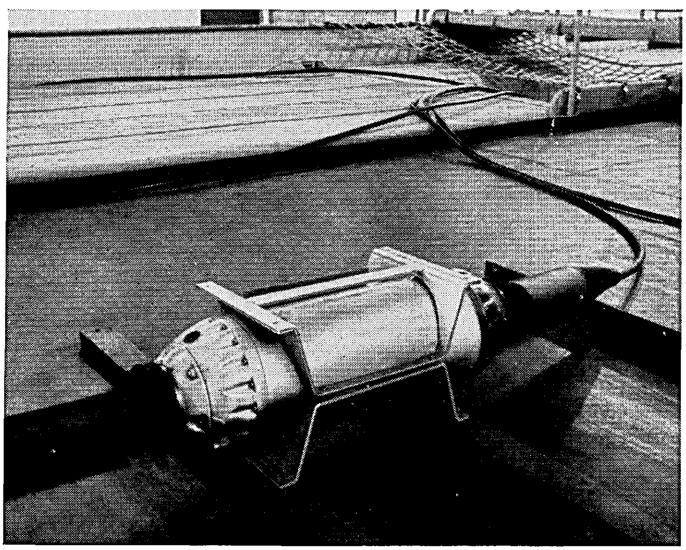

Fig. 4 — Repeater clamped in individual rack framework.

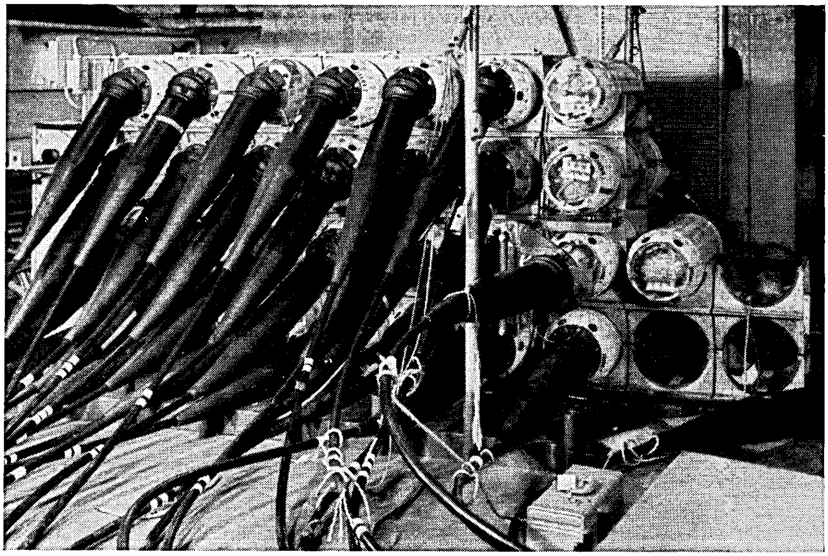

Fig. 5 — Repeater stack.

Repeaters are moved into stowage position and from the stowage area to the launch position by means of an electrically operated hoist. This hoist is driven for both rise and traverse and can reach any of the working areas at the upper deck level.

Because of the large numbers of cables which must be stowed in a repeater bay and because of the need to prevent bending below a minimum radius of 3 feet, the cable runs were carefully worked out, and supports and guides were devised to assure that the proper paths would be followed and that the cable would not be subjected to damaging conditions.

## VI. CABLE WORKING AREA, REPEATER TROUGH AND OVERBOARDING CHUTE

Fig. 6 shows the cable working deck looking aft from forward of tank 2 with a central area called the "highway" raised approximately 6 inches above the deck surface. The cable during payout moves across this highway surface until it enters the repeater trough section shown to the left of the highway in the illustration. This deck has been built without sheer in order that cable lines will lie flat on the deck.

The repeater trough is rectangular in cross-section over most of its length but becomes "vee" shaped a short distance forward of the cable engine and between the cable engine and the stern chute, where it

Fig. 6 — Cable working deck looking aft from forward of cable tank 2.

again becomes rectangular. The transition from rectangle to vee forward of the cable engine is designed to rotate the parachute attached to the repeater through an angle of 25° so that it is outside the gripping surfaces as the repeater moves through the engine. The vee shape continues aft of the engine past the dynamometer (see Fig. 1), where the transition from vee to rectangular shape rotates the parachute back to its original orientation to clear the side of the stern chute.

Since the sensitivity of the dynamometer is a function of the cable angle at the dynamometer bearing surface, it is essential that this angle be constant. This is accomplished by providing a cable hold-down device in the stern chute which restrains the cable and prevents it rising off the trough bottom when the ship pitches. This hold-down is raised automatically before the repeater reaches this position.

When cable moves across broad, flat deck areas and over large-radius faired surfaces at low tension, the stiffness of the cable is sufficient to cause it to move laterally, and surface wear at these surfaces is low although no lubrication is provided. This situation exists on all surfaces over which the cable passes forward of the cable engine.

In the cable trough aft of the cable engine the cable is in contact with the trough bottom at one point and with the dynamometer at another. At these points the cable is under tension (600–7000 lbs.) and is restrained from lateral motion by the trough shape. Tests showed that under these conditions a $\frac{1}{4}$-inch thick plate of mild steel would have a life well over 10,000 nm. To further increase the life and simplify replacement, hardened steel surfaces in the form of bolted inserts are installed at these points, and cooling is provided by water flooding over the wear surfaces.

The cable and repeaters leave the ship through a stern chute instead of over a sheave as is common practice on most cable ships. The chute is advantageous in that the large radius needed ($>$3.5 feet) can be obtained in much less space and at considerably lower cost than by the use of sheaves. Several proposals were considered before the final design, shown in Fig. 7, was reached in which the ship's hull was shaped to form the sides and bottom of the chute. The structural and shaping problems were not difficult, since the intersecting surfaces are all cylindrical sections with no compound curves required. Wear in the chute after 3000 nm has been so small that it has been difficult to detect.

## VII. PARACHUTE DESIGN AND OPERATION

There are two reasons for controlling the rate of descent of the repeater. The first of these has to do with the laying of bottom slack and the second concerns the protection of the repeater from excessive shock on bottoming.

Under steady-state laying conditions the configuration of the cable between the ship and ocean bottom is a straight line; it is desirable to

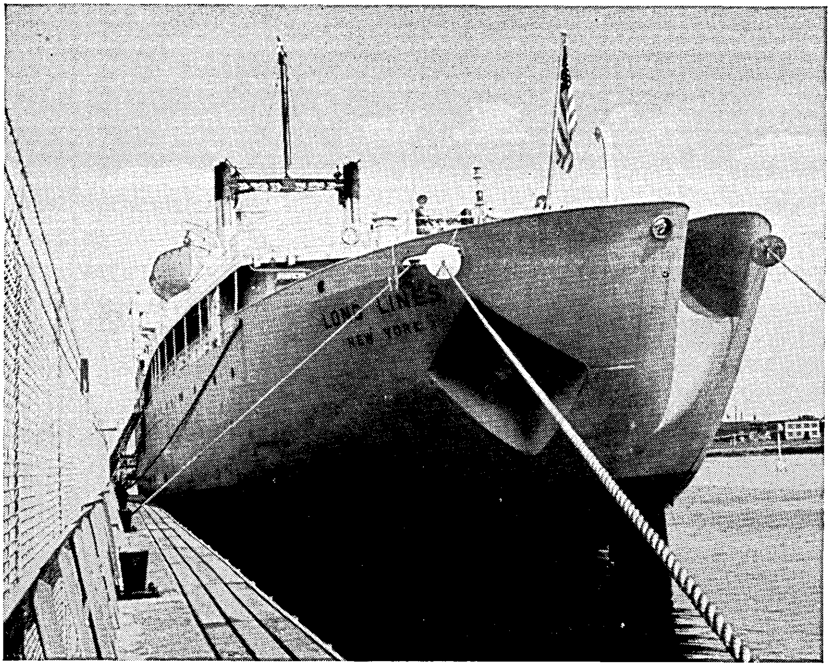


Fig. 7 — View of stern chute of C.S. *Long Lines*.

maintain this configuration to properly control the distribution of slack. The presence of the large mass of the repeater in the suspended cable destroys this condition and adversely affects slack control since the repeater sinking rate is several times that of the cable (8 k vs $\frac{3}{4}$ k).

If the cable were laid in still water the problem would be fairly simple, and substantially perfect match could be obtained between cable and repeater sinking rates. This condition never exists, however, because of the presence of ocean currents of varying and unpredictable velocities which affect the parachute drag. A compromise size was chosen which will not present excessive drag but limits the repeater bottoming speed to a safe magnitude of 2 knots.

The nylon parachute is of simple circular design, seven feet in diameter. The complete parachute mechanism consists of four parts: parachute, container, flotation bag and harness. Fig. 8 shows a repeater ready for launching with a parachute attached.

The parachute is packed in a zipper-closed pocket at the end of a cylindrical air-filled flotation bag. This flotation bag is placed in a fabric

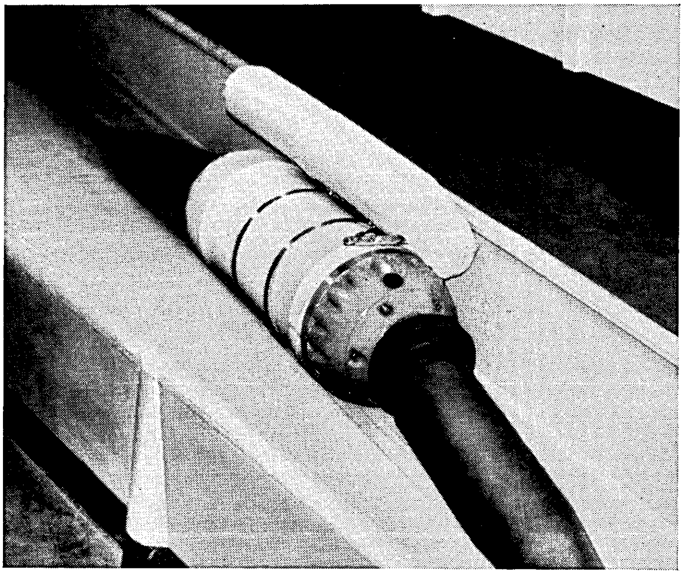

Fig. 8 — Repeater ready for launching with attached parachute.

container which is attached to the harness. The harness serves the dual purpose of fastening the parachute to the repeater and, in connection with the trough shape, positions the parachute properly during payout.

The operation is entirely automatic. When the repeater enters the water the flotation bag pops out and floats to the surface, releasing the parachute to deploy in the water. A corrosive link between the parachute shrouds and the repeater releases the parachute after about 24 hours of exposure to sea water. Several hundred parachutes have been used thus far and there has been no failure in operation.

## VIII. FORE DECK

The fore deck at the boat deck level (shown in Fig. 9) is the location for all repair and recovery and buoy handling operations. It is also expected that a small amount of cable laying, particularly of shore ends, will be done over the bow.

The three large-diameter bow sheaves are housed in the faired surfaces shown in Fig. 10. The three sheaves are mounted coaxially, the outer two being grooved and the center one flat surfaced. Cable, rope and chain are ordinarily carried over the outer sheaves, and heavy, bulky gear such as cable mooring anchors and grapnels is handled over the

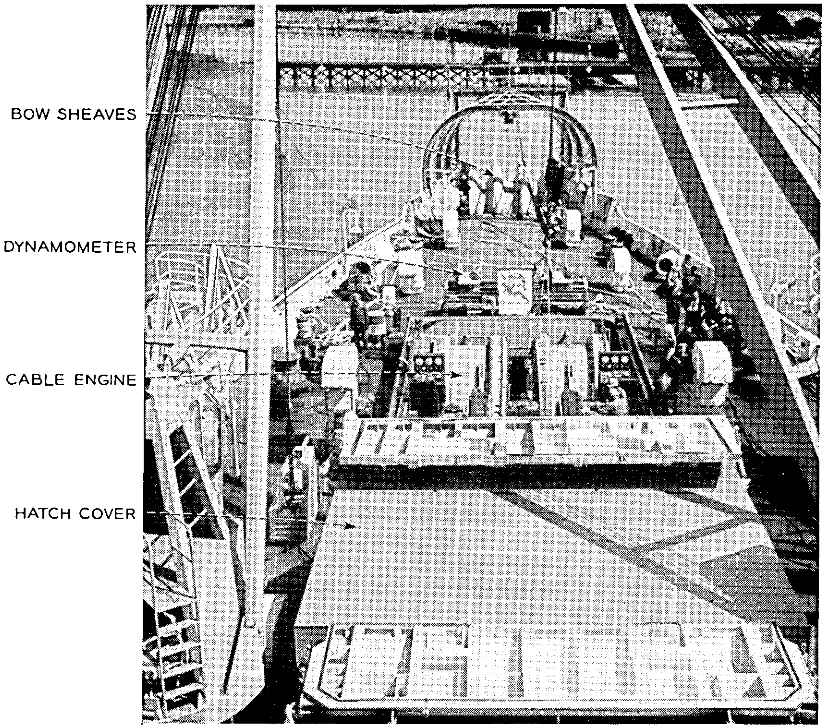


Fig. 9 — Foredeck layout of C.S. *Long Lines*.

center sheave. Two cable handling sheaves are required because during repair or splicing operations two cables are handled simultaneously. The gantry frame shown provides support for an electrically driven hoist used for moving heavy grapnels and mooring anchors over the sheaves.

A ship control station is located just aft of the bow sheaves, and the ship's operation can be handled directly from this position. Cable payout information is also repeated at the foredeck control. This includes cable tension and amount of cable picked up or payed out through the bow engines.

There are two large rectangular hatches located well forward on this deck. The first of these provides access to the two drum-type cable engines located below this hatch at the upper deck level. The after hatch opening gives access to the upper deck, and cable, rope and chain are carried through this hatch to the upper deck.

The covers for these cable working hatches are unique on a cable ship. The after cover telescopes under the forward cover, and the covers can

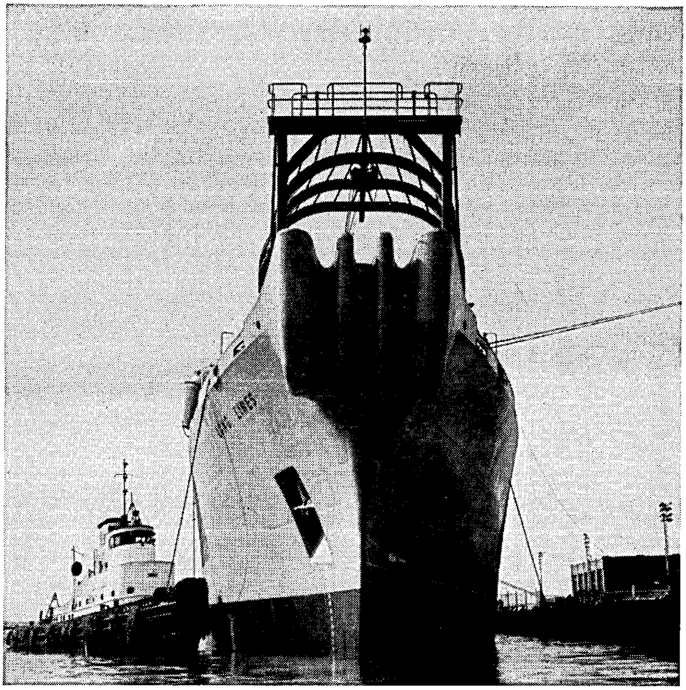

Fig. 10 — Bow sheaves of C.S. *Long Lines*.

be moved individually on longitudinal rails to open either or both of the hatches. By this means and by opening the ends of the covers, almost any degree of protection can be obtained for personnel and machinery during foul weather operations.

## IX. CHESTER LABORATORY DEVELOPMENT WORK

The use of full-scale models as exemplified in the operation of "C.S. Fantastic" was an essential part of the successful development of the cable handling facilities. While scale models were useful for purposes of visualization, they were of little practical value in predicting operating characteristics, since it was impossible to scale the cable dynamically.

All of the details for handling cable and repeaters were built in prototype and subjected to exhaustive tests. Since ship's motion (pitch, roll and yaw) could not be simulated, all of the payout processes were required to operate successfully at speeds well in excess of the design objective of 8 knots to allow for possible adverse effects from this motion.

Cable payout, repeater launching, parachute positioning, crinoline operation and transfer of payout from one tank to another were accomplished successfully at speeds as high as 11.5 knots, the maximum capability of the Chester facility.

Measurements were also made of the shocks to which the repeater was subjected during acceleration from standstill to payout speeds in the launching operation. The validity of these tests was later confirmed by similar measurements aboard ship; even at payout speeds of 9.5 knots, accelerations do not exceed 19 g, well below design requirements.

It is interesting to note that many of the innovations developed at Chester have been used in cable ships other than C.S. *Long Lines.*

## X. CABLE LOADING AND REPEATER JOINING

The arrangements and details for loading, although somewhat less exacting than those required for laying, are of considerable importance. It is here that the possibility of confusion and error is greatest, and extreme care must be taken to prevent locked turns and crosses which could make it impossible to get the cable out without cutting and splicing.

Insofar as possible, the cable is loaded in a single continuous length and the mechanical continuity is never broken. This is possible only to a limited extent, since two load lines are normally in operation simultaneously. It is possible, however, to load each tank with a single mechanically continuous length, and this practice is followed in general on C.S. *Long Lines.*

The individual cable sections are taken in pans to the loading dock area and placed as required at the end of the loading line. The cable is then pulled aboard ship through the load line by a linear transporter located at the forward end of the cable tank slot and fed down into the tank for coiling. On the straight runs and around curves in a vertical plane the cable moves through open troughs or over faired surfaces, but for turns in a horizontal plane, sheaves having a minimum diameter of 6 feet are used.

Coiling of cable is in a clockwise direction, beginning at the outer tank wall and working into the central cone; then it continues working from the cone outward. In the large tanks each flake contains approximately 3 nm of cable and there are about 6 flakes per section.

This is the first time that out-in, in-out coiling of cable has been successfully used. With conventional armored cable the practice has been to coil from the tank wall in to the cone and then lay out to the tank wall and resume coiling again toward the cone. Coiling from the cone outward was not successful with the armored cable because in the reverse operation of paying out there was a possibility of turns sticking, resulting in lifting an adjacent turn with high probability of forming a kink. With the out-in, in-out coiling, load factors approximately 92 per cent of theoretical (57.5 cu. ft./nm) for perfect pack have been achieved.

When the last end of a cable section is reached, it is joined to the first end of the next succeeding section by means of a coupling connector usually referred to as a "dummy repeater." The dummy repeater shown in Fig. 11 consists of two coupling covers connected together by a tie bar; the combination is equal in length to a repeater or equalizer. This dummy serves as a convenient device for positioning the cable section ends in the repeater stack while the cables to and from the tank are being

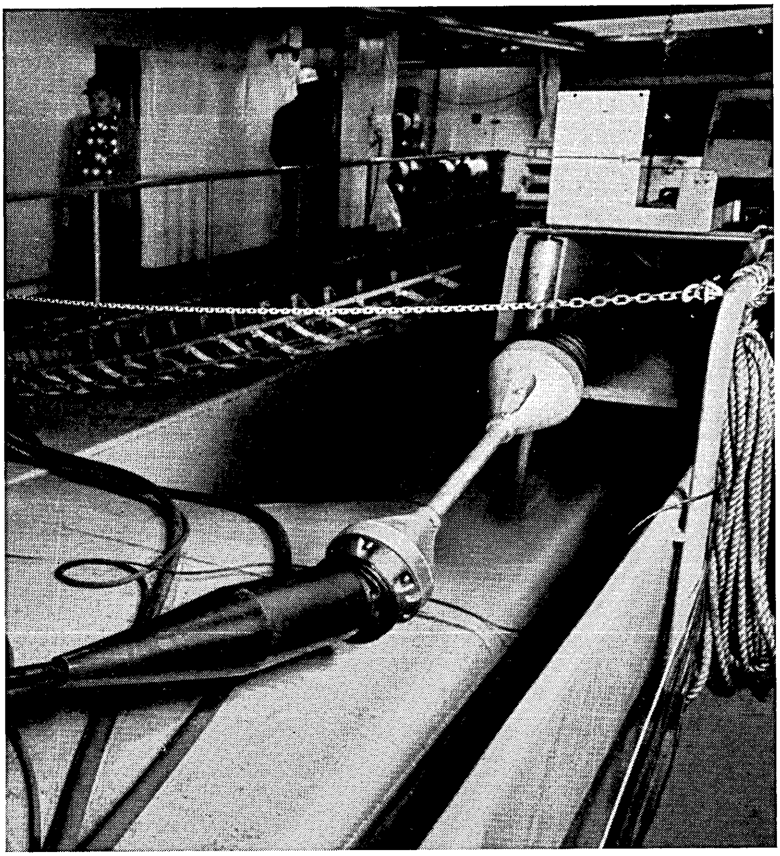

Fig. 11 — Coupling connector ("dummy repeater").

dressed into position and fastened down. In addition to furnishing a means of mechanical connection to the cable section, the coupling covers protect the coupling pigtail and provide mountings for electrical connection to the center conductor for electrical test during loading. Before the couplings are disconnected from the dummy for joining to a repeater, the cable ends are joined together by a rope tie. This tie is not removed until the process of joining the cables to the repeaters is finished and the lead position and continuity have been checked.

Coiling in the tanks is manual and crews of about 25 men per tank are used to perform this work. Loading speeds as high as 4 knots per line can be achieved, and, with allowance for down time to bring the cables from the tank to the repeater stowage area and dress them into position, an average speed of 2.5 knots per line is possible.

As soon as the first cable couplings have been placed in position at the repeater rack, a repeater is moved into place and the work of joining cable to repeaters is started. The space for the electrical and mechanical connection of cable to repeater is restricted, and the equipment designs and processes had to be carefully coordinated to work in the space available.

The joining process requires exact positioning of the coupling with respect to the repeater, preparation of pigtail ends, brazing of center conductor, overmold of conductor joint, X-ray examination of the mold, assembly of ground leads, and bolting of coupling to repeater. Mounting jigs like that shown in Fig. 12 hold the coupling in alignment with the repeater body during the joining procedure, and the jig serves in turn as a mounting for the brazer, molding machine and X-ray unit and as a bolting guide for final assembly. The illustration shows the molding machine in position.

## XI. CABLE AND SYSTEM TESTS

Electrical tests of the cable during loading are rather rudimentary but will indicate any serious cable faults as soon as possible. The tests consist of dc resistance measurements made before, during and after loading; insulation resistance measurements made after loading; and pulse echo tests made after loading.

The system tests are much more comprehensive and are a measure of system transmission performance. The transmission characteristic of each block is measured and the crystal peak gain of each repeater is measured. In addition, each of the equalizers in the system is checked at every one of the 32 positions of the stepping switch.

Since the cable loss — and hence the system characteristic — varies

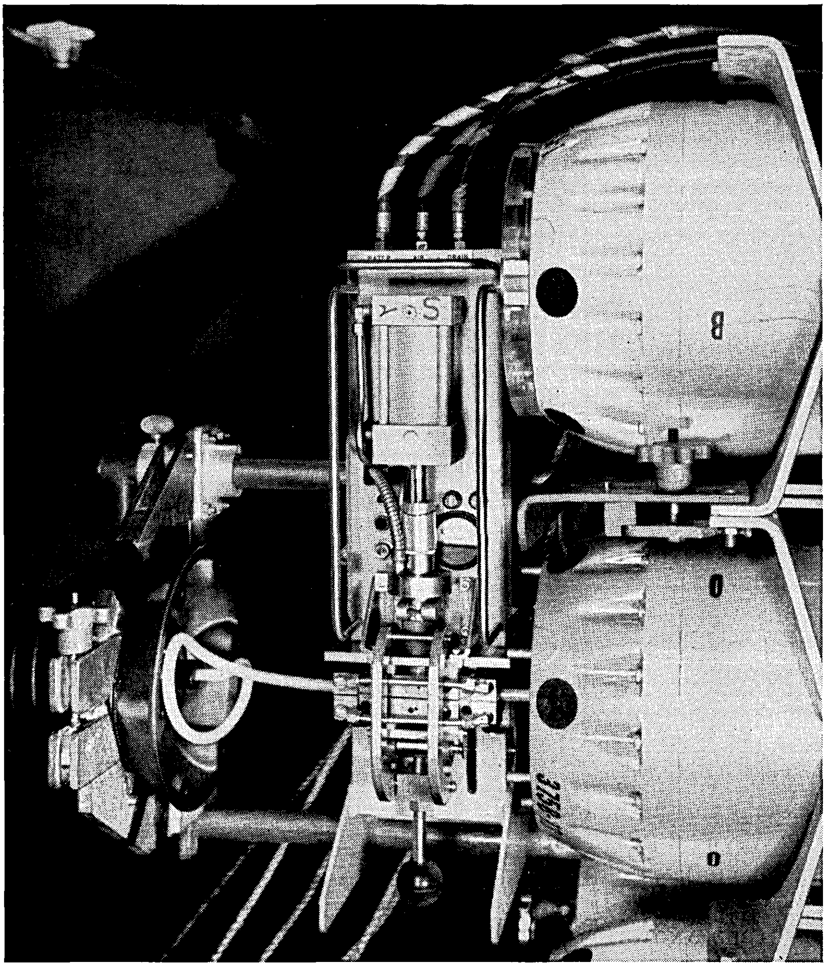

Fig. 12 — Mounting jig with molding machine in position.

with temperature, it is necessary to know the temperature of the cable at the time the transmission measurements are made. Temperature measurements are made at 15 positions in each of the repeater tanks. Three thermocouples are located in the wall of each central cone, and 12 thermocouples are placed in designated positions within the cable coils of each tank. The measurement of temperature is semiautomatic; to determine the temperature at any of the 45 positions, it is necessary only to press the appropriate button and read out the temperature directly on the meter scale.

At the conclusion of these tests, power is turned down and no further measurements are made until the initial splice is made and laying is ready to start.

## XII. SPACE LOCATIONS AND ARRANGEMENTS

Efforts were made to assign spaces for cable operations for the greatest convenience and utility. Consideration was given not only to immediate requirements for equipment areas, working space and servicing needs but also to probable future requirements.

Floor plans were worked out for all of the areas directly or indirectly connected with the cable laying operation. Lighting, air-conditioning and ventilation requirements were set for all these areas.

Special attention was given to the layouts in the drum room, transmission testroom, jointing room and taut wire room, since these are the active operating areas during cable laying, and convenience and efficiency are especially important.

In the transmission testroom all equipment is furnished in duplicate so that the failure of any unit does not interrupt system operation and test. Cable payout information which is of assistance to the transmission eingineers is repeated in the test room. This information consists of cable payout speed, mileage and miles to the next repeater. Cable temperature measuring equipment is also located in this room.

Cable engine control during laying is from the cable operations center, known as the "drum room," and the layout centers around the cable engine control console. All of the payout control equipment is located here. This includes cable engine controls (both bow and stern), mileage counters of cable and taut wire, slack computers, depth sounders, precision depth recorder and ship's speed indicator. Slack computers and cable and taut wire mileage counters are furnished in duplicate.

Cable jointing, whenever possible, is carried on in the jointing room. The location on the upper deck opposite cable tank 1 was chosen, since it is the space most readily accessible for cable ends brought over the bow and through the cable hatch. The layout permits splicing operations on all types of cable without exceeding the minimum bending radius requirements.

The taut wire room houses not only the taut wire machine itself but provides for stowage of full and empty taut wire reels. Racks were designed and layout arranged so that the bulky reels, containing 140 nm of wire weighing approximately 2000 pounds, could be safely handled under rough sea conditions.

## XIII. ELECTRICAL SERVICES AND COMMUNICATIONS

The factors of safety, reliability, stability and convenience determined the choice of electrical service to the working areas. Alternate power sources supply the regular and alternate test and power equipment in the transmission testroom for maximum reliability, and both steady-state and transient voltage and frequency requirements were set for the prime power sources.

Fusing and switching of all of the equipment was specified so that these were compatible with the services furnished. In areas such as the transmission testroom and electronics maintenance room where portable equipment may be used or equipment serviced, the convenience outlets are fed through isolation transformers to provide single-phase grounded service in place of the usual shipboard single-phase balanced-to-ground supply.

Coaxial circuits are installed from the switchboard bay in the transmission testroom to all of the cable working areas and, by appropriate patching at the switchboard, test and communication circuits can be set up between any of these locations.

A cable operations communication circuit connects all of the cable working areas. Operating stations consisting of microphone and loudspeaker are located at strategic locations where there is active cable movement or cable control, and announcements over this circuit are repeated at all locations.

For the purpose of safety to personnel and to cable, "safety alarm" stations are also provided at strategic locations. These stations consist of distinctively colored button switches connected to all of the cable engines and to an audible alarm. The operation of any of these switches immediately stops any operating cable engine and cable payout or pickup comes to an immediate halt. Needless to say, this circuit is used only in extreme emergencies, to stop operations when personnel are endangered or an equipment failure requires immediate or drastic action.

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# Cable Payout System

By R. W. GRETTER

(Manuscript received March 24, 1964)

*This paper describes the development of cable machinery and control equipment capable of laying modern submarine cable systems. The necessity for reliable continuous operation is established, and the problems involved in gripping armorless cable are pointed out. The concept of a linear cable engine is introduced, and the evolution of a track design is followed through several model stages.*

*The various test programs employed to establish feasibility, prove-in component reliability, and check performance of the final machine are discussed. A control philosophy is presented and the development of a control system is described. Final design, construction, and testing of the cable machinery and its control equipment are covered briefly.*

## I. INTRODUCTION

In essence, a cable payout system consists of stowage for the cable, machinery for exerting a braking action on the cable to regulate the payout rate and instrumentation for determining the correct payout rate. In the first attempt to lay a telegraph cable across the English Channel, the stowage and braking functions of a payout system were provided by a reel mounted on the after deck of a tug and fitted with a brake. For cable systems more than a very few miles in length, the size of the reel soon became unreasonable and less obvious approaches had to be taken.

Stowage of cable in cylindrical holds or tanks was employed early in the development of the ocean cable laying art, and seems to have been a natural evolution from the common nautical practice of tiering chain in chain lockers or of coiling whale line in tubs. Similarly, the drum-type cable engines employed for many years as braking devices in handling telegraph cables appear to have been an early adaptation of the anchor windlass.

While a combination of tank stowage with drum machinery was adequate for telegraph systems, it leads to problems when systems with rigid repeaters are laid, since the ship must be stopped and turns taken off the drum while each rigid repeater is passed overboard. Analytical work in the field of cable mechanics has shown that adequate control of slack requires continuity of operation. It was therefore necessary to develop continuous methods of handling rigid repeaters. Drum-type cable engines can be fitted with auxiliary devices for handling rigid repeaters continuously at slow or moderate speeds, and cable engines consisting of multiple V-sheaves have been designed for handling rigid repeaters at slow speeds by means of bypass ropes. For continuous handling of rigid repeaters at full cable laying speeds, however, a linear or straight line cable engine is essential.

## II. LINEAR CABLE ENGINE DESIGN REQUIREMENTS

Modern submarine cable systems, in addition to having large rigid repeaters, differ from previous systems in another aspect which is important from the cable machinery viewpoint, namely that the cable is of the so-called armorless type with the strength member in the center.[1] The strength member is composed of very high-strength steel, and is surrounded by the delicate transmission structure consisting of polyethylene and thin sheet copper.

The cable tension which results from the weight of the length of cable suspended between a ship and the ocean bottom must be transferred to the ship by frictional shear forces exerted on the cable surface. In the case of drum engines the normal forces on the surface required for the development of the frictional forces result from the wrapping of the cable around the drum. In the linear cable engine, the curved surface is absent and the cable tension does not result in any normal force on the cable's surface. The cable must therefore be squeezed between the tracks of the cable engine.

The cable engine design requirements, from the viewpoint of the cable system, can be summarized as follows: the cable engine must handle cable and repeaters continuously at a steady speed, in a straight line, gripping the cable so as to transfer the tension to the ship without damaging the transmission structure and passing repeaters without excessive shock.

## III. DESIGN APPROACH

The development approach adopted for the linear cable engine was strongly influenced by two very firmly held principles. First, the cable engine and associated equipment was to be designed to handle a mechanically optimum cable and repeater system; in other words, the cable system designers would not be asked to compromise their designs in order to ease machinery problems. Secondly, the entire design would be based on achieving the highest possible reliability so that there would be a very high probability of completing a lay (say 2000 nm) in one continuous operation without any interruption due to cable engine failure. Because of the first of these requirements, it was natural to design the cable engine from the inside out; that is, to commence by considering the problem of gripping a straight cable in such a way as to transfer the highest possible cable tension to the ship without damage to the transmission structure. The moving track which accomplished the gripping was then to be designed to accommodate repeaters. A system of sprockets and shafting to support and drive the track would be added next, and addition of a framework and a drive and control system would complete the design. At each stage in its evolution the design was evaluated for reliability, and an extensive testing program was planned to prove-in each element.

### 3.1 *Cable Gripping*

The squeezing forces required to develop cable tension must be applied in a symmetrical manner to avoid any tendency to separate the dielectric from the center conductor. Analysis, described in Appendix A, showed that the cable would have to be gripped along at least four lines, equally spaced around its circumference, if regions of negative pressure on the center conductor interface were to be avoided. The double V-block design which is shown in Fig. 1 gave the desired cable gripping configuration.

Because of the nature of the resulting pressure distribution in the dielectric, the frictional shear forces which can be transmitted across the various unbonded interfaces within the cable are directly proportional to the radii of the interfaces. This means that the stretching of the center conductor which occurs under high tension cannot be accommodated by slip of the entire cable, because slip will occur between the center conductor and the dielectric before the outer jacket slips in the grooved blocks of the cable engine. For this reason, a linear cable engine which is to handle cable without interface bonds must have a so-called "shear-limiting" feature which limits the shear force applied to a unit length of the cable. The allowable value of shear force per unit length depends in turn on the squeeze applied to the cable.

Experimental work on cable samples showed that when the cable was gripped between the double V-blocks no permanent distortion of the

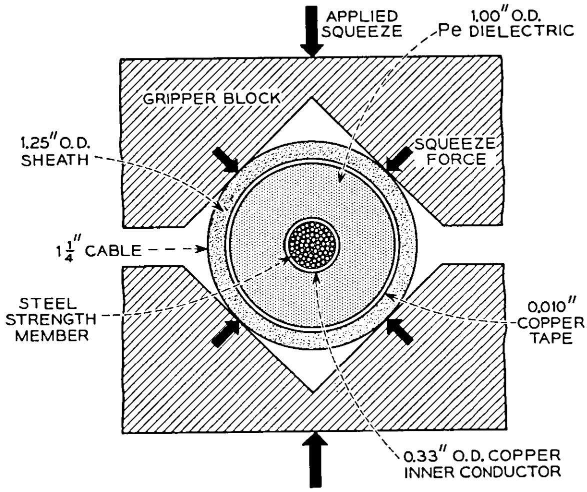



Fig. 1 — Double V-block cable gripping.

cross section would occur if the squeeze force did not exceed the value which gave a contact force of 500 pounds per inch along each contact. A working value of one-half the maximum or 250 pounds was used for design purposes. With this value of squeeze force and a coefficient of friction between copper and polyethylene of approximately 0.16, a tension decay rate of 40 pounds per inch of cable could be obtained without causing slip on the center conductor interface, which had a circumference of approximately one inch. Since the nominal tensile strength of the cable was to be approximately 16,000 pounds, this meant that the cable would have to be gripped over a length of 400 inches, or approximately 33 feet, if it was to be held up to breaking tensions without any internal slip. Thus the length of the gripping region of the cable engine was set by cable characteristics.

### 3.2 *Quarter-Scale Model*

The development of the linear cable engine involved several phases. In the first phase a one-quarter scale model was built to test the basic concept. At this stage in the development the cable gripping problem was not completely understood, and there was considerable optimism regarding the development of a cable having bonds on the various interfaces to transmit shear stresses. It was also thought that the proposed tracks would have to be forced apart by some sort of cam to allow the repeater to pass through. For these reasons the initial quarter-scale model did not include the shear limiting feature, but was fitted with a pair of traveling cams which were clutched into the main drive system so as to spread the tracks apart, leaving a pocket to accommodate the repeater. The tracks which gripped the cable were pressed together by rollers mounted on saddles, the saddles in turn being mounted on compliant air bags. The quarter-scale model, shown in Fig. 2, was operated for several months in carrying out tests of various stowage arrangements and overboarding devices. Tests with this machine indicated that model repeaters would pass through with no difficulty and that the cam system was not necessary.

### 3.3 *Full-Scale Track Tests*

During the evaluation of the quarter-scale engine it was decided that shear limiting would be provided in the final engine, since it was certain that reliable chemically bonded interfaces could not be produced in time.

Before proceeding with the design of a mchine incorporating shear limiting, the shear limiting concept was checked out on a bench-type test rig which gripped a length of cable several feet long between blocks mounted on rollers between squeezing units. Axial motion in the direction of applied cable tension was controlled by the shear limiting units. Various spring configurations were tried and an ordinary coil spring

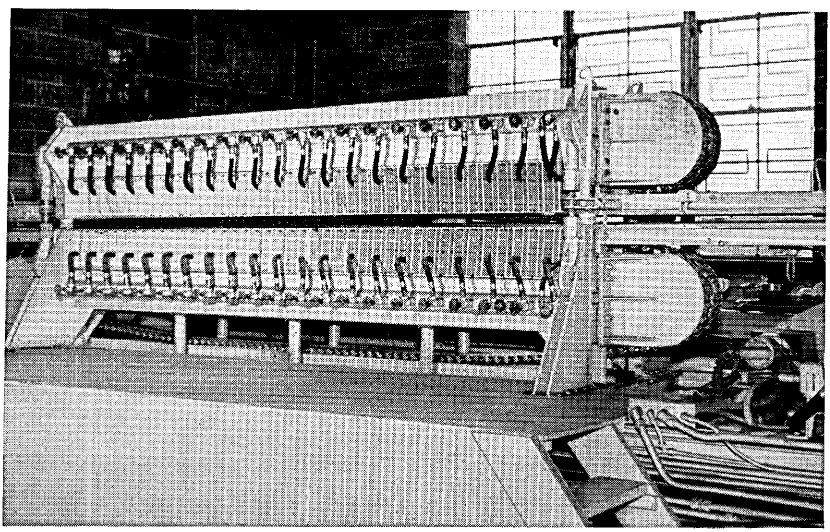


Fig. 2 — Quarter-scale model.

mounted with a preload in a cartridge was found to be the most satisfactory. The shear limiters function as shown schematically in Fig. 3. The observed deflection is essentially parabolic, as predicted by theory.

In order to allow for shear limiting motion, it was necessary to leave gaps between the individual members of the track. The track also had to articulate for envelopment of the repeater. Because the track moves with the cable, it was necessary for the track to move at high speed with respect to the elements which applied the squeezing force. After an investigation of possible sliding contacts, it was decided that rollers on the track elements would be necessary to handle the large squeezing forces and high speeds.

A track test rig was designed to check out the track as conceived at that stage of its development. Fig. 4 shows this machine, which was full size as regards width of track, but was only a few feet in gripping length. In addition, the test rig involved only one track, the opposing track being simulated by a series of simple roller carriages traveling on a rigid base. The moving track was backed up by an articulated belt, and squeeze was applied by air springs as shown in Fig. 5. This test rig was run for many hundreds of miles and at intervals a longitudinally split half repeater was passed through.

### 3.4 *Design and Construction Contractor*

At this point Western Gear Corporation was selected to do final design and to manufacture the linear cable engine. Its representatives joined with engineers of Bell Laboratories and Bergen Research Engineering

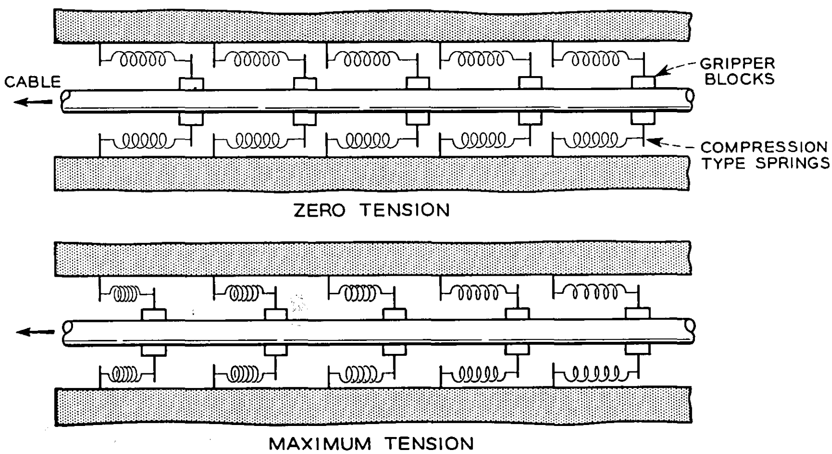



Fig. 3 — Shear limiting.

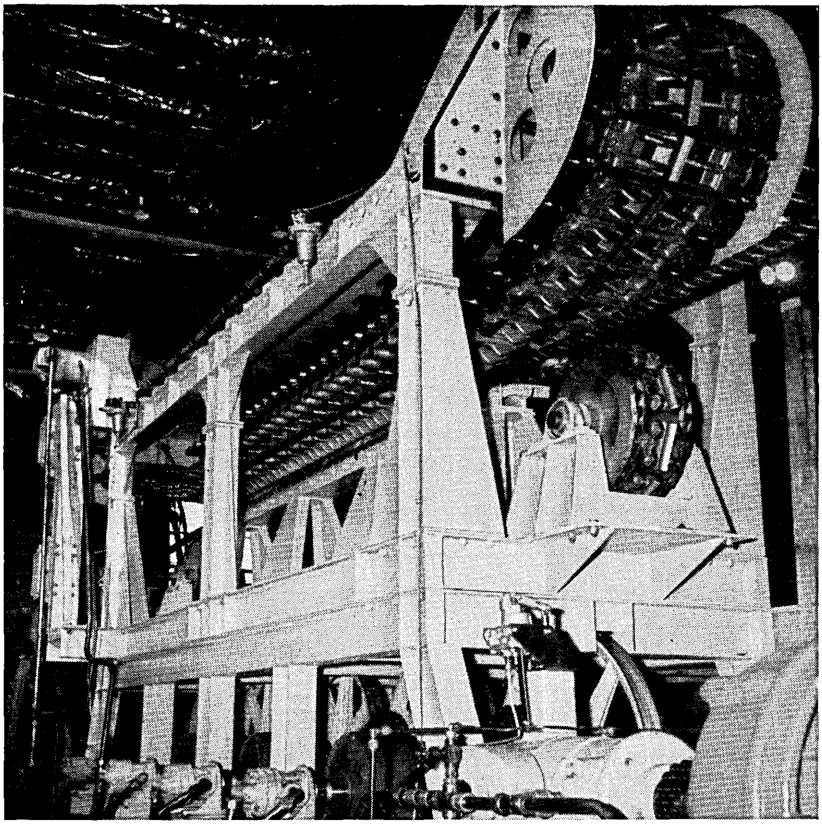


Fig. 4 — Track test apparatus.

Corporation in planning and evaluation of the test program for the track test rig. After observing the tests and studying the test results, the three groups concurred in the opinion that the rubber rollers and their bearings would be the limiting factors in designing a squeeze-type engine to have sufficient reliability. It was also concluded that the air bags which provided the compliant backing for the belts were causing an intolerable pressure increase when repeaters passed through the machine and that the solution of this problem by increasing the number of air bags in each stack would lead to a stability problem.

### 3.5 *Linear Cable Engine Design Studies*

Upon completion of the test program and associated studies, preliminary design work on a prototype linear cable engine was started. Initially,

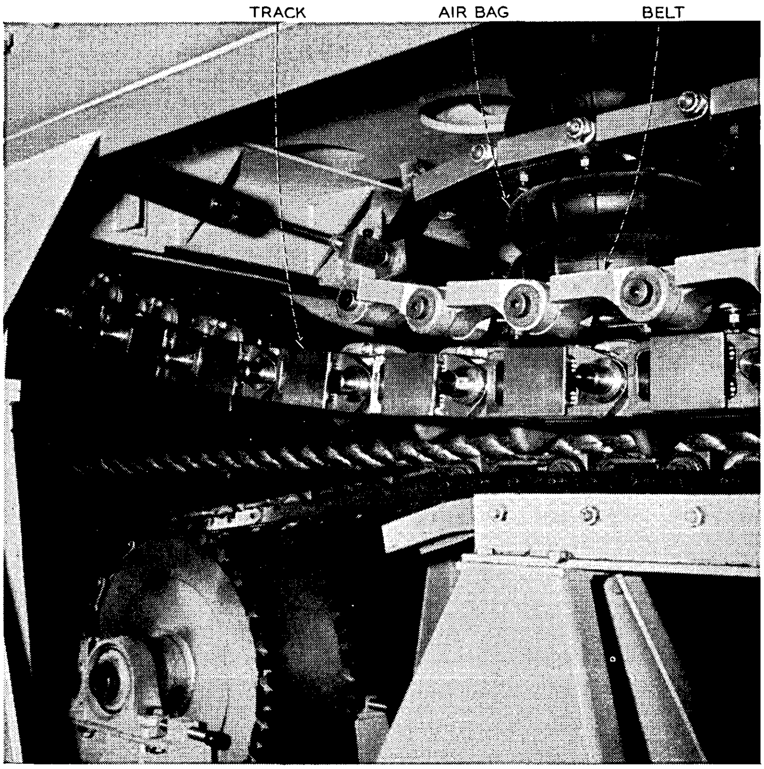



Fig. 5 — Track test apparatus; detail showing articulated belt and air springs.

effort was directed along two parallel lines: first, attempts to resolve the problems inherent in the squeeze-type linear cable engine and second, paper and model studies of alternative linear cable engine concepts proposed by Bell Laboratories.*

A nitrogen-accumulator-backed oil-hydraulic squeeze system, proposed as a substitute for the air bags, was studied. These studies showed that a combination of hydraulic cylinders with linkages could be designed to maintain the squeeze pressure essentially constant as the repeater entered the machine.

The question of transients incidental to repeater passage at high speeds was resolved by means of a test rig based on a large lathe. A cam mounted on the face plate subjected a cylinder and linkage assembly to the displacements and velocities incidental to the passage of a repeater

* These involved other gripping methods which would avoid the problem of applying high squeezing forces to a moving track.

at speeds up to 10 knots. After many hours of operation of this test rig it was concluded that the hydraulic cylinders with their linkages and nitrogen accumulators would be a satisfactory substitute for the air bags used in the previous models.

Discussion of the rubber roller problem with many rubber manufacturers led to the conclusion that the loads and speeds involved in the proposed linear cable engine would be marginal for available rubber compounds. Because our particular operating conditions and duty cycle were unique, a test program was required to establish reliability for the rubber rollers. The rubber compounds which appeared to be most suitable were made up in sample rollers, and these were run for several thousands of hours on rotating drums. The rollers were pressed against the drums intermittently to simulate the duty cycle of rollers passing through the squeeze zone on the linear cable engine. On the basis of the results of these tests, it was concluded that the rollers could be depended upon to function reliably for at least 2000 nm and possibly for several times this figure.

Initial design studies of track configurations capable of passing around sprockets of reasonable size and enveloping repeaters indicated that approximately 3000 antifriction bearings would be required to support the necessary rubber rollers. Because of the space restrictions and the load and speed requirements, the $B_{10}$ life* of the bearings could not be made high enough to give an acceptably large probability of no bearing failures in 2000 miles of operation. Thus it was necessary to assure ourselves that a bearing which had failed by the usual bearing industry criterion would not lead to a catastrophic failure.

The Timken Roller Bearing Company had recommended a bearing identical with that used in the front wheels of compact automobiles for this application. Its engineers felt that because of the heat treatment given to the bearing races an initial fatigue failure would not propagate rapidly and thus lead to an early catastrophic failure. In order to test this hypothesis a roller bearing test program was planned. The Timken Company produced initial fatigue failues in a group of 20 bearings in their laboratory. Prototype rubber rollers were mounted on these bearings and run at prototype loads, speeds, and duty cycles for thousands of hours. The rollers were then disassembled and the bearings photographed. The photographs were compared with photographs taken at the time of initial fatigue failure. In most cases there was no discernible increase in the spalled area of the initial failure. In one or two cases the area did increase noticeably, but there was no indication that catastrophic failure would

* Life exceeded by 90 per cent of a population of bearings.

have occurred within many thousands of hours. Details of the failure propagation study are given in Appendix B.

### 3.6 *Track Side Chains*

The proposed track was to consist of a series of roller carriages mounted on roller chains which were in turn carried on sprockets. From exploratory work it was concluded that it was not feasible to lubricate modern roller chains for high-speed operation in a salt water atmosphere without exposing the cable to contamination by the lubricating medium. A special precision pintle-type chain, having oil-impregnated sintered-metal bearings, was therefore developed. Since there are no rotating rollers in this type of chain and each link merely oscillates through a small angle with respect to its neighbor, it was possible to seal in the lubricating medium by means of rubber shear seals which could tolerate the small angle of rotation. Because of the lack of rollers, there is of course a sliding motion of the links with respect to the sprocket. It was possible to provide lubrication for this motion by means of a very viscous type of grease which would not be thrown off the sprocket onto the cable. A test section of the new type of chain was manufactured and was found to operate satisfactorily under the prototype loads and speeds.

### 3.7 *Roller Carriage Design*

The roller carriages were to be connected to the side, or tension, chains by means of shear limiters which would allow essentially free axial motion of the roller carriage with respect to the chain under a certain axial load, thus limiting the shear force per unit length applied to the cable. In addition, it was necessary to design the roller carriages so that the squeezing forces applied to the cable through the rollers were not transmitted to the chains, since this would put large frictional side loads on the shear limiters. It was also desirable that the two chains be connected transversely by a rigid member. The roller carriage design which met all of these requirements was, of course, somewhat complicated. Fig. 6 is a photograph of a wooden model of the design. The model included three links of the pintle chain on each end of the roller carriage. Fig. 7 shows the relative orientations of the roller carriages, the side chains, and the articulated metal belts which apply the squeezing forces to the roller sides of the carriages.

### 3.8 *Final Design of Linear Cable Engine*

Upon completion of the development testing which proved-in the bearings, rollers, shear limiter, pintle chain, and the hydraulic squeezing

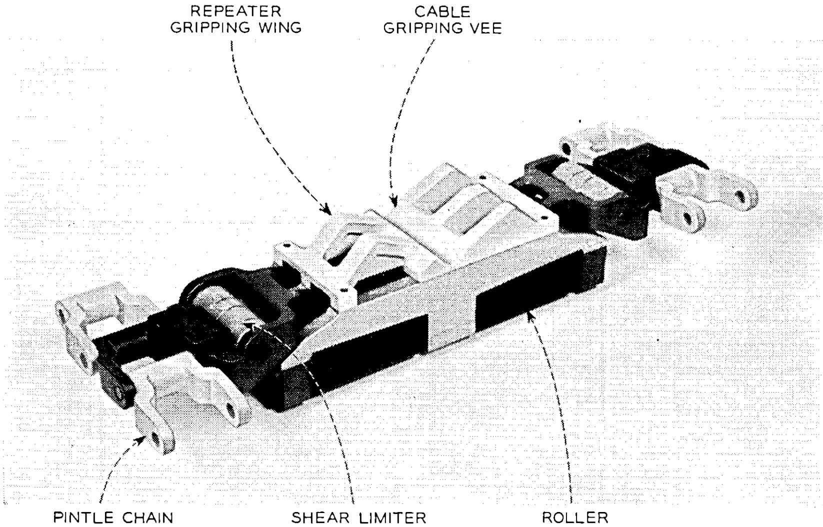



Fig. 6 — Model of roller carriage.

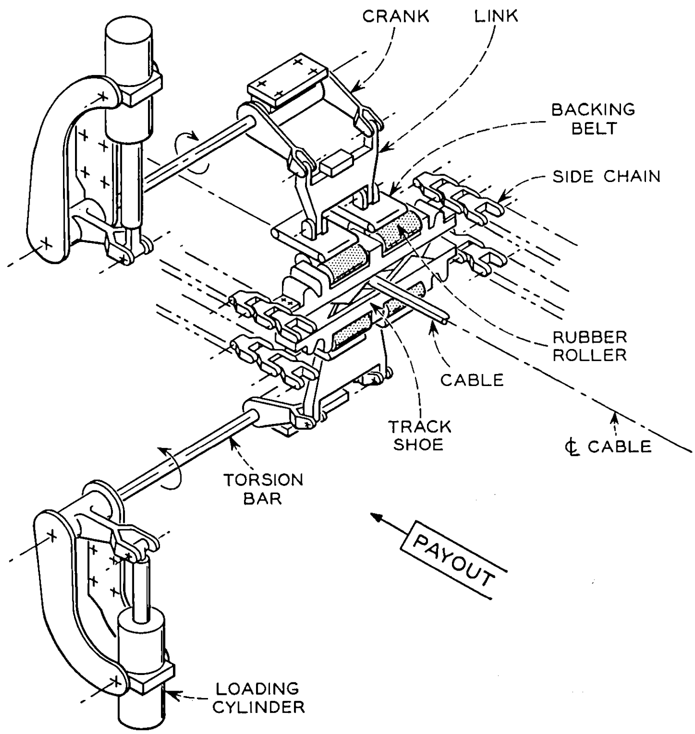
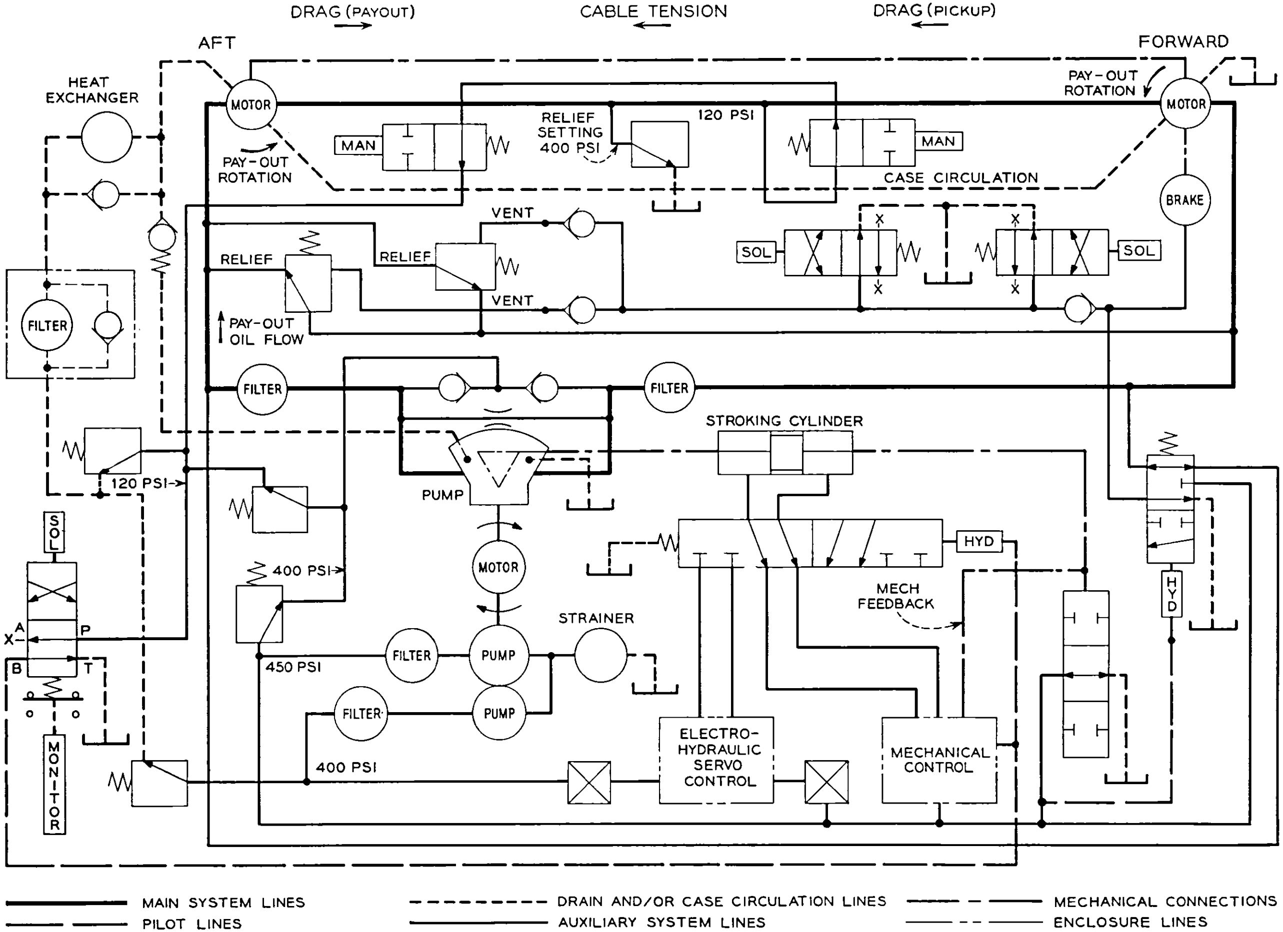



Fig. 7 — Roller carriage assembly detail.


DRAG (PAYOUT)
CABLE TENSION
DRAG (PICKUP)
AFT
FORWARD
HEAT EXCHANGER
MOTOR
PAY-OUT ROTATION
MAN
RELIEF SETTING 400 PSI
120 PSI
CASE CIRCULATION
BRAKE
VENT
RELIEF
SOL
FILTER
PAY-OUT OIL FLOW
STROKING CYLINDER
PUMP
HYD
120 PSI
400 PSI
450 PSI
STRAINER
MECH FEEDBACK
A
P
B
T
X
MONITOR
ELECTRO-HYDRAULIC SERVO CONTROL
MECHANICAL CONTROL
MAIN SYSTEM LINES
PILOT LINES
DRAIN AND/OR CASE CIRCULATION LINES
AUXILIARY SYSTEM LINES
MECHANICAL CONNECTIONS
ENCLOSURE LINES

units, the entire design was reviewed for comparison with some of the other types of linear cable engines under consideration. Although it was felt that at least one of the other approaches was probably capable of yielding a much lighter, smaller and cheaper machine, the schedule did not allow for the additional study and testing work needed to prove-in the alternate design. The development schedule, in conjunction with the encouraging results of the endurance tests on the bearings and rollers, therefore led to a decision to drop further study of alternative designs and to proceed with the final design of a squeeze-type linear cable engine.

Functionally, the linear cable engine was to consist of two major subsystems, the drive system and the squeeze system. The drive system included the track which grips the cable and moves with it, the sprockets, sprocket shafts, gear boxes, and a hydraulic system for driving the track. The squeeze system was comprised of the articulated belts between which the tracks are squeezed, the hydraulic units for applying the squeeze force to the track and the associated piping, accumulators, and hydraulic pumps for supplying oil pressure and nitrogen back-up pressure to the squeezing units.

### 3.8.1 *Drive System*

Because of rolling resistance of the rubber rollers and drag of the bearing seals, it was anticipated that there would be several thousand pounds of track drag. This meant that at low cable tensions it would be necessary to drive the cable engine in the payout direction, while at high cable tensions, on the other hand, it would be necessary to exert a braking effort on the track. To avoid pulling the slack, required to envelope the repeater, out of the return side of the chain and introducing it into the squeezed portion, it was necessary to drive the outboard sprocket when pushing cable out and to drive the inboard sprocket when braking. This called for a drive system consisting of a hydraulic pump with two motors in series, one attached to the sprocket shafts at each end of the machine. The replenishing oil required to prevent cavitation of the pump was introduced into the loop in such a way as to cause the two motors to pull against each other and thus keep the track under tension in the squeezing zone. A hydraulic schematic of the system is shown in Fig. 8.

### 3.8.2 *Squeeze System*

Fig. 9 is an artist's rendering of the linear cable engine as envisioned at this stage in its development. The machine is shown built into the deck of a ship, with a repeater enveloped by the track. The tracks in turn are backed up by the articulated "belts" which appear light-colored

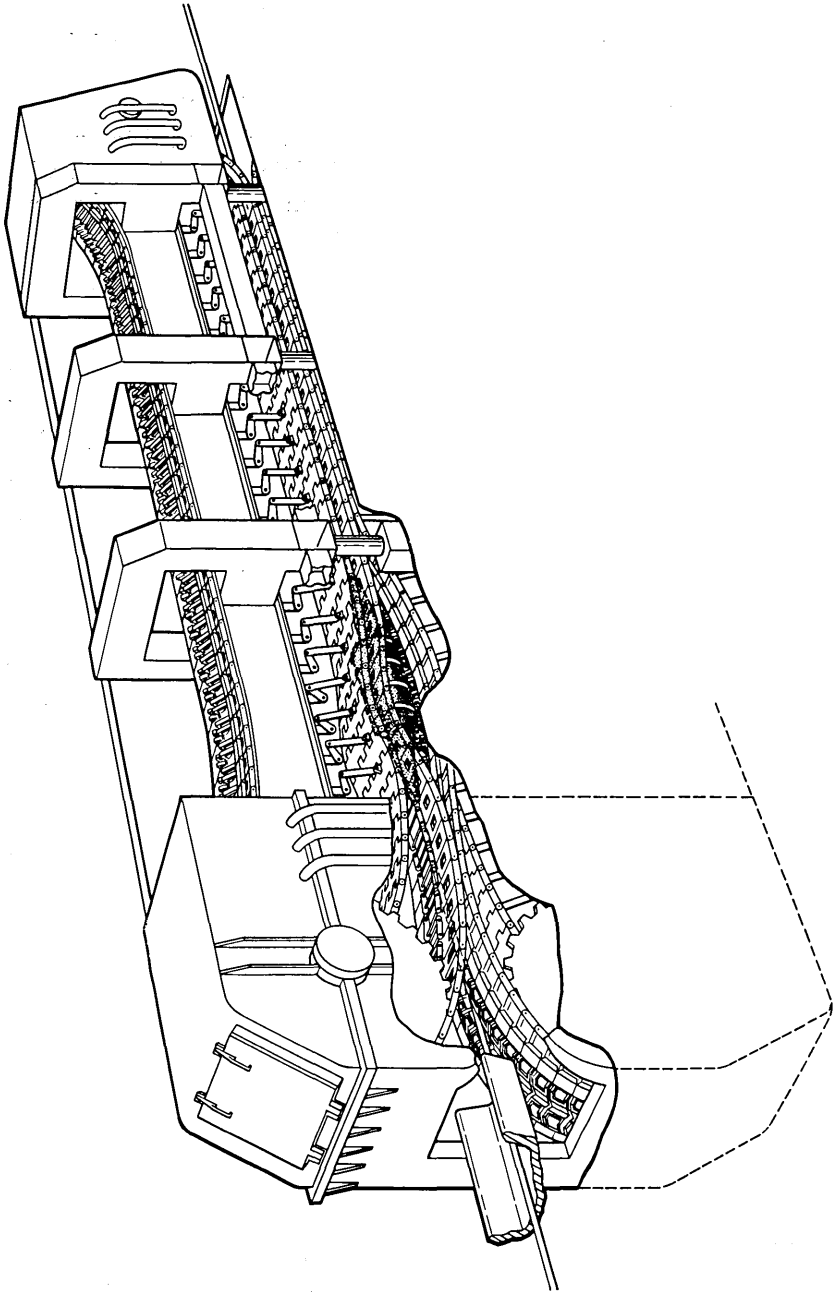


Fig. 9 — Linear cable engine, artist's rendering.

in the figure. Details of the proposed hydraulic squeezing systems are given in Figs. 7 and 10. For reliability, the gripping region of the cable engine was to be divided into seven zones, each of which had its own system of hydraulic valves and accumulator. The seven sections were to be supplied from a dual hydraulic power supply, as shown in the schematic.

## IV. CONSTRUCTION

During the final stages of the design a contract was negotiated between Transoceanic Cable Ship Company, a subsidiary of the American Telephone and Telegraph Company, and Western Gear Corporation for the construction of the linear cable engine and other machinery to be described below. This contract called for manufacture in the Seattle, Washington, area with assembly at a newly acquired facility at Everett, Washington.

The completed linear cable engine is shown in Figs. 11 and 12. Fig. 13 is a close-up of the tracks and belts.

## V. TEST PROGRAM

In addition to the large amount of development testing which was used to prove-in various components and subsystems, two other major testing programs were carried out to insure reliability of the linear cable engine. The first of these was in the area of production testing. As a supplement to a 100 per cent inspection of all machined parts, extensive use was made of X-rays for castings and Magnaflux for the large number of aluminum forgings in the track. Many special production tests were made on subassemblies. For example, a special test rig was made and calibrated for checking the bonding of the rubber rollers to their shafts. Another example was the production testing of the roller carriages. After assembly of the rollers with the Timken tapered roller bearings, each carriage was put on a test rig which pressed it under the full prototype load against a drum which rotated with a peripheral speed of 800 feet per minute. Temperature measurements were made and each carriage was run until the temperatures at several points stabilized. This check was intended to detect bearings with excess axial preload and faulty seals.

The final category of testing involved the completed machine. This program in turn consisted of two categories: first, performance testing in which it was determined that the machine met all of the specification requirements as to speed, tension, etc., and second, an endurance run of approximately 500 miles.

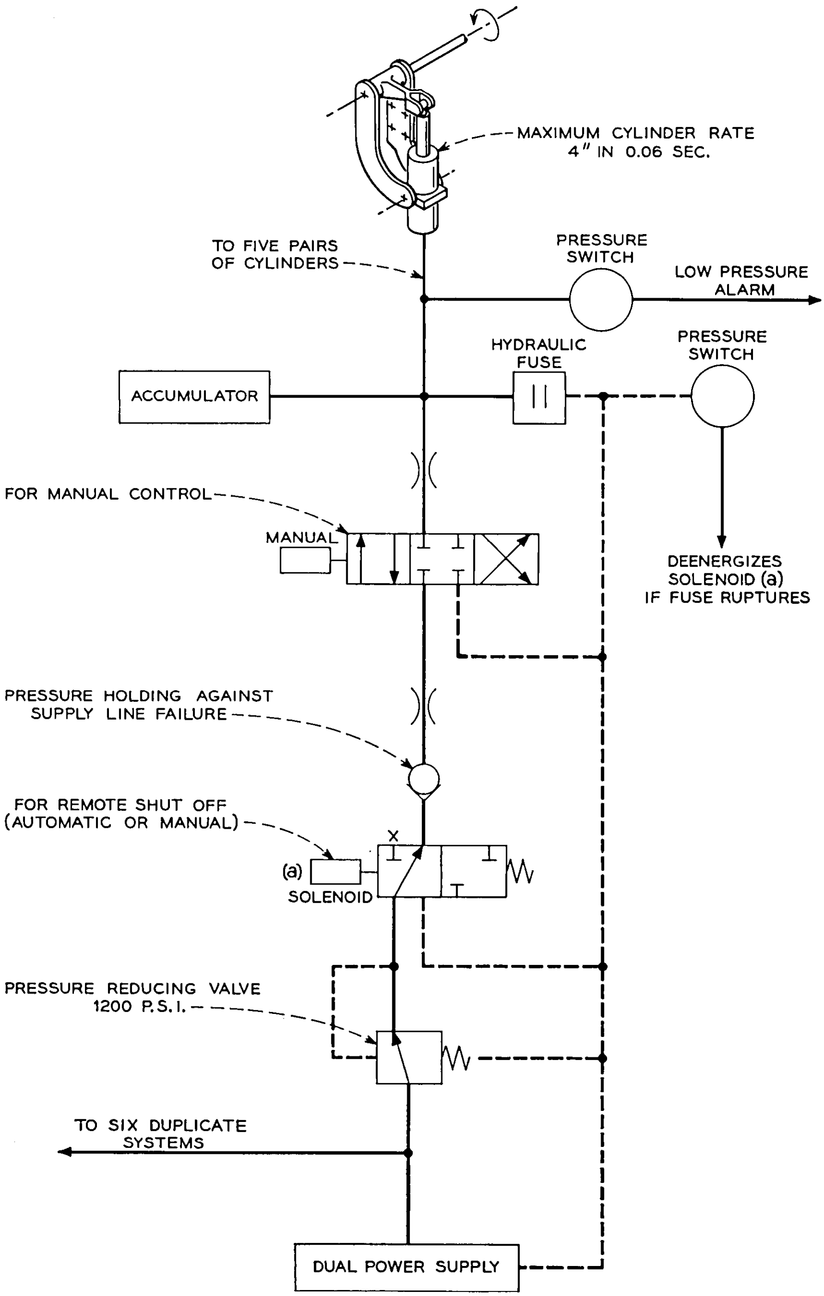



Fig. 10 — Schematic of hydraulic squeezing system.

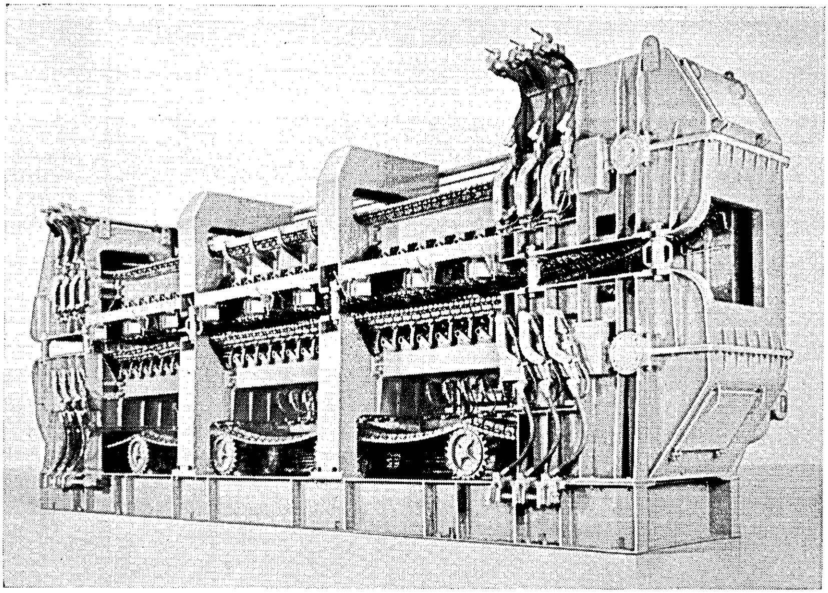


Fig. 11 — Linear cable engine.

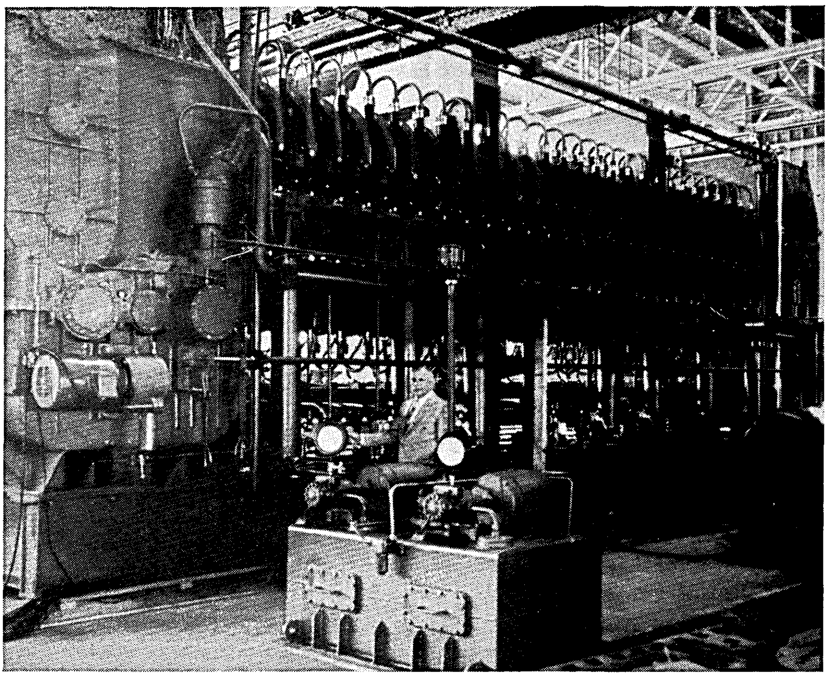


Fig. 12 — Linear cable engine.

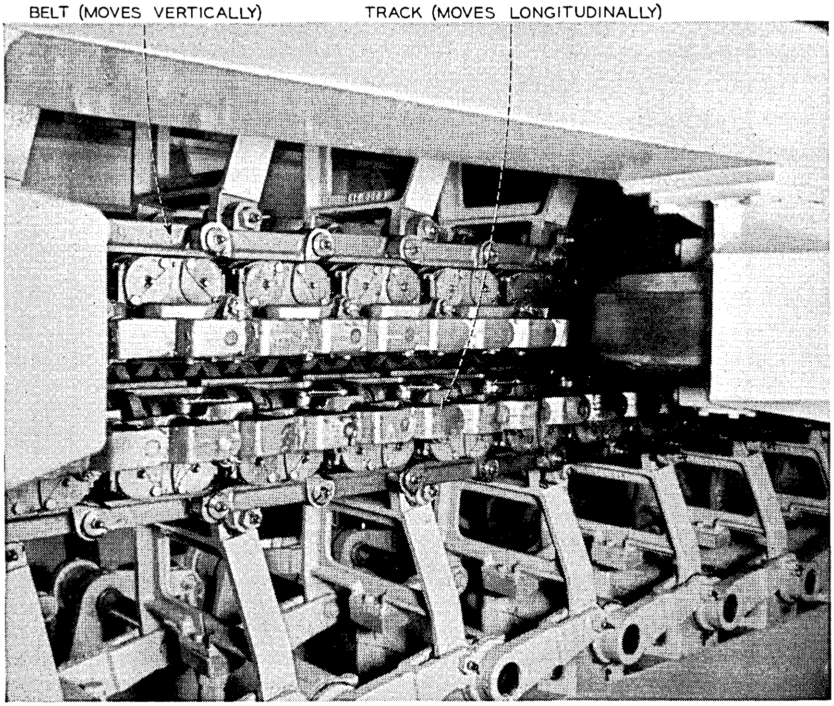



Fig. 13 — Linear cable engine; detail showing tracks and belts.

For the performance evaluation and the endurance test, the completed cable machinery was set up in such a manner that the linear cable engine could be operated against one of the drums of the bow cable machinery which will be described below. A 1000-foot length of $1\frac{1}{2}$-inch diameter "Spring Lay" mooring line was spliced into a closed loop and was run through the linear engine and over one of the drums. Large horizontal sheaves were used to complete the loop. The machine was then run at various speeds and tensions up to a maximum of 8 knots speed and 8000 pounds tension, and a wooden repeater having the size and shape of the prototype repeater was introduced into the inboard end of the machine and run through to check the articulation of the track.

The linear cable engine was designed to pull up to tensions of 16,000 pounds at low speed in the pickup direction. Pickup performance was checked by picking up at high tension with the machine in low gear. Next the brakes were set and a 40,000-pound static pull applied to the linear cable engine without slip or damage.

After successful completion of the performance checkout, the linear cable engine was run continuously day and night for 500 miles at 8 knots with the wooden repeater being sent through at intervals corresponding to the 20-mile repeater spacing. In the final test the linear cable engine was mounted on angle blocks and run inclined at an angle of $22\frac{1}{2}°$. Principal characteristics of the linear cable engine are summarized in Table I.

## VI. OTHER CABLE HANDLING EQUIPMENT

In addition to the linear cable engine which was designed for steady-state high-speed laying, it was necessary to provide drum-type cable engines for handling grapnel rope, buoy moorings, and various kinds of cable encountered in repair work on telephone, telegraph, and other cable systems. Drum cable engines are essentially large-diameter winches in which tensions are built up in several turns of cable. In the case of an ordinary deck winch the necessary back tension is applied by a seaman who pulls on the hawser on the low-tension side of the winch. For a drum-type cable engine, a so-called "drawoff-holdback gear" serves this function.

The double-drum bow cable engine was also designed to handle rigid repeaters at low speeds during repair operations. This requirement called for large-diameter, wide drums and special auxiliary equipment. The 12-foot diameter specified for the drums allowed some margin over the minimum called for by the repeater rigid length, gimbal angle, and cable bending radius; the three-foot width allowed for five turns of heavy shallow-water cable on either side of a repeater.

As each turn of cable comes onto a drum, it tends to fall alongside the

TABLE I — LINEAR CABLE ENGINE CAPABILITIES

| | |
|---|---|
| Cable diameter | |
| armorless cable (double-vee gripping) | 1.20″ min.–1.80″ max. |
| armored cable | 1.20″ min.* |
| Repeater dimensions | |
| diameter | 14″ max. |
| length | 12′ max. |
| Speed | |
| high gear | 9 knots max. |
| low gear | 2 knots max. |
| Tension | |
| high gear | 8,000 lbs max. |
| low gear | 16,000 lbs max. |

* Diameters greater than 1.80″ contacted by "wings" on gripper blocks.

preceding turn; in other words, the cable "spools" itself across the drum. Drum cable engines are therefore normally fitted with so-called "fleeting knives" which plow the cable aside one cable diameter for each rotation of the drum to maintain the several turns of cable in an axially stationary position on the drum surface. To avoid rough treatment of the cable by a stationary knife, the cable engine was fitted with fleeting rings which rotate freely about axes inclined slightly with the axis of each drum. The rings are so oriented that they are further apart at the top of the drum, where the cable comes on, and closer together at the bottom so that, whether the machine is paying out or picking up, the oncoming cable falls freely onto the drum surface and then is pushed axially by contact with the inclined ring as the drum rotates. The several turns of cable, therefore, lie against each other and against one fleeting ring or the other, depending on whether cable is being picked up or payed out.

The two drums are carried on antifriction bearings on stationary shafts which are cantilevered toward the center of the ship from opposite sides of a closed rectangular box frame. This type of mounting has two distinct advantages. First, the end of the "dead" shaft carries the stationary mounting for one fleeting ring. Since this structure is closed in by expanded metal panels, there are no moving parts which can be contacted by a seaman walking between the drums. Second, the fact that the drums face each other facilitates transfer of cable or rope from one drum to another and decreases the size of the deck opening required.

Each drum is driven by an independent direct-current electric drive system consisting of a heavy duty mill-type motor, a separately excited generator driven by one of the main propulsion turbines, and the necessary amplidynes, excitation generators and control equipment. In the payout gear ratio, the engine is capable of paying out or picking up cable at tensions up to 16,000 pounds at speeds up to 8 knots. In two other gear ratios, tensions of up to 100,000 pounds can be handled at lower speeds. The drum speed and direction of rotation can be controlled manually from a console near the engine or remotely from the cable control center. In addition to the dynamic braking inherent in the electrical drive, the drums have mechanical shoe brakes which can be applied hydraulically or by hand.

In order to avoid bending the cable to a small radius and subjecting it to concentrated loads, a linear drawoff-holdback gear was designed. The linear design also facilitates handling of rigid repeaters and of rigid connectors in grapnel rope. A hydraulic drive system is used to allow operation at constant tension when functioning as drawoff or holdback gear and at constant speed if it should be necessary to use the gear as a cable hauler when loading cable.

Cable tension is measured by means of a dynamometer which deflects the cable and weighs the resulting component of cable tension. Earlier dynamometers consisted of large-diameter wheels or sheaves with load cells or other devices for indicating tension. The dynamometers for C.S. *Long Lines* substitute sliding of the cable on a curved "table" for the rotation of a large sheave. The load is weighed by a conventional load cell arrangement.

To allow handling of repeaters without causing the overriding turns on the drum which would result if an attempt were made to fleet large-diameter repeaters and cable together, the drawoff-holdback gear and dynamometer for each drum were arranged to traverse. Auxiliary traversable fleeting knives were also provided. When a repeater approaches the drum, the several turns of cable are fleeted away from the active fleeting ring by the traversable fleeting knife, which is then retracted. The drawoff-holdback gear or dynamometer is then traversed to direct the oncoming lead of cable onto the drum in such a manner that the repeater clears the cable on the drum. Several turns of oncoming cable are then wound onto the drum between the repeater and the active fleeting ring as the turns on the other side come off. Further rotation of the drum causes the turns to "spool" along the drum until they again contact the fleeting ring to complete the cycle.

Fig. 14 is an artist's rendering of one drum of the bow cable engine

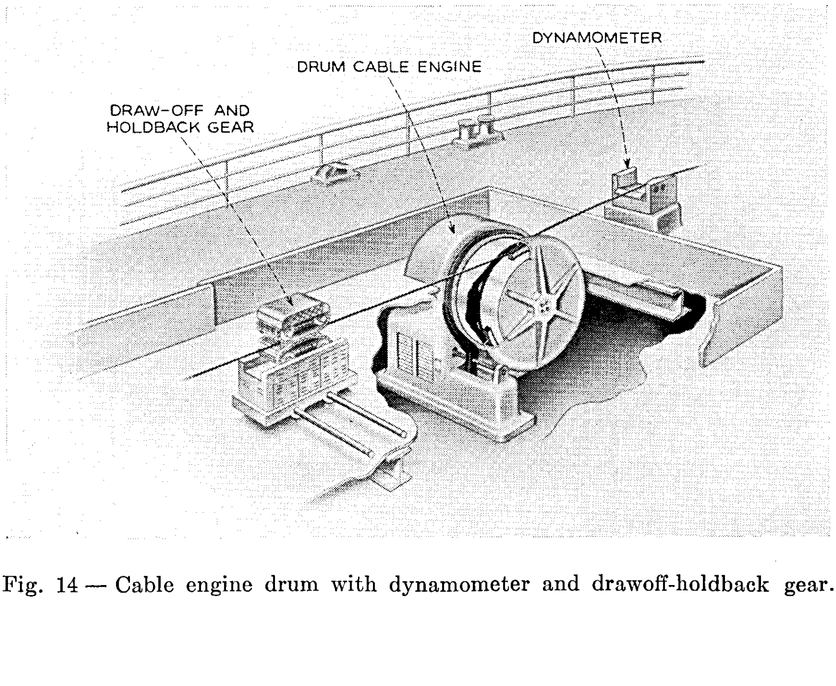



Fig. 14 — Cable engine drum with dynamometer and drawoff-holdback gear.

with its associated dynamometer and drawoff-holdback gear. Fig. 15 is a photograph of the actual drums as set up for test at the plant of the manufacturer. The fleeting rings can be seen in Fig. 16, which shows the starboard drum as installed in C.S. *Long Lines.*

### 6.1 *Cable Control Center*

On previous cable ships it has been the practice to control each cable engine from a nearby station so that the operator could maintain a watch on the engine and make speed adjustments by hand. Information needed for calculation of the required payout speed was collected from various sources throughout the ship. The required payout speed was then calculated, generally on the bridge, and payout speed or tension orders were then relayed to the engine operator. To integrate the cable laying operations and to permit a degree of automation, the concept of a "cable control center" has been introduced. This center was to be a room, located beneath the ship's bridge, containing all the instrumentation relating to the cable laying operation. It was also to be a control station from which any of the cable engines could be operated. Local

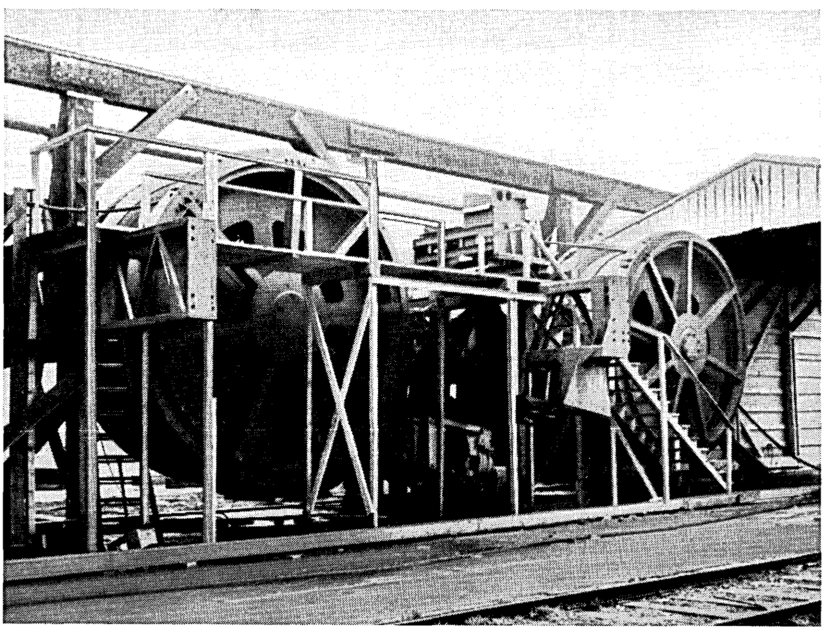


Fig. 15 — Cable engine drums set up for manufacturer's tests.

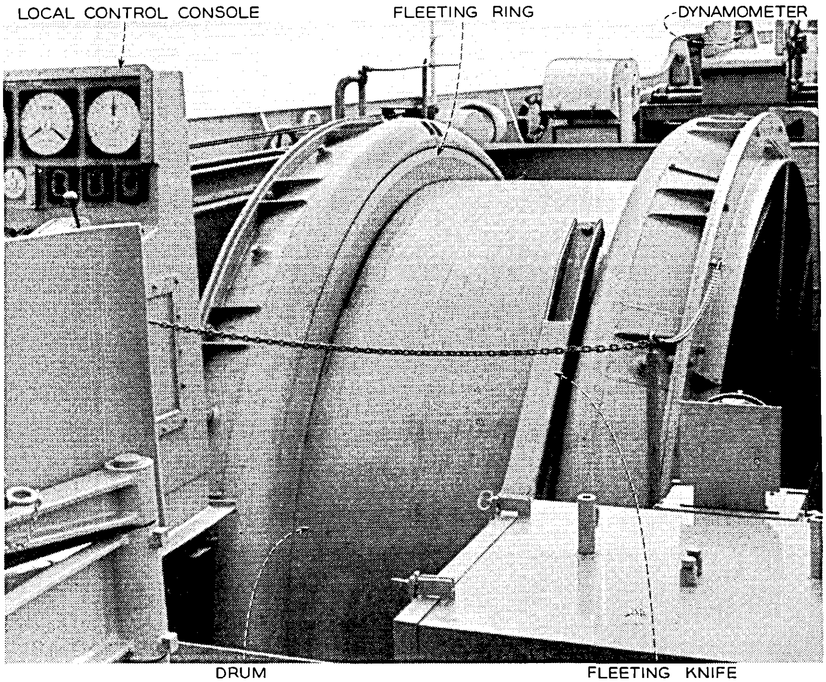



Fig. 16 — Cable engine drum installed in C.S. *Long Lines*.

control stations at each engine were still to be retained for periods when engine observation was necessary, such as during start-up or for cable repair operations. Fig. 17 shows the cable payout control console in the cable control center on C.S. *Long Lines*.

### 6.2 *Cable Engine Payout Control — Control Modes*

Submarine cable should be laid with just sufficient slack to enable conformance with the ocean bed, and to avoid residual tension in the cable after laying. Under these ideal conditions the cable tension at the ship during steady-state laying conditions would be essentially equal to what is usually referred to as the *wh* factor — that is, the product of the weight per unit length of the cable in sea water and the depth of the water. The tension at the ship will increase above this value if residual tension exists in the cable on the sea bed and conversely will be less than *wh* if sufficient excess slack is payed out to result in a significant longitudinal velocity of the cable relative to the water. Severe ship's motion

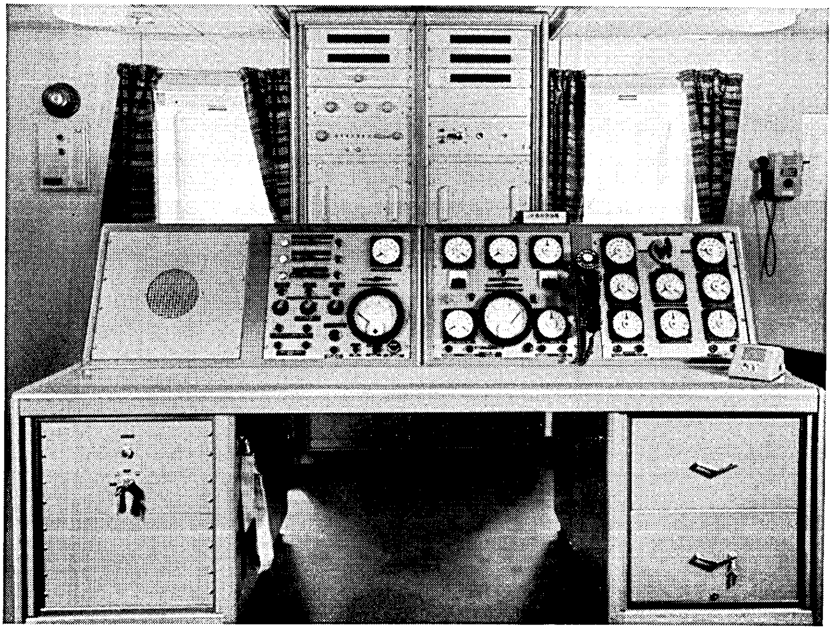


Fig. 17 — Cable payout control console.

will introduce transients into the steady-state laying conditions and will cause undesirable tension surges if the cable is payed out at a fixed speed. These tension surges can be eliminated by paying out at a fixed tension.

Because of the relationship among cable tension, payout rate, ship's speed, depth of water, and cable characteristics, a particular value of tension will yield a slack percentage which depends on the values of the other parameters. Because of uncertainties in some of these values and because of the sensitivity of payout rate to small changes in tension, it is not feasible to calculate the required value of tension from measured values of the other variables. A practical method, however, is to set up the steady-state laying conditions on the basis of cable engine speed as a result of ship speed and desired slack, to observe the resultant tension at that particular depth of water, and then to use this value of tension if ship's motion becomes excessive. Under tension control, the cable mileage payed out would be compared with distance steamed and the tension adjusted to increase or decrease the payout rate as required to produce the desired percentage of slack on the bottom.

From these considerations the following basic modes of operation were selected:

(a) Manual speed control, to obtain a desired amount of slack to cover the contour of the sea bed. Because the linear cable engine can actually push cable out, it is possible to lay slack even in very shallow water where the tensions approach zero.

(b) Manual tension control, to adjust the tension to give the average speed of the engine which results in the desired amount of slack. The instantaneous speed of the engine varies to reduce short-term tension variations.

(c) Automatic slack control, in which the amount of required slack is calculated and set into a computer which controls the cable engine average speed to maintain the required amount of slack despite changes in ship speed. The fast-acting constant tension mode can still be retained to operate within the slow acting automatic slack control, and hence the effect of ship motion on the cable tension can be reduced.

The control system design was based on these principles and also incorporated a fail-safe feature which was intended to ensure that if a component or power source should fail during the operation, control would revert without interruption to one of the simpler modes. The primary control of the engine was therefore mechanical speed control operating from a lever connected by a mechanical linkage to the stroke of the hydraulic pump which drives the engine.

Improving on this to enable a more precise adjustment of speed is the closed-loop speed control system in which a handwheel, operating through clutches and gear reductions, drives a dc-excited potentiometer, the output of which is compared with a tachometer signal from the cable engine to yield an error signal capable of operating the pump stroke control via a servo valve and linkage. The basic tension control was constructed in a similar manner, but in this case the feedback signal is obtained from a load cell arranged to measure cable tension. Again the error signal adjusts engine speed via the servo valve. Fig. 18 is a block diagram of the cable engine control system.

The manual inputs for these three control arrangements are all in close proximity to the cable engine, and remote operation of the latter two systems is obtained by means of control motors activated by push buttons on the console in the cable control center. When remote operation is desired, the motors are clutched into the systems in place of the handwheels. All necessary information regarding the behavior of the engine or cable is transmitted to the cable control center by selsyn signals, or as dc voltages, and displayed on the cable payout control console as shown in Fig. 17.

Once control of the engine, in either the speed or tension modes, is

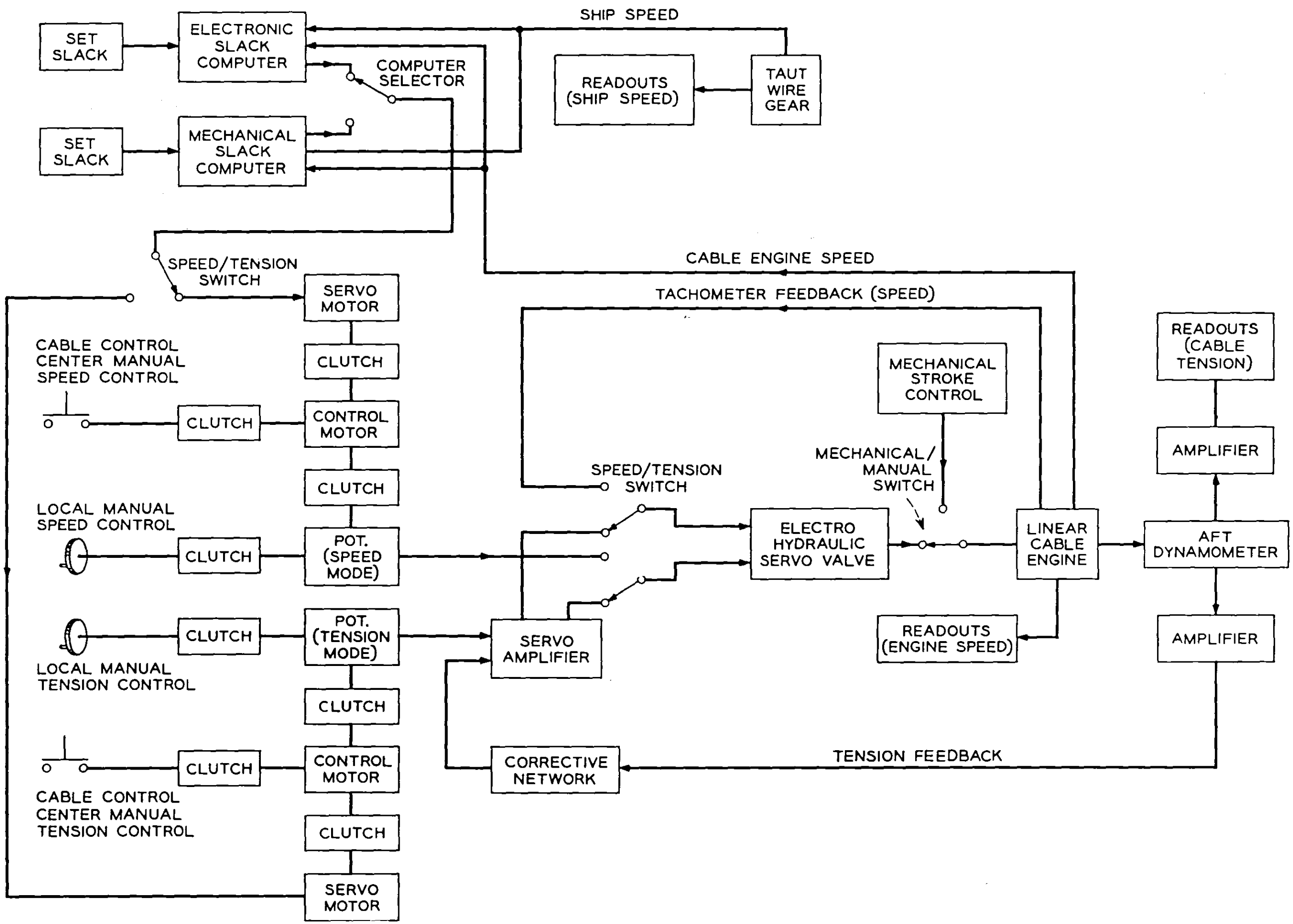



Fig. 18 — Cable engine control system.

transferred to the cable control center, the automatic slack mode can be superimposed on the system. Now the operator is merely required to set the required slack as the input to a computer, which then operates the speed or tension control potentiometers via a further series of servo motors, clutches and gear reductions.

The computer is, for reasons of simplicity and reliability, merely a refinement of the cone-and-cylinder type of mechanical computer used for many years on cable ships and miniaturized for convenience. As a standby a proprietary electronic computer is also available in the cable control center, and control could be readily transferred to this if necessary.

A separate unit was provided in the cable control center for the sole function of providing a continuous indication of cable mileage and taut wire mileage. This unit, which is shown in Fig. 17, operates independently of the other systems and is actuated by small pulse generators attached to each engine. The pulse generating units transmit one pulse for each fathom of cable or wire to an assembly of stepping switches. The accumulated count is displayed on "Nixie" readouts. Remote repeaters with identical readouts are also provided in the test room, on the bridge, and on the forecastle. This type of presentation was selected to avoid the noise of counting relays in the test room and on the bridge, and to allow all units to be zero-set or reset simultaneously from one location.

## VII. CONCLUSION

The cable engines and control system were checked out during several short crew-training cruises soon after delivery of the ship. Cable and repeaters were payed out by the linear cable engine at speeds up to 8 knots in all control modes. The drum engines successfully handled armored cable, armorless cable, repeaters, grapnel rope, chains, shackles and other hardware.

### *Note Added in Proof*

As of May 15, 1964, the linear cable engine has payed out approximately 8200 nm of SD cable systems.

## APPENDIX A

### *Cable Gripping*

Consider an armorless coaxial submarine cable having a high-strength steel central member surrounded by a coaxial transmission structure consisting of thin copper sheet and polyethylene dielectric. An axial tensile load on the strength member can only be dissipated by axial shear forces applied to the external surface and transmitted through the transmission structure to the central strength member. The magnitude of the maximum allowable axial shear force per unit length will be limited because the shear stresses in the copper and polyethylene, and particularly on the interfaces, must be kept to a minimum. For a given allowable maximum shear force per unit length, the linear cable engine which makes most efficient use of gripping length is that which applies a uniform shear force per unit length to the cable.

Assume that a linear cable engine can be designed so that the tension in the cable is dissipated uniformly in a gripping length $\lambda$. The tension distribution will then be as shown in Fig. 19. As a basis for the design of a cable engine which would achieve this tension decay, it is of interest to calculate the displacement of the cross section of the center conductor at the high-tension end of the machine.

The axial strain in the center conductor is given by

$$\epsilon = T/EA \tag{1}$$

where

$T$ = local tension

$E$ = Young's modulus

$A$ = cross-sectional area of the strand.

If the axial strain is integrated from the point in the cable at which the tension is zero, we find that the cross section at the high-tension end will move, with respect to the assumed stationary cross section at the zero tension point, an amount given by

$$u = \tfrac{1}{2}\epsilon_{\max}\lambda \tag{2}$$

or

$$u = T_o\lambda/2AE. \tag{3}$$

With a knowledge of the cable properties the maximum displacement could be calculated from (3). To avoid becoming involved in the details of the cable design it is more convenient to work directly with (2) and the fact that the strength member will be composed of "improved plow steel." Since this type of steel has a tensile strength of 300,000 psi and its Young's modulus is 30 million psi, the maximum strain in the strength member will reach 1 per cent under the ultimate load. For lower tensile

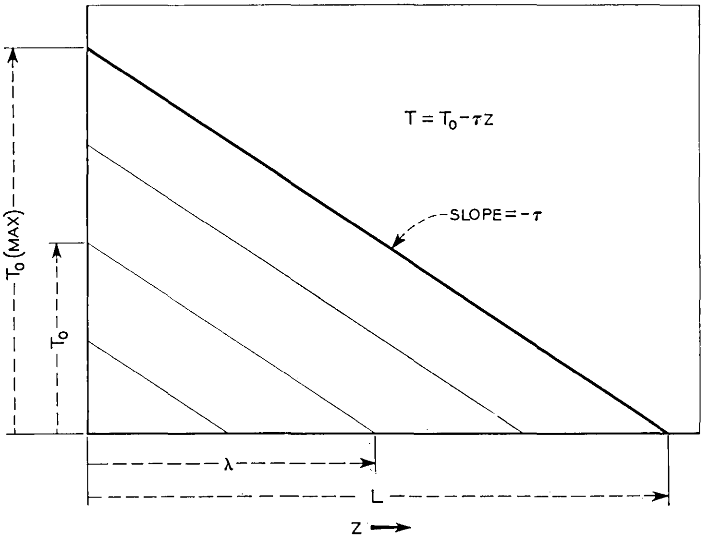



Fig. 19 — Uniformly dissipated cable tension distribution.

loads the maximum strain in the cable will be given, approximately, by

$$\epsilon_{\max} = \frac{T_o}{T_{o(\text{ultimate})}} \cdot \epsilon_{(\max)(\text{ultimate})} \,. \tag{4}$$

Equation (1) can now be put into the form

$$u = \frac{1}{2} \frac{T_o}{T_{o(\text{ultimate})}} \cdot \epsilon_{(\max)(\text{ultimate})} \cdot \lambda \tag{5}$$

and the total displacement can be evaluated for a given operating tension, ultimate tension, and gripping length. The gripping length, in turn, is determined by the allowable shear force per unit length.

Fig. 20 is a plot of normal stress on the center conductor of an armorless cable having bonded interfaces and subjected to a tension $T$ on a V-groove sheave of radius $R$ and V-groove angle $\varphi$. In the special case where the V-groove angle equals 180°, the two normal reaction forces on the cable surface coalesce into one and we have an ordinary cylindrical drum. The calculations were actually made for this case, and the 90° situation was obtained by superposition.

For both the 90° V-groove and the plain cylindrical drum there are negative normal stresses on the center conductor in certain regions. Unless the cable has a bonded interface with sufficient strength to tolerate

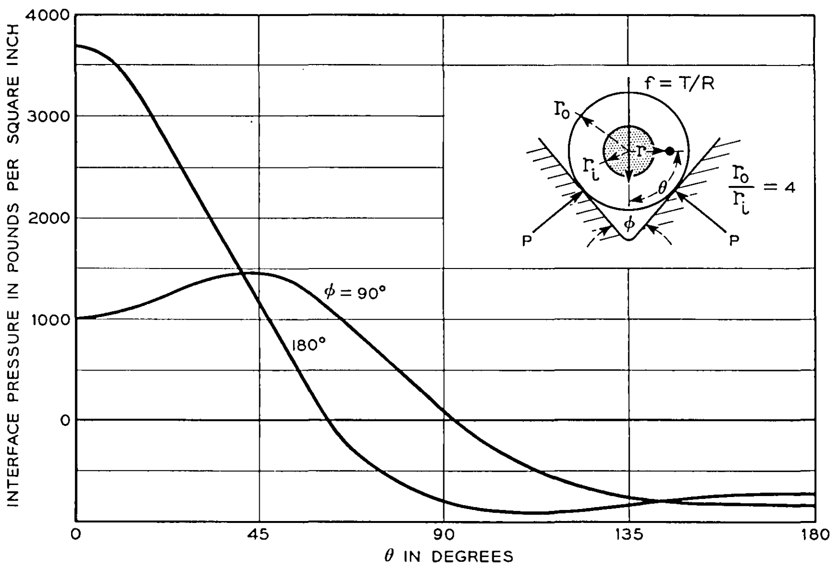



Fig. 20 — Center conductor normal stress — one V-block.

the tensile stresses or there is a shrink pressure on this interface equal to the maximum tensile stress, there will be separation and of course the calculated stress distributions will no longer apply.

Fig. 21 depicts the center conductor normal stress distribution for the case of two symmetrically located V-blocks which represent the gripper blocks of a linear cable engine. In this case the radius of the equivalent V-groove sheave has gone to infinity and the finite cable tension can give no normal component of force. The two blocks must therefore be squeezed together. It is to be noted that the normal stress on the center conductor interface does not become tensile anywhere around the circumference. This type of gripping will therefore not cause radial separation of an armorless cable with unbonded interfaces, a polyethylene dielectric and a ratio of outside radius to center conductor radius of four.

The cable gripping forces which are shown as concentrated in Fig. 21 will actually cause slight flat spots to develop on the cable and the contact stress distribution will be semielliptical, as shown in Fig. 22. The pressure distribution around the outer periphery of the cable can be represented by a Fourier series which will have a constant term given by the average pressure distribution which, in turn, is simply the sum of the four contact forces divided by the outside circumference. In addition there will be a series of sinusoidal terms. If the center conductor is as-

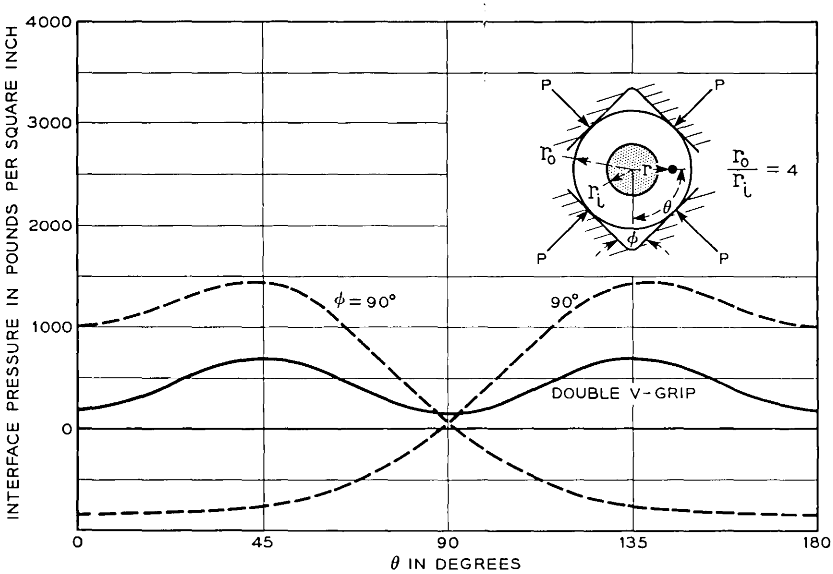



Fig. 21 — Center conductor normal stress — two V blocks.

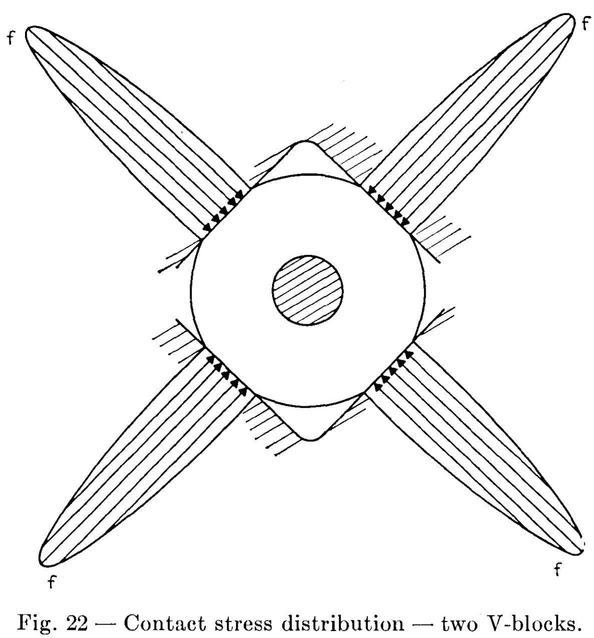



Fig. 22 — Contact stress distribution — two V-blocks.

sumed to be infinitely rigid and the polyethylene incompressible, the average pressure term will be transmitted undiminished to the center conductor. The various sinusoidal terms will be attenuated in some fashion, but in any case their contribution to the average pressure on the center conductor interface will be zero. The average pressure on the center conductor interface will therefore be equal to the average pressure on the external circumference of the cable.

The frictional shear stress which can be developed on any cylindrical interface will be given by the product of the coefficient of friction upon that interface and the normal pressure. The shear force per unit length which can be transmitted across the interface can be obtained by integrating the frictional shear stress around the circumference. If the coefficient of friction is independent of pressure, the frictional shear force at the condition of impending slippage will be given by the product of the coefficient of friction, the circumference, and the average interface pressure. For the center conductor interface we have

$$\tau_i = 2\pi r_i \mu_i P_{i(\text{av})} \tag{6}$$

and for the outer surface

$$\tau_o = 4\mu_o f \tag{7}$$

where

$$P_{i(\text{av})} = P_{o(\text{av})} \tag{8}$$

$$P_{o(\text{av})} = 4f/2\pi r_o \tag{9}$$

$\tau$ = slip value of frictional shear force per unit length

$r$ = interface radius

$\mu$ = coefficient of friction

$P$ = pressure

and

$f$ = compressive force per unit length for the area of contact with each of the four plane faces of the gripper

and the subscripts "$i$" and "$o$" refer to inner and outer, respectively. Combining (6), (7), (8), and (9) yields

$$\tau_i/\tau_o = \mu_i r_i/\mu_o r_o \,. \tag{10}$$

Equation (10) indicates that slip will occur on the center conductor interface for values of shear force per unit length which will not cause the outer jacket to slip in the V-blocks unless we have

$$\mu_0/\mu_i \leqq r_i/r_o \tag{11}$$

Since the coefficient of friction on the center conductor interface will be approximately 0.16 and the ratio of outside to inside radius will be approximately four, inequality (11) calls for an external friction coefficient of less than 0.04. It was not considered feasible to maintain this value of coefficient of friction between the outer surface of the cable and the gripping elements of the cable engine. A shear limiting feature, which allowed axial motion of the gripper block at a shear force per unit length which would not cause slip on the center conductor interface, was therefore included in the track design.

Equations (6), (8), and (9) can be combined to give

$$\tau_i = 4\mu_i(r_i/r_o)f \tag{12}$$

or, for our case

$$\tau_i = \mu_i f \tag{13}$$

since the outside-to-inside radius ratio is four.

Experimental work on gripping of cable in double V-blocks has established 500 pounds per inch as the maximum allowable contact force. A design value of 250 pounds per inch was used in setting the allowable shear force per unit length. Substitution of this value and of the previously mentioned coefficient of friction of 0.16 into (13) gives

$$\tau_{(\text{shear limit})} \leqq \tau_{i(\max)} = 40 \text{ lb/in.} \tag{14}$$

The $\tau$ notation is used for the shear limiter setting because the effect of an ideal shear limiter is equivalent to slip of the jacket in a gripper block. The active gripping length is then

$$\lambda = \frac{T_o}{\tau_{(\text{shear limit})}} \tag{15}$$

and (3) and (5) can be written

$$u = \frac{T_o^2}{2AE\tau_{(\text{shear limit})}} \tag{16}$$

and

$$u = \frac{T_o^2 \epsilon_{(\max)(\text{ultimate})}}{2T_{o(\text{ultimate})}\, \tau_{(\text{shear limit})}} \tag{17}$$

respectively. For the cable in question we have

$$T_{o(\text{ultimate})} = 16{,}000 \text{ lb}$$

$$\epsilon_{(\text{max})\ (\text{ultimate})} = 0.01$$

and

$$\tau_{(\text{shear limit})} = 40 \text{ lb/in.}$$

whence

$$u = \frac{T_o^2}{128 \times 10^6} \text{ in.} \tag{18}$$

for $T_o$ in pounds.

If this cable were gripped and tensioned in such a manner as to achieve the linear decay of Fig. 19 for all tensions up to the nominal ultimate, (18) would give

$$u_{(T_o=16{,}000 \text{ lb})} = 2 \text{ in.}$$

For smaller working tensions the required shear limiter travel decreases parabolically and

$$u_{(T_o=8{,}000 \text{ lb})} = \tfrac{1}{2} \text{ in.}$$

APPENDIX B

## *Bearing Reliability**

The bearing industry defines the life of bearings as that period of service which is limited by fatigue phenomena. The fatigue-limited life terminates in what will be referred to as the "initial failure" of a bearing. It is characterized by fatigue of the material due to repeated stress under rotation resulting in flaking and ultimately in spalled areas on the rollers and/or races of the bearing. This initial failure will not make a bearing inoperable for cable engine application but will merely tend to increase the noise level and possibly the rotating torque to a small degree.

When a bearing is operated after initial failure the spalled areas increase in size until ultimately the bearing is incapable of performing its design function. It may "lock-up" so that the cup and cone cannot rotate with respect to each other, or the rollers and cage may disintegrate, allowing large radial displacements of cup with respect to cone. In either of these cases the bearing will be said to have failed catastrophically.

Since castrophic failure is a result of running an initially failed bearing

* Furnished by G. J. Levenbach and T. N. Grogean.

beyond initial failure, it is necessary to discuss the fatigue life of bearings as a basis for discussion of the subsequent catastrophic failure.

B.1 *Initial Fatigue Failure*

The following discussion is based on the assumption that the bearings are run under ideal conditions. We assume proper lubrication, the absence of foreign materials, isolation from the atmosphere, and proper installation and handling.

With these assumed running conditions, the probability that no initial fatigue failure will occur in a bearing running for a given time is contained in a formula given by Palmgren:[2]

$$\mathrm{Log}_{10} \frac{1}{S} = (L_s)^b \log_{10} \frac{1}{0.9} \tag{19}$$

where

$S$ = probability of a bearing exceeding a life $L_s$

$L_s$ = life measured as a fraction of the life exceeded by 90 per cent of population of bearings (so-called $B_{10}$ life)

$b$ = shape constant in the Weibull distribution.

Palmgren's formula is based on extensive experimental evidence that the fatigue failure time distribution can be described by a Weibull distribution.

For a sample of $n$ bearings the probability, $S_n$, that all of them exceed $L_s$ is derived from (19) and takes the form

$$S_n = \exp\left[-(L_s)^b \cdot \frac{n}{a}\right] \tag{20}$$

where $a$ is a conversion constant given by

$$a = \frac{\log_{10} e}{\log_{10} (0.9)^{-1}} = 9.5$$

and $e$ is the base of the Naperian logarithm.

The shape constant $b$ is a property of a specific type of bearing.[3] Palmgren notes that for commonly used bearing steels $b$ has values in the range of 1.1 to 1.5.

Data obtained from 30 bearings fatigue-failed by Timken Roller Bearing Company can be used to estimate the shape factor $b$. When the data listed in Table II are plotted on Weibull probability paper the sample distribution should appear as a straight line.[4] The slope of the line

TABLE II — INITIAL FAILURE PATTERN OF TEST LOT OF 30 LM11700 SERIES TIMKEN BEARINGS (TIMKEN TEST NUMBER 151.3-G)

| | | | | | |
|---|---|---|---|---|---|
| Number of bearings exceeding life $L_s$ | 29 | 23 | 16 | 10 | 3 |
| $L_s$ | 0.64 | 2.80 | 5.00 | 9.0 | 9.90 |

gives an estimate of $b = 1.45$. Using (20), this can be used to calculate the probability that no bearing failure will occur in $h$ hours of operation. This probability is plotted in Fig. 23.

The expected number of failures ($n'$) in $h$ hours can be determined by multiplying the probability of a bearing failure $p$ by the total number of bearings $n$ and noting that the probability of a bearing fatigue-failing is $p = 1 - S$.

$$n' = pn = (1 - S)n = \left[1 - \exp\left\{-(L_s)^b \cdot \frac{1}{a}\right\}\right] n. \qquad (21)$$

Equation (21) is plotted in Fig. 24 showing the expected number of failures vs hours of operation.

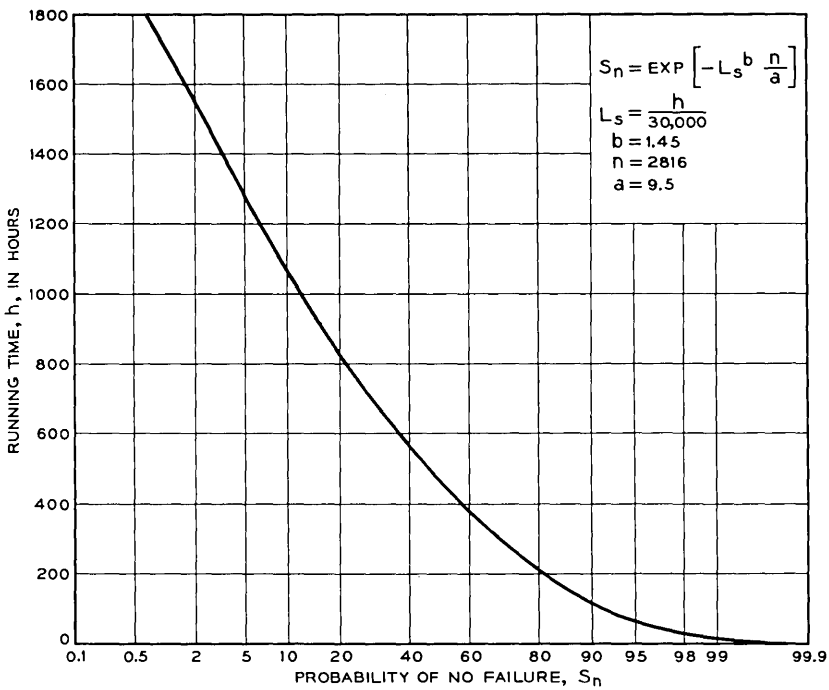



Fig. 23 — Probability of no bearing failure in $l$ hours.

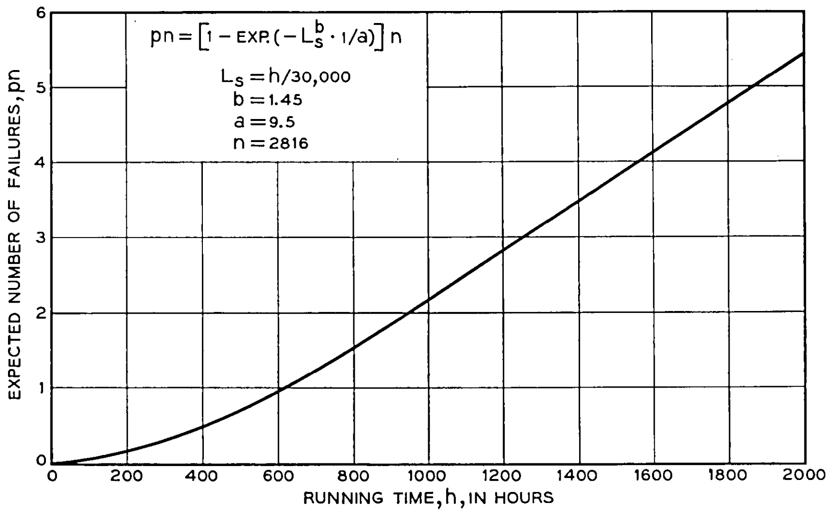



Fig. 24 — Expected number of failures in $h$ hours.

Another useful result is the probability that there will be $N$ or more bearing failures in a given number of hours. Basically this can be described by a binomial process. The binomial formula gives the probability of $N$ failures of a total of $n$ bearings. For easy computation, this can be approximated by using the $pn$ in the previous discussion as the parameter in the Poisson distribution. The resulting relation shows

$$P = e^{-pn} \sum_{i=N}^{n} \frac{(pn)^i}{i!} \tag{22}$$

where $P$ is the probability that there will be $N$ or more failures in a total number $n$ with $pn$ the expected number of failures. Equation (22) is plotted in Fig. 25 for $P$ vs $N$ for various values of $h$.

It is seen from the previous discussion that there is a high probability that there will be initial failures in relatively short operating times. For example, in 300 hours, which is roughly the time for one ocean crossing, Fig. 23 shows that there is only 70 per cent probability that there will be no bearing failures; Fig. 24 shows that the probable number of failures is approximately 1; and Fig. 25 shows that there is a 5 per cent probability that there will be 2 or more.

With these facts known for bearings run under ideal conditions, it is necessary to accept the fact that there will be initially failed bearings in the cable engine during extended running periods. The possibility of propagation to catastrophic failure is therefore of interest.

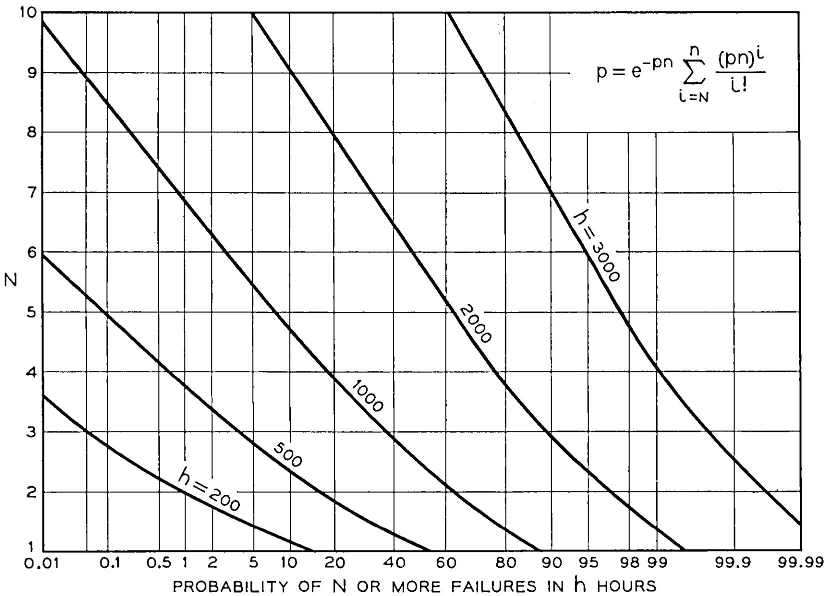



Fig. 25 — Probability of $N$ or more failures for various hours of operation.

### B.2 *Failure Propagation*

The bearing industry has not been greatly concerned with catastrophic failure; consequently, little information is available. At the request of Bell Laboratories, Timken Roller Bearing Company ran accelerated life tests on four bearings of the type considered here. The four bearings were run on their laboratory fatigue test machines at high speed under heavy load with oil lubrication. Two of the four bearings experienced what might be considered catastrophic failure at the end of 3.4 and 4.0 $B_{10}$ life. The other two were still operable at the end of 4.7 $B_{10}$ life.

In addition to this accelerated test result, Timken supplied Bell Laboratories with twenty bearings which had been run to the point of initial fatigue failure with oil lubrication. Eight of the twenty bearings were run under prototype loads at prototype speed by Western Gear Corporation and lubricated every 400 hours with Shell Darina A-X. The test was terminated after 3020 hours with little change in running properties. Pictures taken before and after the test indicate that the failure did not propagate to any considerable degree.

The remaining twelve fatigue-failed bearings were tested at Bergen Research Engineering Corporation. In this case they were initially greased with Shell Darina A-X and run continuously without further lubrication. At 5500 hours the driving torque on one roller had increased significantly, and the test rig was shut down. Inspection indicated that the grease had become dry and hard in both bearings of the offending roller. The remaining rollers were regreased and the test resumed.

At 5850 hours, it was observed that several seals had been forced out against the ends of the rollers, apparently because dried grease had blocked the vent fittings. The test was therefore terminated at 5850 hours and all twelve bearings were returned to the Timken Roller Bearing Company for examination. Photographs taken before and after the 5850-hour failure propagation test were compared. Although there had been a considerable increase in spalled areas in some cases none of the bearings could be said to have failed catastrophically.

### B.3 *Interpretation of Results*

Because of the small amount of failure propagation data available, it is not possible to develop a failure distribution theory similar to that which applies to the initial fatigue failure. It might, however, be of interest to look at the results under the somewhat tenuous assumption that the times to catastrophic failures are exponentially distributed.

(a) Assuming the accelerated life test of the four bearings terminated at 4.0 $B_{10}$, which is conservative, we estimate the mean life for catatrophic failure to be[5]

$$\theta_a = 231{,}000 \text{ hours} = 7.7\ B_{10}.$$

(b) Assuming one failure in the eight-bearing test to have occurred at 3020 hours provides an estimate of

$$\theta_b = 24{,}000 \text{ hours} = 0.8\ B_{10}.$$

(c) Assuming one failure in the 12-bearing test to have occurred at 5500 hours provides an estimate of

$$\theta_c = 66{,}000 \text{ hours} = 2.2\ B_{10}.$$

Taking the lowest estimate at its face value would yield a probability that an undetected initial fatigue failure would not propagate in the next 300 hours to the point of catastrophic failure as

$$\exp(-t/\theta) = \exp(-300/24{,}000) = 0.99.$$

This result is conservative in that there was actually no catastrophic failure in the eight-bearing test.

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# Design and Powering of Cable Ship "Long Lines"

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(Manuscript received March 31, 1964)

*The C.S. "Long Lines" was designed both to lay the new SD submarine cable system and to repair new and existing undersea cables. Within the limits imposed by this dual purpose, an entirely new cable ship design has been evolved which gives maximum working efficiency, maneuverability, and stability. While most of the special features of the ship — wide-range power plant, cable storage and handling facilities, etc. — are the result of its special function, a great deal of attention has been paid to providing optimum working conditions for, and safety of, the ship's complement.*

## I. INTRODUCTION

### 1.1 *Factors Affecting Ship Design*

The primary purpose of the new Cable Ship *Long Lines* was to lay a new type of cable system. Its secondary, but scarcely less important, purpose was to be capable of repairing all existing and new cable systems, both telephone and telegraph. The ship then, a tool in itself, had to carry other tools or hardware to do the job for which it was designed. First in importance were the cable tanks, the number and size depending on the amount and type of cable to be carried, then the means of payout for laying, and last the type of pickup for repair work.[1,2]

Speed and range were developed when the owner specified the extent of the ship's run, its longest service steaming time, and its time on the so-called "cable grounds."

Since the *Long Lines* was to be at sea for long periods of time and carry a multimillion-dollar cargo, great emphasis was put on the reliability of the ship and its component parts. All machinery and equipment used were designed to operate satisfactorily with a momentary roll of 30 degrees to either side or a pitch of 10 degrees, a permanent list of

* All of Gibbs & Cox, Inc., New York, N.Y.

15 degrees to either side, and a permanent inclination of 5 degrees in either direction fore and aft.

Various agencies whose regulations had to be considered in the design, construction, and installation of all its parts, equipment, and outfit are listed in Appendix A. This listing shows that, in addition to the owner's specifications, regulations had to be followed with regard to the construction of the ship itself, the machinery, auxiliaries and outfit, the safety of the ship in the event of damage by flooding or fire, and the safety of the crew and those engaged in loading the ship.

### 1.2 *Contract Specifications and Plans*

When the cable and repeater laying techniques had been developed and test facilities and other requirements determined, authorization was given by the Long Lines Department of the American Telephone and Telegraph Company to proceed with the preparation of bidding data for a new cable ship. These data included the preparation of detailed ship specifications incorporating the requirements for the ship itself, its detailed characteristics, full machinery and electrical requirements, outfit, accommodations, messing, and decoration.

In addition to these specifications, approximately 30 contract plans and numerous other detail plans were prepared as further guidance to the prospective contractor. These included ship construction, ship arrangements, and plans peculiar to a cable ship, viz., bow sheaves, electronic spaces, jointing room, drum room, etc.

### 1.3 *Opening of Bids and Contract Award*

All of the foregoing bidding data were incorporated as a package unit and transmitted to shipyards in several countries who had expressed a desire to bid on the ship. A period of eight weeks was allowed for the preparation and submittal of the bids to the owner. The contract was awarded to Schlieker Werft of Hamburg, West Germany, who submitted the lowest bid.

Owing to the unfortunate circumstances of bankruptcy proceedings against Schlieker Werft when the ship was about ninety per cent completed, it was taken out of this yard and completed at Deutsche Werft, Hamburg, West Germany.

## II. DESIGN

The design of a special-purpose ship such as a cable ship is complex and requires consideration of many factors not usually encountered in cargo ship design. The discussion that follows has been limited to areas of particular importance in cable operations.

### 2.1 *Selection of Hull Form*

A cable ship must be a stable working platform and have good sea-keeping qualities. It must operate at a variety of speeds and with varying loads. Consequently, considerable attention must be paid to the hull form.

A ship that is to be operated at high speeds is designed with relatively fine lines, while a ship operated at lower speed can have much fuller lines. This is because at low speeds the frictional resistance, which depends on the area of the ship below the water line, is most important, but at higher speeds the wave-making resistance increases in importance; it is desirable to reduce this as much as possible by fining down the ends of the ship. The fineness of a ship is indicated by the block coefficient,[3] which is the volume up to the designed water line divided by the product of the length, beam and draft of the circumscribing block, thus:

$$C_b = \frac{V}{L \times B \times d}$$

where

$V$ = volume of displacement in cubic feet
$L$ = length of ship at load waterline in feet
$B$ = extreme immersed breadth in feet
$d$ = draft of water in feet
$C_b$ = block coefficient (or coefficient of fineness).

The block coefficient is selected fine enough to give a reasonably low resistance when the ship is propelled at the design speed, but high enough to avoid an excessively large and costly ship. In selecting the block coefficient, the speed of the ship considered is not the actual speed but a speed in relation to the length of the ship, namely the design speed divided by the square root of the length. A longer ship can therefore be made fuller than a shorter ship for the same speed.

The heavy weights of the bow sheaves and the cable engines located at the ends of the vessel increase the moment of inertia and have a tendency to increase the pitching motion. This was considered in the development of the lines in order to reduce this adverse effect as much as possible.

### 2.2 *Displacement and Light Ship Weight*[3]

The displacement of a ship is the total weight of the water displaced by the ship, and is equal to the weight of the ship itself (light ship weight) and all weights carried on board. The full load displacement is the light ship weight plus the deadweight. The deadweight is the total of the variable weights on board.

The light ship weight can be divided up into the weight of the hull structure, equipment and outfit, and machinery. In the case of the *Long Lines*, these weights and the deadweight are subdivided as follows:

(1) hull structure, the weight of the steel in the hull;

(2) equipment and outfit, the weight of all joiner work and furniture, all machinery for handling the cable, steering gear, anchors and cable gear, boats and all other equipment needed for operating the ship, including the electric generating plants for the ship's use, and the approximately 62 miles of electric cable in the ship;

(3) machinery, the weight of all machinery and auxiliaries needed for the propulsion of the ship at the required speed; and

(4) deadweight, the weight of the cable, water in cable tanks, spare cable, cable gear (such as buoys, grapnel, rope, etc), crew, stores, fresh water for ship's use, reserve feed water for boilers, and fuel oil for the specified cruising range, part at full speed, part at cable laying speed.

With the exception of the first few items of deadweight that are the owner's requirements, all other weights are interrelated and depend on the size of the vessel. The procedure, therefore, is to select a family of ships of different displacements with proportions and coefficients based on data from other ships. Preliminary rough estimates of the weight of hull, equipment and outfit, horsepower required and weight of machinery and fuel oil for each of these ships are then made. Based on these estimates, dimensions of a hull able to carry the required payload are selected for further consideration. Arrangements are then drawn up to check that sufficient space is available for cable tanks, cable handling, machinery, crew accommodation, etc. Based on these arrangements, additional checks are made of the weight, and adjustments are then made of the dimensions.

### 2.3 *Stability*

In selecting the dimensions of the ship, the operational stability of the ship has to be considered. The stability depends on both the vertical location of the center of gravity of the loaded ship and the beam of the vessel. With a given center of gravity, the beam must be wide enough to avoid excessive heel due to high wind abeam or excessive angles of roll in a seaway. On the other hand the beam must not be too wide, since this may result in an excessively fast period of roll and violent motions when rolling, making it hazardous to move around on the deck.

When the ship is floating upright as shown in Fig. 1(a), the weight of the ship and its contents, $W$, acting downwards through its center of gravity, $G$, is opposed by an equal buoyance force acting upwards through the center of buoyancy, $B$, and the ship is in equilibrium. The buoyancy is the sum of the vertical components of the water pressure acting on the outside of the hull, and is equal to the weight of the water displaced by the ship. The center of buoyancy is the center of gravity of the underwater volume of the ship.

If the ship is heeled over by an external moment, the buoyancy provided by the wedge $A$ in the upright position is replaced by the buoyancy provided by the wedge $A_1$. As a result the center of buoyancy moves from $B$ to $B_1$ and the weight and the buoyancy are no longer in line but provide a couple, $W \cdot \overline{GZ}$, tending to bring the ship back to the upright position, as shown in Fig. 1(b).

The force acting through the center of buoyancy intersects the centerline of the ship at a point $M$. This point is called the metacenter. It is constant for moderate angles of heel at a particular water line.

The location of the metacenter for different drafts depends only on the width and properties of the water line and the displacement at that draft, and can readily be calculated.

Since the stability of the ship depends on the location of the center of gravity in the different loading conditions, careful calculations of the center of gravity of the light ship and all items of deadweight are made in

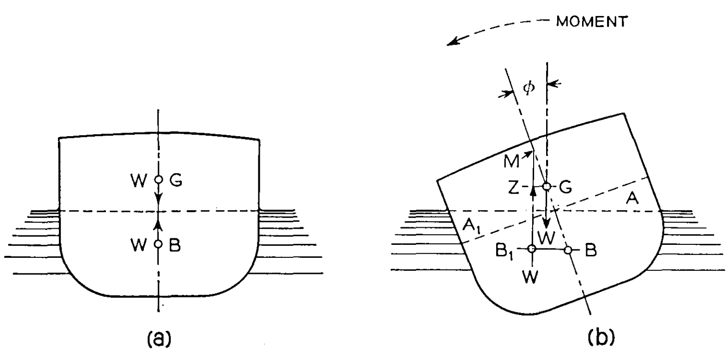


Fig. 1 — Factors affecting stability: (a) equilibrium state; (b) heeling.

order to be able to calculate the center of gravity and the stability for each loading condition.

The freeboard, or the distance between the water line and the deck at side, is also an important factor in the safety of the ship, since it determines the maximum angle of heel the ship can take without losing stability and increasing the chance of capsizing.

The righting moment is $W \cdot \overline{GZ}$ where $\overline{GZ} = \overline{GM} \sin \phi$. $\overline{GM}$ is referred to as the metacentric height, and is a measure of the stability of the ship.

### 2.4 *Model Testing*

When the dimensions and coefficients of the ship have been selected, a preliminary set of lines defining the shape of the hull is drawn, and a scale model of the ship's hull is built for testing.

This model is towed in a tank to determine the resistances of the hull at different speeds. The results of these tests are compared with the results of other model tests to determine that the resistance is reasonably low. Often several sets of lines are tested in order to obtain the best possible lines.

After completion of this towing test for bare hull resistance, the hull is tested with appendages added such as bilge keels* and rudders, and finally a self-propelled test is conducted to determine the interaction of the hull and propeller, the propulsion coefficient, and the actual horsepower required to drive the ship at different speeds.

In order to insure that the flow around the hull is as smooth as possible, especially near the propellers, where an unsatisfactory condition could lead to hull vibrations, the models are frequently tested in a circulating water tank. In this tank the water is moved in a uniform stream at different speeds by large pumps and the model remains stationary. Tufts are attached directly to the hull or to small pins a short distance from the hull. Windows are provided in the side and bottom of the tank, permitting observation of the direction and steadiness of the flow as indicated by the tufts. In addition, small quantities of dye are injected in the water at different points along the hull to indicate the flow. The model is observed both with and without the propeller running at the correct rpm for the relative speed of the ship and water, in order to observe the effect of the propeller on the flow around the model.

For *Long Lines*, preliminary tests for bare hull and appendaged hull

* A bilge keel is a long fin running fore and aft and fitted to the hull, port and starboard sides at the turn of the bilge, to reduce rolling. In the case of the *Long Lines* these bilge keels were designed with a deeper than usual profile and a shorter longitudinal extent in order to minimize resistance and increase damping to effect a steady cable laying platform.

(with bilge keels attached to the hull, bossings and rudders) resistance were conducted at Stevens Institute of Technology using a scale model of wood, approximately five feet long.

In addition to these still water tests, the Stevens Institute Towing Tank conducted tests on the 5-foot model to evaluate the behavior of the ship in waves. Two types of long-crested irregular "seas" were chosen, a moderate sea with a significant height* of 19 feet generated by a 28-knot wind, and a steep sea with a significant height of 28 feet generated by a 33-knot wind. Test conditions were chosen to simulate full-scale operation when laying cable over the stern at slow speeds and repairing cable over the bow at zero speed. For each sea type, ship speeds were varied from zero to 14.6 knots for head seas, zero to 11.6 knots for following seas and zero speed for bow, beam and quartering seas. The model demonstrated superior seakeeping qualities under all conditions, and it was concluded that cable operations could be conducted under all conditions except steep head seas for ship speeds of about 10 knots and above.

On the basis of these test results, final ship lines were chosen for testing at the David Taylor Model Basin, Washington, D.C. Using a larger scale model, about twenty feet long, made of special wax, bare hull and appendaged hull resistance of the ship were tested. Then, with a suitably chosen set of stock propellers, the self-propelled tests were run. The deep water basin where these tests were conducted is 2775 feet long, 51 feet wide and 22 feet deep.

Lines of flow for bilge keel locations were also determined at the David Taylor Model Basin. After completion of the self-propelled test series, the fully appendaged model was checked in the circulating water channel at several displacements and under various operating conditions.

Final model tests were conducted by Schlieker Werft at the Hamburg Model Basin, Hamburg, Germany. These tests were all conducted at the full load displacement of the ship, and comprised an appendaged resistance test with several self-propelled tests. The self-propelled tests employed a series of propellers and formed the basis for the selection of important characteristics of the propellers designed for the ship.

### 2.5 *Inclining Experiment*

When the ship is essentially completed, the calculated light ship weight and the center of gravity of the ship are checked by the shipbuilder by means of an inclining experiment.

* The significant height of a wave system is the average of the highest one-third of the waves which pass during an interval.

The ship is moored in such a way that it floats freely with minimum restraint. The draft of the ship at the draft marks is measured carefully from open boats simultaneously on both sides, forward, aft and midship, and the specific gravity of the water is obtained from samples at several locations along the ship. From this information and the shape of the hull the displacement of the ship in the inclined condition is very accurately determined.

The ship is inclined by moving one or more weights from a location on the centerline of the ship, Fig. 2(a).

The weights are moved to several positions away from the centerline of the ship, first on one side, then on the other, and finally on the centerline. The distance of the weights from the initial position is carefully measured after each movement and the resulting heeling moment $w \cdot x$ (a moment tending to incline the ship away from the upright position) is calculated.[3]

The angles of heel $\phi$ for each position of the weights are obtained by measuring the deviation of three long pendulums in different locations in the ship. The tangents of these angles are plotted against the corresponding heeling moments to keep a check on the consistency of the readings, since theoretically all observed points should fall in a straight line through the origin of coordinates.

If the displacement of the ship is $W$, and the heeling moment is $w \cdot x$, then, from Fig. 2(b)

$$\overline{GG_1} = \frac{wx}{W} = \overline{GM} \tan \phi$$

$$\overline{GM} = \left[ W \left( \frac{\tan \phi}{wx} \right) \right]^{-1}$$

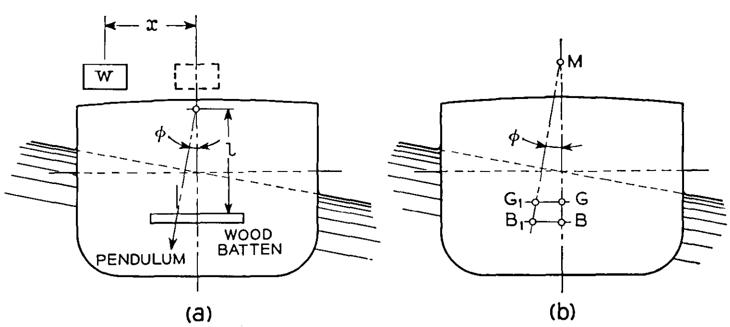


Fig. 2 — Inclining experiments: (a) placement of weights; (b) forces affecting height of center of gravity during heeling.

Taking the average value of ($\tan \phi/wx$) from the plot, the distance $GM$ is calculated. Since the location of the metacenter $M$ for the inclined condition is known, the location of the center of gravity of the ship in the inclined condition can be determined.

At the time of the inclining experiment the ship is completely surveyed, and the weight and location of all items needed to complete the ship is noted. All items aboard the ship not belonging to the light ship weight, such as inclining weights, liquids in tanks, tools, etc., are also recorded. By addition or deduction of the weight and moments of these items from the weight and moments of the ship as inclined, the light ship weight and center of gravity can be calculated.

Based on the inclining experiment, a stability book is prepared giving all information to the Master to enable him to load the ship to insure sufficient stability in all conditions of loading.

### 2.6 *Flooding and Damaged Stability*

The ship is divided into compartments by transverse watertight bulkheads spaced so that if any two adjacent compartments are flooded the ship will not sink. The ship loses stability when flooded, and it is possible that even if the ship would not sink, it could capsize due to insufficient stability or excessive heeling moments due to unsymmetrical flooding. The effect of the flooding of adjacent compartments on the stability of the ship is therefore calculated for different drafts, and the minimum initial stability that the ship requires before damage occurs is obtained. The stability required to prevent capsizing in case of damage of the most critical adjacent compartments for different drafts is tabulated in the stability book, and the ship must meet this requirement in all conditions of loading.

## III. MANEUVERABILITY

Early in the conceptual period of *Long Lines* it was recognized that a high order of maneuverability and precise control of propulsion power were required to permit the full exploitation of the advanced cable handling techniques.

A cable ship should be capable of precise, rapid maneuvering at low speeds, such as is desirable in grappling and coming-up on a buoy, and should be able to maintain accurate station-keeping in adverse sea and weather conditions when standing on a cable. These requirements demand consideration of maneuverability aids and a propulsion system which is easily and rapidly controllable and can provide high propeller torques at low speeds for rapid accelerations. Further, it is desirable that the propulsion plant be readily adaptable to remote control, in order to permit maneuvering the ship for cable handling from the most advantageous position. This approach eliminates the time lag and opportunity for misunderstanding inherent in systems in which orders are communicated through several people to the engine room.

### 3.1 *Maneuverability Aids*

#### 3.1.1 *Number of Screws*

Twin screws versus a single screw were considered and selection was made in favor of twin screws.

#### 3.1.2 *Rudders*

Twin spade rudders were selected and are located in the propeller race. They have an area 50 per cent larger than normally used for merchant vessels, and rudder angles of 45 degrees instead of the usual 35 degrees, thus providing sharper turning angles.

#### 3.1.3 *Bow Jet*

A propeller-driven bow jet was decided upon as an effective aid in maneuvering with the vessel operating at very low speed. The propeller, 5 feet in diameter, is mounted in an athwartship tunnel near the bow and is driven by a reversible dc electric motor through a reduction gear. It is controlled from the wheelhouse and from forward and aft control stations.

## IV. PROPULSION STUDIES

Various propulsion schemes were studied in the light of the ship requirements, and it quickly became apparent that a variable-voltage direct current system provided precisely the requirements desired. Its primary advantages are as follows:

(1) Very large torques (limited by shaft strength to 175 per cent of full load torque) are available at any propeller speed from zero to full speed. This is essential to provide the rapid propeller accelerations and reversals demanded by the precise ship maneuvering requirements. Propeller reversals from full ahead can be accomplished in less than two seconds.

(2) Remote control is easily accomplished by the provision of a simple rheostat and appropriate instrumentation at the remote location.

(3) Propeller speed is smoothly and continuously variable from zero to full in either direction.

(4) The ship will spend a great deal of its life at reduced powers during cable operations; electric drive permits available propulsion prime mover power during these periods to be used for other purposes, such as supplying cable engines and some of the ship's service electric power.

(5) Electric propulsion is inherently flexible, permitting shutdown of unused units during periods of low demand and easy cross-connection in the event of a casualty.

The major disadvantages of dc electric propulsion are its relatively high weight and somewhat low efficiency. The high weight is acceptable in return for the desired operating characteristics. The low efficiency is not very significant in this ship because the low propulsion power of the ship, combined with the high hotel and auxiliary power demand created by the working nature of the vessel, results in the propulsion power being a much smaller percentage of the total ship's power requirements than in most conventional ships. A large portion of the ship's operating time will be at very low propulsion power for cable laying (about one-eighth power), decreasing the importance of high propulsion efficiency.

### 4.1 *Selection of Prime Mover*

Having selected dc electric drive, there remained the question of the type of prime mover to power the generators. After preliminary studies diesel engine and steam turbine prime movers were selected for further study. Their respective advantages are as follows:

(1) Advantages of the diesel engine
- (a) lower first cost,
- (b) lower weight of fuel required,
- (c) lower machinery weight,
- (d) lower amount of fresh water required, and
- (e) smaller machinery spaces.

(2) Advantages of the steam turbine:
- (a) lower operating fuel costs,
- (b) lower maintenance and repair costs,
- (c) increased reliability,
- (d) less noise and vibration, and
- (e) the large number of seagoing licensed marine steam engineers available.

### 4.2 *Final Selection of Propulsion Plant Drive*

After consideration of all the facts, such as the heavy work schedule for the new cable ship, limited availability of licensed marine diesel engineers, reliability and minimum time out for maintenance and repair, and the problem of noise and vibration in the engine room and crew quarters, it was concluded that the propulsion plant drive should be of the steam turbine type.

TABLE I — PRINCIPAL CHARACTERISTICS OF C.S. "LONG LINES"

| | |
|---|---|
| Length over-all | 511′-6″ |
| Beam | 69′-6″ |
| Load draft | 26′-9″ |
| Horsepower normal, total | 7700 shp |
| Sustained sea speed | 15 knots |
| Cable capacity ($1\frac{1}{4}$″ dia. cable) | 2000 nm |

## V. OVER-ALL DESCRIPTION OF SHIP

The principal characteristics of the *Long Lines* are given in Table I. The hull is all steel and is designed with transverse framing except for

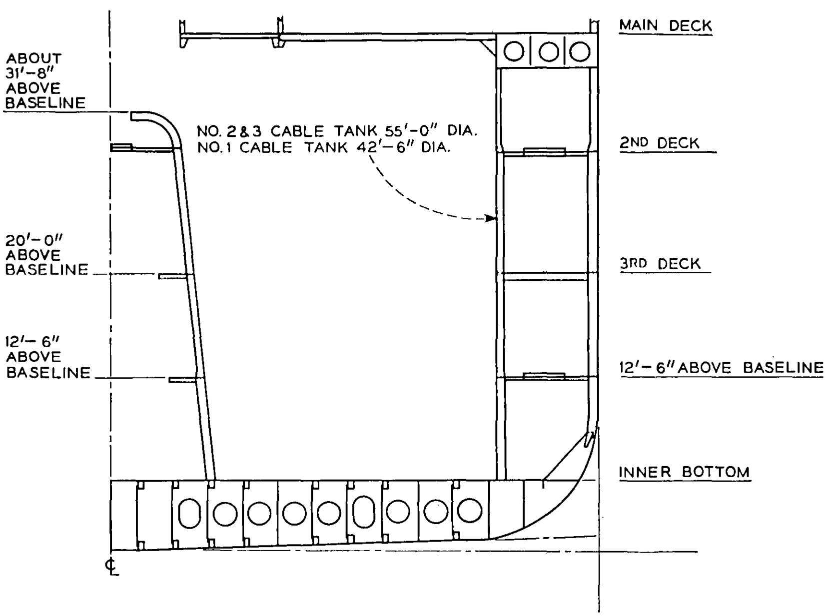


Fig. 3 — Typical cross section in way of cable tanks.

the inner bottom and bottom shell, which are framed longitudinally. It is of welded construction throughout except for certain shell seams and deck edge connections which are riveted. The shell is strengthened for navigation in ice. The propeller shafts also include an allowance for ice strengthening.

The three large-diameter cable tanks are located forward of the machinery spaces and provide approximately 138,500 cubic feet of space for cable storage. They are fitted with watertight cones and also with recesses for cable bights[1] at the forward end which extend for the full depth of the tanks. Fig. 3 shows the cable tank construction.

Ship service electric power and power for the linear cable engine are furnished by four ac generators, two driven by the propulsion turbines and two driven by independent steam turbines. Emergency service electric power is furnished by a diesel engine-driven ac generator set. Electric power for the bow cable engines is furnished by two dc generators driven by the propulsion turbines.

A helicopter deck, with its own lighting and with special safety rails around its periphery, is located at the aft end of the houses.

All joiner work throughout the ship, linings, bulkheads and ceilings, is of incombustible construction. Incombustible furniture and fire-resistant draperies, portieres, bedspreads, etc., are installed throughout as far as possible. All living accommodations, offices, lounges, wheelhouse, chartroom, radio room, and the principal working spaces are air-conditioned for personnel comfort and to provide a good environment for the large amount of electronic equipment.

A general arrangement of the decks is shown in Fig. 4.

## VI. PROPULSION PLANT

The propulsion machinery is of the twin screw, steam turbine, direct current electric drive type.

### 6.1 *Design Conditions*

Design conditions for the propulsion plant are given in Table II. The layout of the main machinery spaces is shown in Fig. 5.

### 6.2 *Generator Train and Propulsion Motors*

Each generator train is driven through a single reduction gear by a 5000-hp steam turbine. Each train consists of the following, all driven in tandem at a constant 900 rpm by the propulsion turbine (see also Fig. 6):

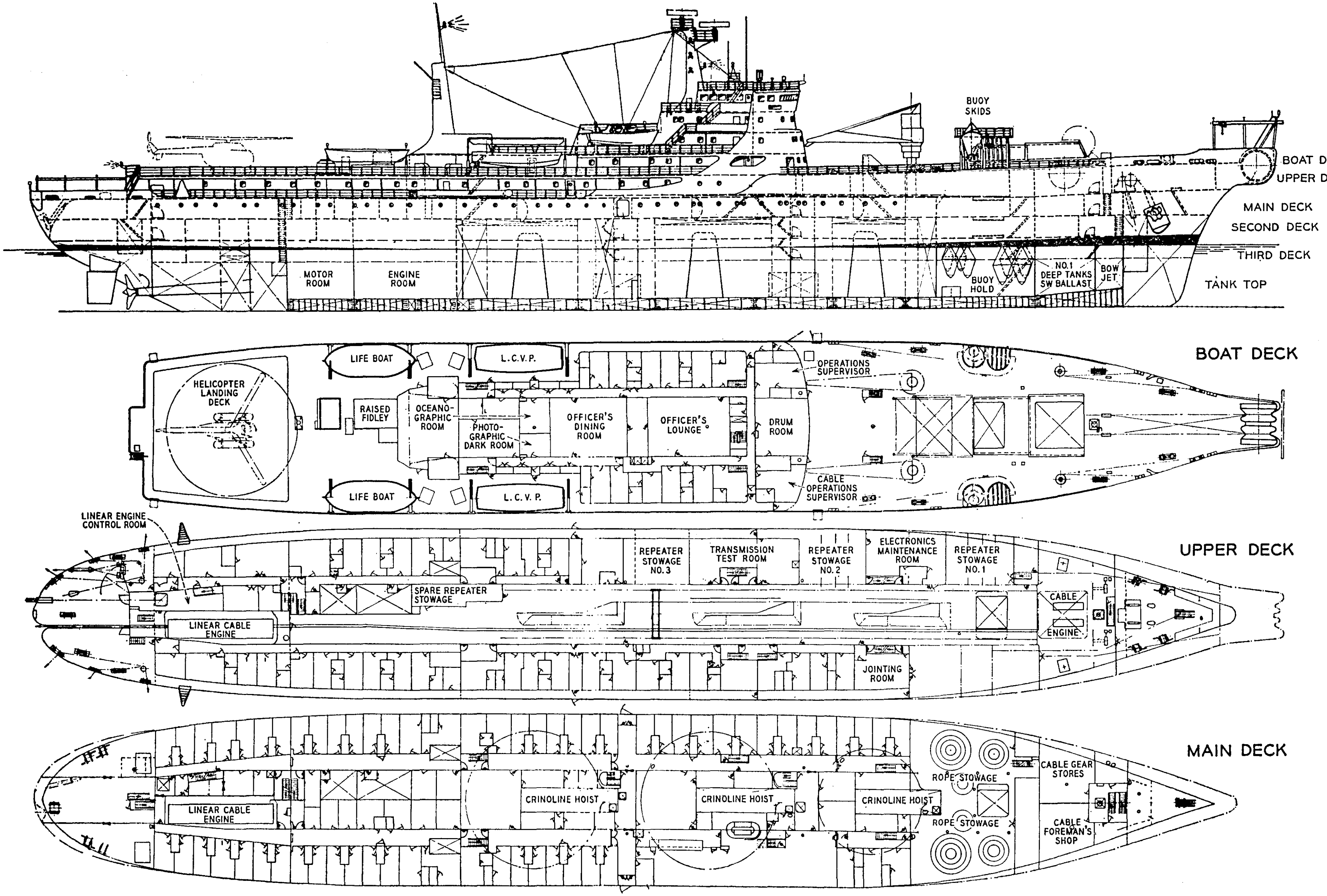


Fig. 4 — General arrangement of decks.

TABLE II — PROPULSION MACHINERY DESIGN CONDITIONS

| | |
|---|---|
| Shaft horsepower — normal, each shaft | 3,850 |
| Shaft horsepower — normal, total | 7,700 |
| Shaft horsepower — maximum, each shaft | 4,250 |
| Shaft horsepower — maximum, total | 8,500 |
| Sustained sea speed (at 80 per cent of normal power at full load draft) | 15 knots |
| Steam conditions at boiler superheater outlet | 600 psig — 850°F |
| Full fuel capacity (half cruising at full power 15 knots and half cruising 7.5 knots) | 14,350 nm |

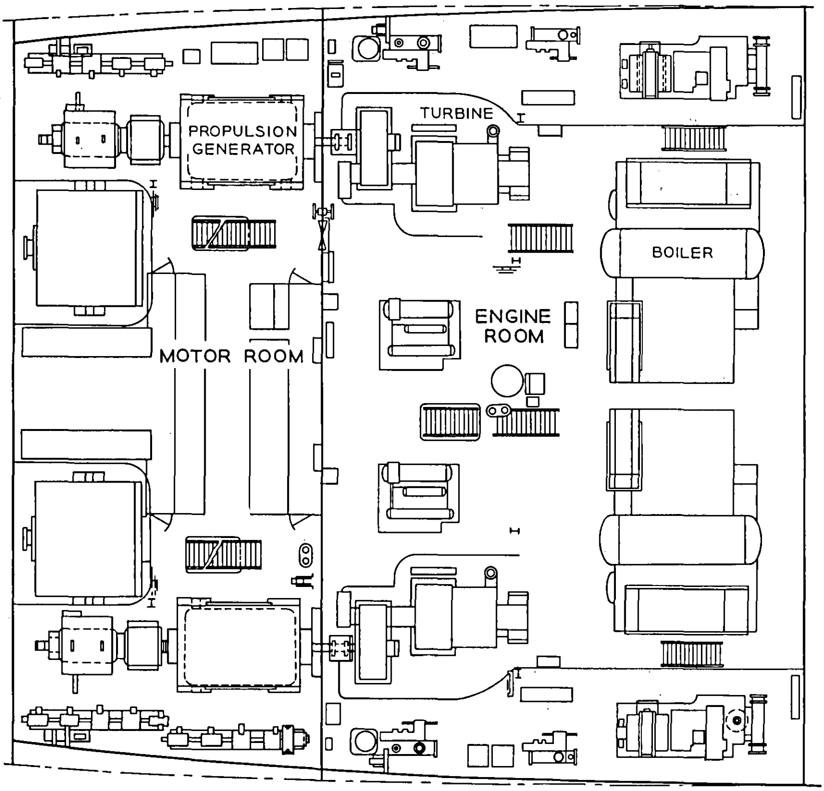


Fig. 5 — Layout of main machinery spaces.

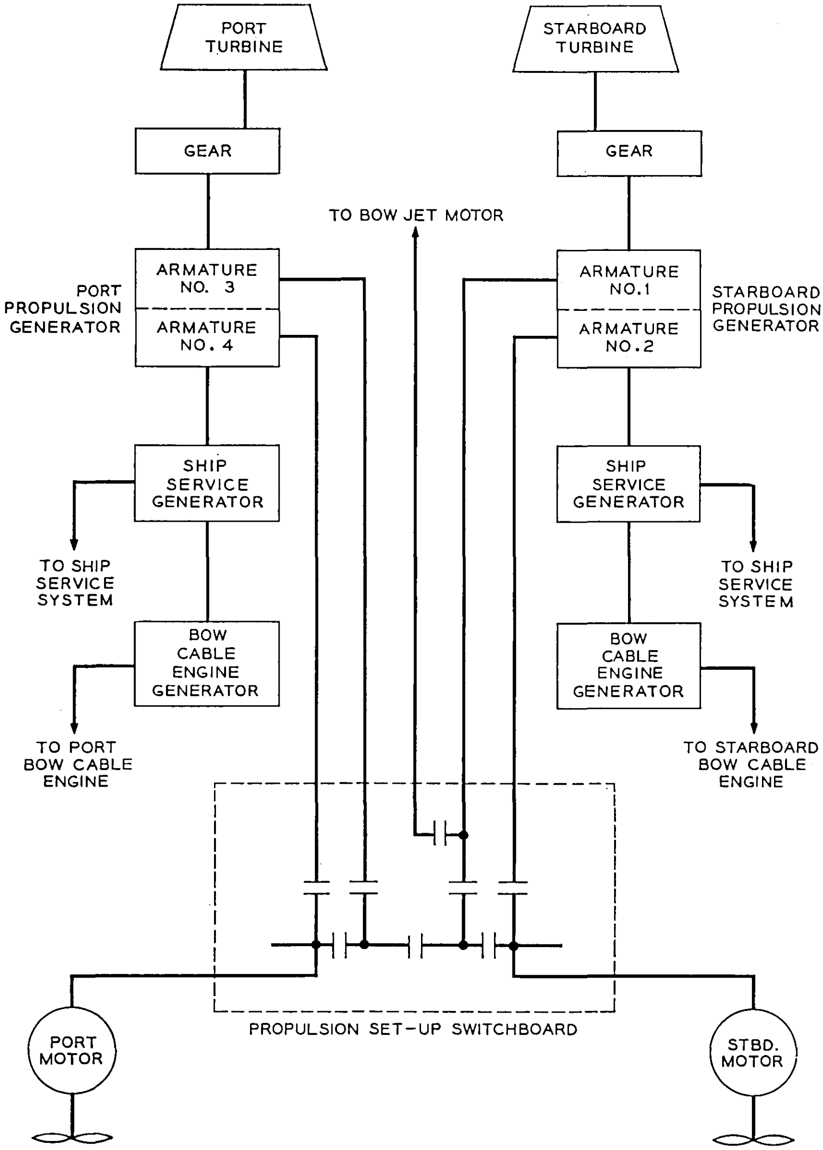


Fig. 6 — Generator train.

6.2.1 *DC Main Propulsion Generators*

The two armatures in each generator are completely independent electrically. The generator is totally enclosed, water cooled and force ventilated by a separately driven cooling blower.

6.2.2 *Ship Service Generators — 3-phase ac*

The machine is open and air cooled. This generator can be utilized to supply some of the ship's service power during periods when the ship is not operating at full propulsion power.

6.2.3 *Bow Cable Engine Generators*

This generator, rated 480 kw, 800 amperes at 600 volts, is totally enclosed, water cooled, and force ventilated by a separately powered 3-hp blower. Because of the infrequent service it is also provided with an externally operable brush-lifting device to lift the brushes off the commutator when the generator is not in use.

6.2.4 *Propulsion Motors*

Each propulsion motor is rated 4250 horsepower at 135 rpm. It is separately excited, with field weakening to reach 147 rpm in order to utilize full available power in the light ship condition. The motors are totally enclosed, water cooled and force ventilated by a separately powered 30-hp blower.

6.2.5 *Cooling of Units*

All propulsion motors and generators are kept slightly pressurized by means of a small make-up air fan. This fan supplies clean, electrostatically filtered air to the inside of the machines and maintains a slight positive pressure so that any leakage will be out of the machine. Thus the machine interiors are protected from engine room air contaminants.

6.2.6 *Control and Switching*

The basic principle of control is motor speed control by variable armature voltage with constant motor field. The manually operated speed control rheostat works in a control field of an amplidyne, the output of which supplies generator excitation. Since generator speed is held constant, this varies armature voltage, thus controlling motor speed. The system is speed regulated by means of generator output voltage feedback, and current and power limiting controls are incorporated to prevent overstressing or overloading the mechanical portions of the system. In addition, the necessary switching, interlocks and safety devices are incorporated in the control to take advantage of the flexibility available, yet prevent malfunction. One of the switching arrangements provides the ability to connect one of the propulsion armatures to the bow jet motor, thus providing 750 hp to the bow jet without the need for a separate generator. The control components and switchgear are contained in a propulsion set-up switchboard and a propulsion control console, both located in the motor room. In addition, there are propulsion control consoles in the bow of the ship, near the bow sheaves; in the wheelhouse, port, centerline and starboard; and in the stern of the ship, in view of the overboarding chute.

### 6.3 *Main Turbines*

The main turbines are of the high-speed, single-casing type and are connected to the main reduction gears through a flexible mechanical dental-type coupling. The port and starboard turbines are identical and have the same rotation. The turbines are designed to deliver the normal rated horsepower at the point of best economy with initial steam condition at the turbine throttle of 585 psig and 840°F total temperature and a vacuum of 28.5 inches Hg at the exhaust. The turbines are also designed for uncontrolled bleed steam for feedwater heating, boiler combustion air heating and other purposes.

### 6.4 *Reduction Gears*

The reduction gears are of the single-reduction, double-helical type, arranged to allow the main condensers to be mounted athwartship under the turbine.

### 6.5 *Shafting*

The shafts are solid forged steel, American Bureau of Shipping Grade No. 2 material.

## VII. ENGINE AND MOTOR ROOM AUXILIARIES

### 7.1 *Distilling Plant*

Since the ship will be at sea for long periods of time, all the fresh water required on board is produced by two complete sea water distilling plants of the flash type. Each distilling plant is designed to meet the fresh water purity requirements of the United States Public Health Service, and each unit has a capacity of 12,000 gallons per day of fresh water of potable quality. One distilling plant can provide all the fresh water requirements for drinking water, hot and cold washing water, hot and cold fresh water for galley and pantry service (cooking and dishwashing), laundries, and make-up water for the boilers.

### 7.2 *Boilers*

Two natural circulation water tube boilers are installed, and each boiler is of the bent tube, oil-fired, single-furnace, single-uptake, air-encased type with water-walled furnaces. Each boiler is fitted with double-cavity, walk-in type superheaters, economizers, steam air heater and submerged internal type desuperheaters installed in the steam drum. These boilers produce superheated steam at 600 psig, 850°F at the superheater outlet.

The boilers are fitted with steam-mechanical atomizing fuel oil burners suitable for use with the automatic combustion control system. These burners combine the features of steam and mechanical fuel oil atomization. The system is unique in that the burners are used in two ways. They provide straight mechanical atomization (no steam assistance) of the fuel burned when the ship is operating at full power. In addition, they function as a steam atomizing burner (steam assisting in the atomization of the fuel oil) at low steaming rates, as during periods of reduced propulsion steam demands (cable laying and cable repair). This second function results in reduced fuel consumption when the straight mechanical atomizing efficiency falls. The primary advantage of the steam-mechanical atomizer is that good combustion efficiency over a wide range of operation is obtained with minimum steam consumption and a low fuel oil system operating pressure. The importance of wide-range burners may be appreciated when considering that the ship will operate for extended periods at light steaming loads, as during cable laying, cable repairing, maneuvering and in-port operation. These burners also have the advantage that the furnace can be kept clean under low steam demand operation of the vessel, because more efficient steam atomization of the oil results in more complete combustion.

The boilers are fitted with a pneumatic-type automatic combustion control system designed to maintain constant superheater outlet pressure. The combustion control system attains maximum fuel economy by maintaining the boiler steam pressure and temperature at the highest design conditions by controlling the quantity of oil and air being delivered to the boiler in the proper ratio to maintain maximum combustion efficiency. Maintaining the proper steam pressure and temperature insures maximum turbine performance. The control system will follow the fluctuations in the boiler loads due to changes in the ship's speed or electrical load changes, at the same time maintaining maximum fuel economy with a minimum of smoke.

## VIII. SHIP'S SERVICE REFRIGERATION MACHINERY

A ship's service refrigeration system is provided and designed for the direct expansion of Freon 12 gas. Since the ship will be at sea for long periods of time, approximately 8000 cubic feet of refrigerated stores have been provided.

## IX. PIPING

All piping installed in the ship was designed to meet the highest marine piping standards used in the U.S.A. Corrosion-resistant materials were used to reduce maintenance and repair costs and to obtain long life in service. All piping carrying sea water is of 90-10 copper-nickel alloy. This alloy is very resistant to the corrosion-erosion effect of sea water. Stainless steel has been used in many of the other piping systems. There are approximately 12 miles of piping installed in the *Long Lines.*

## X. SAFETY AIDS

### 10.1 *Watertight Doors, Firescreen Doors*

Five watertight horizontal sliding doors have been installed at vantage points in some bulkheads to maintain the watertight integrity of the ship. These doors, normally open, are electrically operated and can be controlled collectively or individually from the wheelhouse. There are local door controls on both sides of each door.

Approximately 48 firescreen doors, normally held open by magnet control, can be operated from the wheelhouse and locally; about 30 more firescreen doors, normally closed, are operated locally. All of these are installed in the firescreen bulkheads for protection against fire.

### 10.2 *Fire Detection System*

A thermostatic detection system is provided to sound an alarm in the event of a fire. Detectors are installed in all public spaces, lockers, holds and similar unattended spaces. Manually operated alarm boxes are provided in all fire zones in readily accessible locations. An annunciator panel, which indicates the area originating an alarm, is installed in the wheelhouse, and alarm bells are provided in the wheelhouse, engine room and quarters of the firefighting crew.

### 10.3 *Firefighting Systems — General*

The vessel is equipped with the following firefighting systems:

(1) sea water extinguishing system for use in fighting fires in ordinary combustible materials, such as dunnage, canvas, wood, etc,

(2) carbon dioxide extinguishing systems and liquid foam extinguishing systems for use in fighting fires in substances such as gasoline, oils, etc., and fires in live electrical equipment, and

(3) steam smothering extinguishing system for limited use in fighting fires in substances such as fuel and diesel oil.

## XI. BOW SHEAVES

An assembly of three roller-bearing bow sheaves is mounted in the overhang of the stem and enclosed within a supporting structure fairing into the forward body of the ship. The center sheave has a diameter of 11 feet, and the two outboard sheaves are each 10 feet in diameter at the root. The ring and hub of each sheave is of cast steel, and the sheave body is made up of steel weldments. The shafting is in three sections of different diameters to permit easy installation and removal. Automatic lubrication for the bearings has been provided.

For handling forward, a monorail and hoist have been provided extending over the bow sheaves. This is an impressive looking structure, since it includes a frame of heavy scantlings for overboarding repeaters at the bow. The frame can be fitted with a vinyl-coated nylon fabric covering for protection in severe weather.

## XII. STERN CHUTE

Instead of a conventional sheave at the stern, a stern chute has been employed. This chute is located to starboard of the centerline of the ship and is formed by a 16-inch wide indent in the upper deck plating at the extreme aft end. This indent gradually falls away and fairs into the shell plating at the stern.

XIII. ALUMINUM ROLLING HATCH

A power operated aluminum rolling hatch about 50 feet long and constructed of two nesting sections is located over the bow cable engines. This construction coupled with rolling end flaps, also power operated, permits continuous bow cable operations in adverse weather.

XIV. SPECIAL STOWAGE

Stowages for various types of apparatus and equipment peculiar to the functions of cable laying have been provided and are located at vantage points throughout the ship.

Buoys are stowed in a large hold, two decks high, located forward of the cable tanks. This stowage is conveniently arranged so that the buoys can be transferred by a minimum amount of handling with a monorail and hoist device into the center of the hold; the hoist device picks up each buoy from its stowage position and, through a self-releasing hook, transfers the buoy to the deck crane hoist and from there to its "ready" stowage on the port or starboard buoy skids, or directly overboard. These buoy skids have been especially designed with overhead platforms to facilitate control in launching and positioning the buoys.

Stowages for grapnels, mushroom anchors and similar heavy equipment, together with chains and buoy rope, are located in the same hold as the buoys, but in the two tween decks directly above the buoy stowage. The chain is stowed in bins having a raised floor in portable sections, all to permit easy maintenance. Chain pipes are installed port and starboard, extending from the upper deck to the stowage on the third deck. By means of swiveling devices at the lower ends of these chain pipes, the chain can be run direct into each of the seven chain stowage compartments.

A total of four tanks, each 20 feet in diameter by 10.5 feet high, for the stowage of spare cable, are installed on the tank top level, port and starboard, between the main cable tanks. Twelve circular steel bins, all 4 feet high but of diameters varying from 4 to 16 feet, are provided for grapnel rope stowage. New rope is stowed on one side of the ship and used rope on the other side.

XV. NAVIGATION EQUIPMENT

In considering the nature of the mission of the *Long Lines*, it becomes apparent that it is of utmost importance that navigational facilities be provided that will determine the ship's location with the maximum possible accuracy at all times during cable laying or pick-up and repair operations.

Standard radio direction finding equipment, as required for certification by the United States Coast Guard, has been provided for taking fixes on land-based telegraph stations and beacons and on other ships at sea.

Loran equipment installed is of the latest type, known as Loran "C." This system provides greater range and greater accuracy than the standard Loran "A". It also has Loran "A" capabilities built-in for use in areas where Loran "C" signals are not available.

Decca Navigator equipment is installed in the chartroom. This equipment, operating in an area of Decca signal coverage, provides a continuous instantaneous indication that will give the ship's location by reference to Decca charts.

Two Decca true-motion radar sets are installed with indicators in the wheelhouse. True-motion presentation shows a fixed geographic area on the indicator with all moving objects, including own ship, moving across the displayed area, making it easier to plot vessel speeds, approach paths, etc., than is possible on the standard relative motion display. One radar, operating on a 10-cm wavelength, is superior at long range and in penetrating adverse weather conditions. The other radar is a 3-cm set that exhibits superior qualities in close navigation, as in rivers, harbors, buoyed channels and in close proximity to other vessels.

In order to provide correlation with charted depths and to furnish accurate depth information regarding a cable lay, two echo depth sounders are installed. Each sounder is provided with alternate transducers, one set forward and one aft. Kelvin-Hughes sounding equipment is provided in the chartroom for navigational purposes, and a duplicate indicator is installed in the drum room. The second echo sounder, located in the drum room, is an EDO instrument. In addition to the two echo depth sounders, there is a Westrex Model XV Precision Depth Recorder that is capable of extremely accurate depth recordings in conjunction with either the Kelvin-Hughes or EDO equipment in either the drum room or chartroom.

In addition to the foregoing, there is a standard Sperry Gyro Compass system. Steering control may be manual or by gyro pilot, using either of the dual controls in the wheelhouse, or manual from the bow or stern ship control console or, in emergency, from the trick wheels in the steering gear room.

A Pitometer Log is provided for showing the ship speed in the chartroom and wheelhouse and the draft of the vessel in the wheelhouse. A Chernikeeff Log System is provided to show ship speed in the drum room and to furnish input of ship speed to the true-motion radars.

## XVI. EXTERIOR COMMUNICATION FACILITIES

A standard radiotelegraph installation has been installed for ship-to-shore and ship-to-ship communications, as is customary on all vessels of this size.

In addition, to provide optimum communications between the ship and the shore stations during her long periods at sea, a 5-kw single-sideband transmitter has been provided. As a back-up for this unit, and for use when maximum power is not required, a 1-kw single-sideband transmitter is provided. Compatible receiving equipment is installed, and interconnecting facilities are provided to permit use of the radiotelephone equipment from selected stations of the ship's automatic telephone system.

Low-power radiotelephone equipment is provided for use in harbor communications and VHF frequency-modulated units are provided for communication with the cable work boats or for communication with similarly equipped stations on other ships or on shore.

## XVII. INTERIOR COMMUNICATION FACILITIES

Communication between key stations for ship operation is provided by sound-powered telephone, since the Coast Guard requires that such communication be independent of any other system on the ship. Normal communications facilities are provided by an automatic dial telephone system of latest design which incorporates private tie-lines between selected points in addition to dialing facilities.

Two public address systems are provided, one for general ship's use and the other for communication between functional stations of the cable operations system.

## XVIII. SHIP'S ILLUMINATION

Conventional marine illumination standards, as set forth in the Illuminating Engineering Society's "Recommended Practice for Marine Lighting,"[4] were applied to all interior living spaces, work spaces, machinery compartments and exterior areas. The standards were modified to provide special illumination treatment to suit the function of each area, since it was important that good lighting always be available.

Recreation, berthing, messing and office spaces were illuminated to a standard employed for first-class passenger ships.

The floodlight installation on the forward open deck was designed to facilitate cable handling operations at night and includes special fixtures to illuminate the exposed cable from the deck to the water surface.

## XIX. SEA TRIALS

On March 6, 1963, C.S. *Long Lines* sailed from Hamburg to the North Sea for sea trials, and returned on March 12, 1963.

These trials included the usual proving of all systems: speed and economy trials; the adequacy of the control system under all conditions of operation; steering and maneuvering tests, including ahead and astern steering, Z maneuvers and turning circles; and special steering trials to determine the maneuverability of the ship when laying and repairing cable.

All the trials and tests were successfully conducted and the ship was remarkably steady and free from vibration.

## APPENDIX A

Various agencies whose regulations were required to be met in the construction and installation of all parts, equipment and outfit of C.S. *Long Lines*, include the following:

(1) American Bureau of Shipping to the highest class,

(2) United States Coast Guard,

(3) United States Public Health Service,

(4) Federal Communications Commission,

(5) United States Customs,

(6) Panama Canal Company,

(7) Suez Canal Authorities, and

(8) International Convention for the Safety of Life at Sea, London, 1948.

In addition to the foregoing, it was required that the recommended methods, materials and practices contained in the latest issue of the following published standards be followed in the construction of the ship:

(1) American Institute of Electrical Engineers, Standard No. 45,

(2) American Standard Safety Code for Elevators, Dumb-waiters and Escalators,

(3) American Bureau of Shipping recommendations for reducing stress concentration at keyways in propeller shafts,

(4) Code of Recommended Precautions Against Accidents connected with the loading and unloading of Merchant Vessels,

(5) American Society of Refrigerating Engineers Recommended Practice for Shipboard Installation, and

(6) Society of Naval Architects and Marine Engineers Ship Trials and Test Codes.

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# Contributors to This Issue

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MILES W. BOWKER, Bell Telephone Laboratories, 1940—. Mr. Bowker's early work was concerned with the development of outside plant apparatus, construction methods, and maintenance methods. This work included the development of the first solderless splice for polyethylene insulated coaxial cable and the original feasibility studies on the use of gas pressure in the exchange plant. From 1956 to 1960, he contributed to the design of, and the manufacturing feasibility studies for, the armorless ocean cable. From 1960 to 1963, he was concerned with the fabrication and placing methods for experimental circular waveguide. Currently, he is involved in analytical and experimental engineering mechanics studies covering a variety of problems, including infrared transmission, heat transfer, servomechanisms, statics and dynamics, and nuclear weapon effects.

S. THEODORE BREWER, B.S. in E.E., 1937, M.S. in E., 1938, Purdue University, Bell Telephone Laboratories, 1937—. In his early assignments, he contributed to the development of broadband coaxial systems and video feedback amplifiers, including the design of measuring equipment associated with these developments. Later, he was concerned with electronically controlled automatic switching. He holds patents on control and feedback systems, switching networks, and repeater circuits. In the SD system development, he was in charge of a group responsible for the electrical design of the undersea repeater. Currently, he is in charge of the repeater circuit design for a high-capacity transistor submarine cable system. During World War II, he served as radar staff officer with the 62nd Fighter Wing. Member, IEEE, Eta Kappa Nu, Tau Beta Pi and Sigma Xi.

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R. D. EHRBAR, B.S.E.E., 1937, Johns Hopkins University; Bell Telephone Laboratories, 1937—. He first worked on K and L-type carrier equipment. During World War II he participated in the development of various airborne radar systems. After the war he worked on development of the L3 coaxial cable system. In 1955 he became Head, Submarine Cable Systems Department, and has since been associated with various submarine cable projects. Senior member, IEEE.

JOHN M. FRASER, B.S. in E.E., 1945, Polytechnic Institute of Brooklyn; Bell Telephone Laboratories, 1934—. His early work dealt with the design and evaluation of communication systems for both the military and the Bell System. Since then he has been engaged in transmission system engineering on a variety of carrier systems, including submarine cable systems. He is currently responsible for a group working on a new

TASI, the SD submarine cable, and new terminals to improve high-frequency overseas radio transmission. Senior member, IEEE; member, Sigma Xi, Tau Beta Pi and Eta Kappa Nu.

R. W. Gretter, S.B. in M.E., 1950, S.M. in M.E. 1951, Mech. E. 1953, and Sc.D. in M.E. 1956, Massachusetts Institute of Technology; Bell Telephone Laboratories 1955—. Initially Mr. Gretter did analytical work in cable mechanics. This was followed by participation in the development of cable machinery for C.S. *Long Lines*. He now supervises a group which is responsible for cable handling equipment and for some aspects of the submarine cable burier. He is a licensed professional engineer and a member of Pi Tau Sigma, Tau Beta Pi and Sigma Xi.

O. D. Grismore, B.S.E.E., 1927, Purdue University; American Telephone and Telegraph Co., 1927–1934; Bell Telephone Laboratories, 1934—. He first worked on field measurements of inductive interference from power systems and electrical railways; following this he became concerned with field trial installations and equalization studies of coaxial carrier systems. During World War II he worked on weapons, high-altitude radar bombing, and field studies of radar target identification. After the war he resumed work on coaxial carrier systems. His work with submarine cable systems started with the transmission aspects of cable manufacture and has continued in cable handling operations on cable ships. Registered professional engineer; member, Eta Kappa Nu and Tau Beta Pi.

V. Lyman Holdaway, B.S., 1929, M.S., 1930, California Institute of Technology; Bell Telephone Laboratories, 1930—. He was first engaged in the development of a family of mercury vapor rectifier tubes for radio transmitters and public address systems. This was followed by work on the development of a series of thyratron tubes for telephone power plants. During World War II, he worked on medium-voltage temperature-free thyratrons for use in gun directors and military communications systems and on ruggedized miniature cold cathode tubes for use in magnetic mines laid from aircraft. Later work was concerned with cold cathode tubes for telephone plants. These included multi-element tubes for selective ringing, voltage reference and regulator tubes, and the talking-path diode for the first electronic switching system (Morris, Ill.). He was also active in the renovation of the safety organization of Bell Laboratories. More recently his work was centered on gas tubes for the protection of submarine cable systems, and his latest assignment is in the field of gas masers. He holds nine Bell System patents, is a member of IEEE and Sigma Xi, and is a registered professional engineer of the State of New York.

Sven G. Johansson, B.S. in E.E. 1924, Tekniska Gymnasiet, Orebro, Sweden. Mr. Johansson joined the Western Electric Company Engineer of Manufacture Organization at Kearny, New Jersey, in 1929. After various assignments in the physical electrical laboratory, design of electrical testing equipment, and crystal unit manufacturing planning, he was promoted to Department Chief in charge of Microwave Electron Tube Engineering at Western Electric, Allentown Works, in 1947. In 1953 he was assigned to Hillside, New Jersey, as Engineering Department Chief on flexible submarine cable repeaters. In 1959 he was promoted to his present position, Assistant Superintendent in charge of engineering organizations for manufacture of flexible and rigid submarine cable repeaters at the Western Electric Hillside and Clark, N.J., shops. Member, IEEE.

R. A. Kelley, B.S.E.E., 1947, and M.S.E.E., 1948, Purdue University; Eastman Kodak 1948–1950; Bell Telephone Laboratories, 1950—. After working on the L3 coaxial system, Mr. Kelley was concerned with the development of broadband submarine cable systems, including the system design and repeater circuitry for the SD System. He is now Director, Digital Transmission Laboratory. Member, IEEE, Tau Beta Pi, Eta Kappa Nu and Sigma Xi.

Brooke W. Lerch, B.S. in M.E., University of Michigan, 1931; Western Electric Company, Inc., 1937—. Mr. Lerch's first assignments at the Baltimore Works of Western Electric Co. were textile applications and rubber extrusion for drop and station wires. During World War II he was the engineering department chief at the Western Electric Scranton, Pa. shops, engaged in design and production of cords and field cables for the armed forces. Returning to Baltimore Works, Mr. Lerch's assignments were concerned with outside plant wires and cords. Later, he became Assistant Superintendent, Toll and PIC Exchange Cable. In 1961 his duties included ocean cable engineering and inspection. Member, Wire Association.

Robert J. McSweeney, B.S., Stevens Institute of Technology, 1954, Gibbs & Cox, 1954—. He was originally involved in analysis of propulsion systems for naval vessels and was responsible for purchase specification preparation and subsequent technical evaluation of resultant proposals. He is at present responsible, with others, for the design of complete shipboard electric power systems. In connection with C.S. *Long Lines*, he was responsible for the preliminary and detailed design of the electric propulsion system, including coordination of the drive characteristics with the dynamics of the ship-propeller-water system and the boiler-steam-turbine cycle. He maintained liaison with the shipyard during and after construction, and organized, directed, and analyzed the main propulsion system sea trials.

L. H. Morris, B.S.E.E., 1935, City College of New York; Bell Telephone Laboratories, 1928—. He has worked on coaxial cable systems from the early one-megacycle trial systems through the L3 system, and on the TH microwave radio relay system. Since 1959 he has headed a department responsible for system and terminal aspects of various submarine cable projects.

Samuel Mottel, B.S.M.E., 1950, City College of New York, Bell Telephone Laboratories, 1952—. Mr. Mottel has been concerned with power equipment and systems development since joining the Laboratories. He has worked on power for carrier systems, microwave systems, Bell System and military submarine cable systems, data systems and various military communications systems. Since 1963 he has supervised a group working in systems power equipment development areas. Member, A.S.M.E.

Elliott T. Mottram, B.S.M.E., 1928, Columbia University; Bell Telephone Laboratories 1928—. His early work was in development of disc recording and reproducing equipment and techniques. Later he was concerned with development related to recording and reproducing sound on film and on tape. During, and for a short time after, World War II (1939–50) he was engaged in development of airborne radio and radar equipment, electronic computers and bomb sights, and airborne homing missiles. In 1950 he became Director of Transmission Systems Development with responsibility for development of television, wire and military communication systems. This included submarine cable development, which has occupied an increasing proportion of his interest as new systems have been developed and laid. Member, IEEE.

Wendell G. Nutt, B.S.M.E., 1949, Texas Technological College; Southwestern Bell Telephone Co. 1949–1953; Bell Telephone Laboratories, 1953—. At Bell Laboratories he first worked on gas pressure maintenance and splicing of multipair cables. Next he was concerned with the development of armorless ocean cable and with waveguide for the circular electric mode. He is currently supervisor of a group concerned with the development of broadband multicoaxial cables for land routes. Member, Tau Beta Pi, Kappa Mu Epsilon and Alpha Chi.

James W. Phelps, B.S.E.E., Iowa State University, 1951; Bell Telephone Laboratories, 1951—. His early work was in the design and specification of electrical protection systems. In 1956 he transferred to a group responsible for the design and development of armorless ocean cable. He headed the group responsible for the operation of the experimental cable laboratory in Cambridge, Massachusetts, where the early cable samples were produced. At present he supervises a group working on a new cable structure for broadband use. Member, Tau Beta Pi and Eta Kappa Nu.

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Philip W. Rounds, A.B., 1929, Harvard University; Bell Telephone Laboratories, 1929—. Prior to World War II, Mr. Rounds was concerned with the development of transmission networks for toll telephone, telephoto and program systems. During the war he developed computing networks for antiaircraft gun directors and bombsights, as well as transmission networks for sonar systems. He has since worked on the development of transmission networks for television systems and more recently the development of submarine cable systems. Member, IEEE.

Laurus E. Sutton, III, M.E., 1948, Stevens Institute of Technology; graduate study, Stevens Institute of Technology, Columbia University and Massachusetts Institute of Technology; Gibbs and Cox, Inc., 1948—. He has worked on the design of various experimental naval craft, including hydrofoil research craft, and commercial ship design. He is presently head of the scientific section of the electrical division of Gibbs and Cox, Inc. Member, IEEE and American Ordnance Association.

WILBUR VAN HASTE, B.S.E.E., 1936, New York University; Bell Telephone Laboratories, 1928—. He has been concerned with the design and development of grid-controlled electron tubes for use in a wide variety of Bell System communication projects. These include tubes for open wire, coaxial cable, microwave, and submarine cable systems. He presently supervises a group responsible for the final design and acceptability of tubes for SD submarine cable systems. Senior member, IEEE; member, Iota Alpha.

CHARLES A. VON ROESGEN, Dipl. Ing., 1952, Swiss Federal Institute of Technology, Zurich (Switzerland); Bell Telephone Laboratories 1953—. He first worked on the development of cables for submarine use; following that he engaged in automatic transmission test equipment design. In 1960 he became a supervisor of a group concerned with the development of the SD repeater. At present, Mr. von Roesgen is responsible for the design of new submarine cable terminal equipment. Member, IEEE.

EDWARD J. WALSH, Bell Telephone Laboratories, 1928—. He has chiefly been engaged in the mechanical design of electron tube structures and enclosures, including the design during World War II of proximity fuse tubes and the thermally tuned klystron, and later of the frame-grid tubes used in microwave radio relay systems. More recently he has supervised a group responsible for mechanical design of electron tubes for the SD submarine cable system; he is presently in charge of a group working on structures for the gaseous optical maser, photomultipliers, and other electron devices.

# B. S. T. J. BRIEFS

## A Lens or Light Guide Using Convectively Distorted Thermal Gradients in Gases

By D. W. BERREMAN

(Manuscript received May 26, 1964)

Development of systems for long-distance communications using laser beams is of considerable current interest. A major problem is to avoid losses in transmission systems for light. Losses by scattering and absorption in solid transmission schemes are likely to be large. By using gases as the media that guide the light beam, such losses should be minimized. A number of schemes in which gases can be made to guide a light beam have recently been investigated.

Tests on models of one type of gas lens or light guide utilizing refractive index gradients caused by temperature gradients are to be described in this paper. These particular models consisted of a suitably shaped continuous heating element or train of separate elements supported by insulating material inside a cooler pipe.

Heating elements composed either of a series of closely spaced, doughnut-shaped rings or toruses, or of a single, continuous helix of suitable dimensions were used in the experiments to be described. The beam travels through the doughnut holes or down the axis of the helix. Helices were used in the more detailed tests to be reported here because they are much easier to construct and to support in the cooler outer jacket. They focus at least as strongly and with as little aberration as toruses of approximately equivalent dimensions.

Lens trains of the types described focus to some extent by the alternating gradient (AG) focusing mechanism.*[1,2] However, if the temperature distribution is suitably distorted by moving the gas past the heating element, a great enhancement of focusing can be obtained. The enhancement is due to the ordinary focusing effect of a radially decreasing average refractive index, which is absent if the gas is static. Convection alone caused the gas motion in the lenses described here.

The best of several experimental models of convective thermal gas

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* A. R. Hutson first proposed use of AG focusing in gas lenses to the author in private discussion.

lenses, in terms of specific convergence* vs power consumption by the heating element as well as absence of aberrations, is illustrated in Fig. 1. The model contains a helix about 0.75 meters long and is closed at the ends with flat glass plates to confine the gas. In tests of power consumption the helix was warmed electrically, but for detailed tests for convergence vs temperature difference between helix and outer jacket, it proved more convenient to run warm water through the helix, which was made of copper tubing. Temperature differences were measured with a thermocouple (not shown), fastened to the helix and to the inside of the outer jacket. Measurements of focusing strength and aberration were made with considerable precision using a modification of the Foucault knife-edge test.[3] A very fine pinhole light source, two 80-cm telescope objective lenses (one for making the incident light parallel and the other for enhancing its reconvergence), and both horizontal and vertical knife edges were used in the tests. The two knife-edge orientations enabled us to measure not only focal length, but also spherical aberration, astigmatism, and a type of aberration that might be characterized as "S-shaped" or "sagging lens" aberration. The latter was revealed by the *horizontal* knife-edge test as an inequality in focal length between the upper and lower halves of the clear aperture. One should expect astigmatism and sagging lens aberration in a convective system.

The amount of astigmatism is surprisingly small, and the amounts of spherical and "sagging lens" aberration were too small to detect with the gas lens shown in Fig. 1, using air, $CO_2$ or propane gas at temperature differences that gave focal lengths of more than about 5 meters or specific convergences less than about 0.3 meters$^{-2}$. At higher temperature differences, both astigmatism and sagging lens aberration began to appear, but were relatively small perturbations on the convergence. Fig. 2 shows a detailed study of the astigmatism and convergence ($1/F$) versus temperature difference (helix temperature minus jacket temperature) with the jacket at approximately room temperature using $CO_2$ at one atmosphere pressure.

When helices with considerably larger apertures for the light beam

* The periodic light guides described here had the property that the focal length of any one cycle of the guide was very much longer than the length of one cycle. Consequently, AG focusing was very weak and the focusing was due largely to the fact that the mean refractive index along the axis was higher than along parallel lines off the axis. The mean refractive index at radius $r$ from the axis can be described by the equation $n = n_0(1 - \frac{1}{2}Cr^2)$ when aberrations are absent. When AG focusing is negligible, the quantity $C$ is equal to average focusing power, or convergence, of a segment of unit length out of the continuous "lens train." Hence, it is appropriate to call $C$ the *specific convergence* of such a light guide, a term suggested by W. L. Bond. The maximum allowable curvature of such a light guide is proportional to its specific convergence and to the diameter of its aperture.

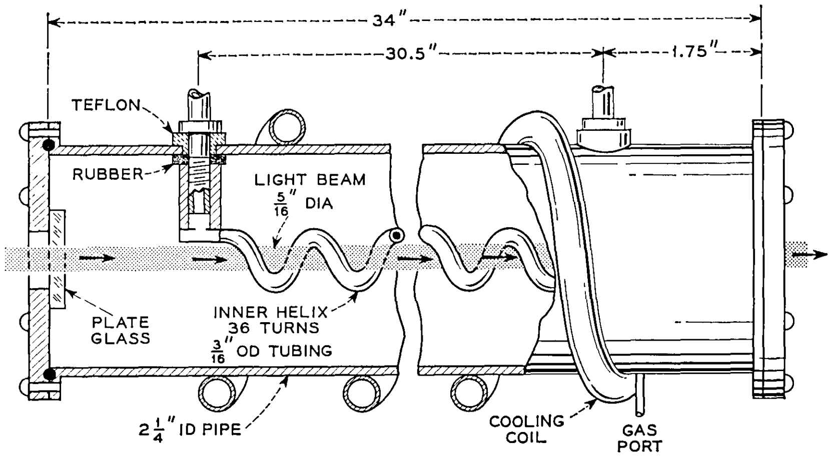


Fig. 1 — Convective gas lens showing the best of several warming elements, a helix, inserted in such a way as to be heated with warm water; the jacket is also kept at a fixed lower temperature with water.

were tested, there was a large amount of spherical aberration when pure $CO_2$ was used, but not when a mixture of half $CO_2$ and half helium or when pure argon was used. Likewise, the helix shown in Fig. 1 gave measurable spherical aberration when $C_4F_{10}$ was used but not with any of the lighter gases tested. A helix with an even smaller aperture would probably greatly reduce the spherical aberration with $C_4F_{10}$. These facts are consequences of the differences in relative rates of convective and conductive heat flow in the gases.

Another effect that depends on these factors, and also on the specific refractive index of the gases, is the specific convergence when the power per unit length consumed by the heating element is fixed, or what may be called the *efficiency* of the lens. Efficiency has the dimensions of meters$^{-1}$ watts$^{-1}$, or diopters per watt. The efficiency of the lens shown in Fig. 1 was found to be almost independent of power consumption in the range where aberrations were small. Measurements at different pressures with $CO_2$ showed that efficiency is approximately proportional to pressure. When one watt of electrical power was supplied continuously to the helix with the jacket at room temperature, the temperature differences, efficiencies and values of specific convergence shown in Table I were measured with the gases listed.

The amount of AG focusing with a helical heating element was calculated and shown to be entirely negligible when the helix turns are as closely spaced as in the lens shown in Fig. 1. This is confirmed by the

TABLE I

| Gas | ΔT | Efficiency | Specific Convergence |
|---|---|---|---|
| air | 4.0°C | 0.045 $m^{-1}w^{-1}$ | 0.06 $m^{-2}$ |
| $CO_2$ | 3.9°C | 0.091 $m^{-1}w^{-1}$ | 0.12 $m^{-2}$ |
| $C_3H_8$ | 3.4°C | 0.12 $m^{-1}w^{-1}$ | 0.16 $m^{-2}$ |
| $C_4F_{10}$* | 2.6°C | 0.15 $m^{-1}w^{-1}$ | 0.20 $m^{-2}$ |

* This gas was suggested by K. B. McAfee. The focal length is only approximate because of spherical aberration.

symmetry of Fig. 2, since AG focusing would be independent of the sign of the temperature difference. Fig. 3(a) is a three-dimensional plot showing how the refractive index, $n$, would vary as a function of position in a plane normal to the optic axis if there were negligible convection. In that case, both the temperature and the refractive index would very nearly obey Laplace's equation. Suppose one considers two orthogonal cross sections of the plot parallel to and containing the optic axis. Near the axis, a cross section that cuts through the helix has curvature $\partial^2 n/\partial y^2$ that is equal in magnitude but opposite in sign to the curvature $\partial^2 n/\partial x^2$ in the orthogonal cross section. (Cf. lines $YOY'$ and $XOX'$ on Fig. 3a.) This is a direct consequence of the Laplace equation and the symmetry

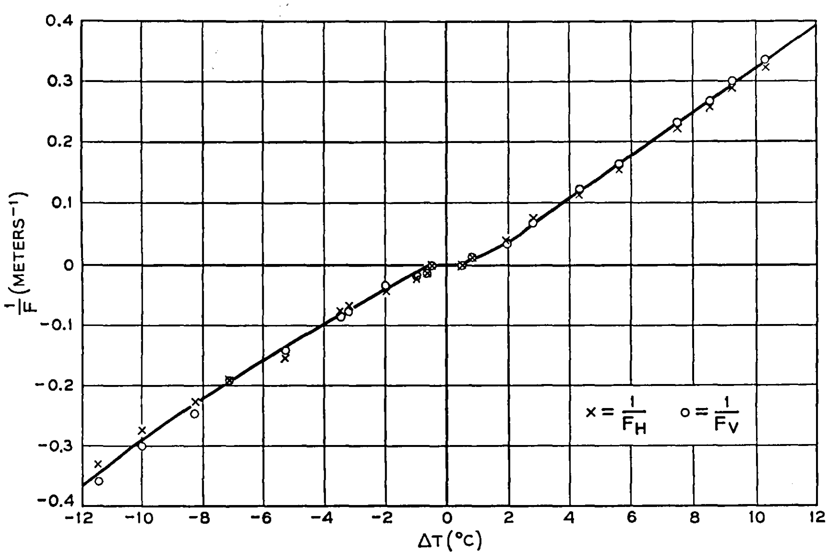


Fig. 2 — Reciprocal focal length, or convergence in vertical plane ($1/F_V$) and in horizontal plane ($1/F_H$), vs temperature of inner helix minus temperature of outer tube for the lens shown in Fig. 1 with $CO_2$ at one atmosphere pressure. The difference between horizontal and vertical convergence is a measure of astigmatism.

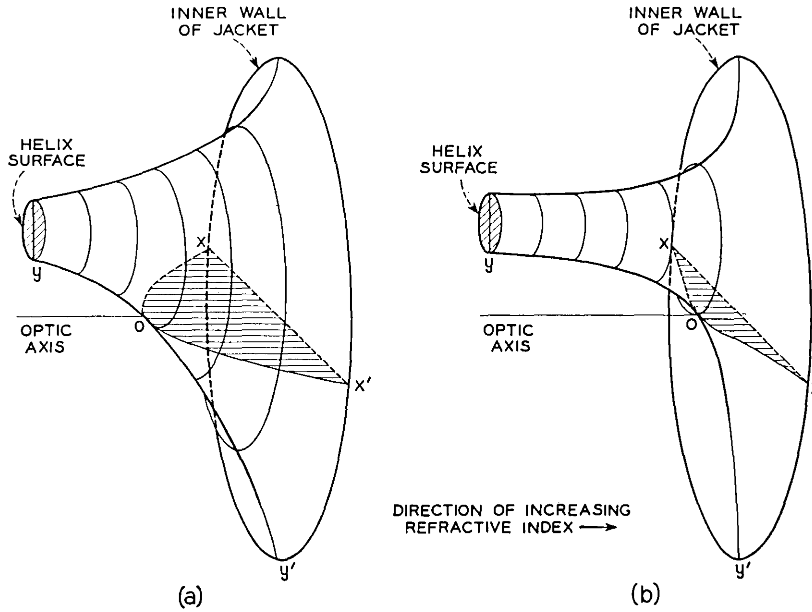


Fig. 3 —(a) Refractive index vs two coordinates of position in a plane normal to the optic axis in the gas lens. The refractive index is highest at the jacket wall, represented by the large circle seen in perspective on the right side, and lowest at the warm helix wall, represented in cross section by the small circle on the left. This figure represents the hypothetical situation in the absence of convection. (b) Similar to (a) but with convection. Note difference in magnitudes of curvature of the plot in cross sections through the optic axis normal ($XOX'$) and parallel ($YOY'$) to the plane of the drawing. Such difference is zero in (a). Details would vary somewhat with azimuth of helix at the plane of the plot.

of the helix. No ordinary focusing occurs in this case, because there is no change in *average* refractive index with radial distance from the axis on lines parallel to the axis. A more rigorous analysis shows that no ordinary focusing occurs anywhere inside the aperture of any system having either helical or ordinary axial symmetry if $n$ obeys Laplace's equation. Fig. 3(b) is the same sort of plot as Fig. 3(a), except that the contours are changed by convection. The convection produces a sharper temperature gradient near the helix surface and the temperature is more nearly uniform elsewhere. Consequently, the plot of refractive index curves more sharply, near the axis, than before in the cross section through the axis and the helical tube, and less sharply in the orthogonal direction. The result is that the *average* refractive index is then higher along lines near the axis than along lines farther away, so that there is a net positive ordinary focusing effect.

A detailed mathematical analysis of such convective flow has not been made to the author's knowledge, but experiments on temperatures and flow in gases between concentric cylinders of unequal temperature have been reported in Ref. 4. That paper shows temperature distribution alteration by convection in a quantitative way and also presents the relation between convection and the relative size of inner and outer cylinders and the viscosity, specific heat, density and heat conductivity of the convective fluid.

Although any element of the helix is far from straight and is not very near the center in any cross-sectional element, the convective flow in any plane is qualitatively very similar to that described for small flow rates in Ref. 4. The flow patterns in several planes were observed and photographed in a glass-walled replica of the lens using tobacco smoke in air. The flow was perfectly steady and nonturbulent, even with a temperature

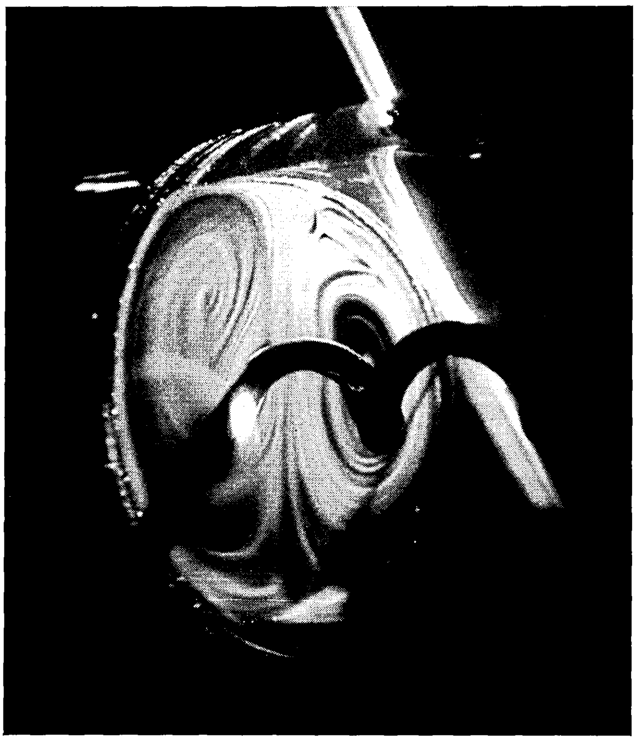

Fig. 4 — Smoke moving with air in glass-walled gas lens. The camera is somewhat below and to one side of the lens. Smoke is flowing upward around the helix and downward on both sides, inside the jacket. Helix is 10°C warmer than the jacket. Illumination is from the upper right through a narrow slit normal to the axis. The illuminated region cuts through the helix at a point level with the axis.

difference of over 10°C, and always showed a two-kidney shaped pattern similar to that obtained with a concentric cylinders.[4] Fig. 4 is one of these photographs, taken in a plane where the helical tube is on a horizontal line from the axis, where one might expect greatest departure from the results with concentric cylinders.

It is evident, especially from Ref. 4, that temperature gradients are not axially symmetric even when averaged over a complete loop of the helix, because of the relation between the convective flow patterns and the direction of gravity. It is therefore surprising, but none the less true, that nearly perfect, aberration-free focusing can be achieved with the convective gas lens if a uniform helix of the proper cross-sectional dimensions is chosen for the warming element. There seems to be no reason why a continuous helix and tubular jacket of similar cross section but of great length might not have the same local focusing properties as the short segment that was tested.

*Acknowledgments.* The author wishes to acknowledge the assistance of D. E. Collins in the construction and testing of the lenses and taking the smoke photographs. A. R. Hutson, K. B. McAfee and J. A. Lewis have been especially helpful in discussions of the gas lens.

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# A Gas Lens Using Unlike, Counter-Flowing Gases

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(Manuscript received May 26, 1964)

Because of the current interest in gas lenses for possibe use in long-distance laser beam transmission, it seems worthwhile to report on the successful operation of an example of another class of gas lenses. This class of lenses utilizes the difference of specific refractive index of different gases to achieve focusing in a region where there is a variation in relative concentration of different gases. In the device to be described, two gases flow together continuously from opposing tubes into a mixing chamber. The chamber is designed so that the effective interface where the gases meet is an axially symmetric curved surface, which acts as a lens for light passing down the axis of the opposing tubes.

In order to minimize distortion due to gravitational force, it is desirable to use two gases of about the same density. It may be most economical to separate and recycle the gases after they have run together. In principle, continuous separation with a semipermeable membrane would consume only a moderate amount of power. Except for a computation of the theoretical minimum of power consumption, no further discussion of the problem of gas separation will be presented in this paper.

A working model of a single element of a counter-flowing gas lens is shown in Fig. 1. Rather elaborate precautions were taken to avoid

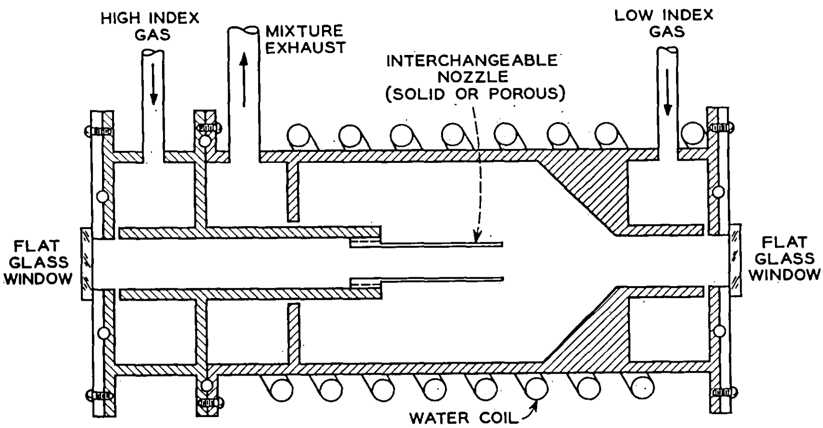


Fig. 1 — Experimental model of counter-flowing, unlike gas lens; over-all length is 8 inches.

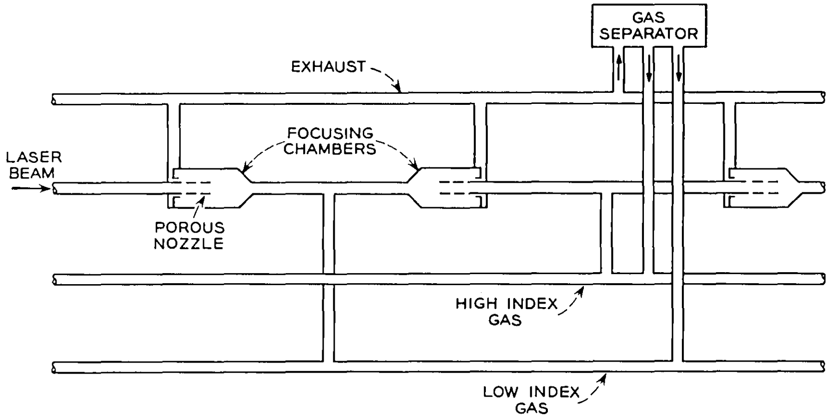


Fig. 2 — Schematic diagram of a part of a continuous series of counter-flowing, unlike gas lenses connected to a separator for recycling gases.

turbulence or asymmetry that might be introduced if the gas entered directly into the tubes through holes in the walls. Such precautions could probably be dropped if greater length of tubes existed between the points at which the gases enter and the regions in which they mix (see Fig. 2). For a continuous series of such lenses, one might have the actual lenses or "mixing chambers" a few feet apart, with gases of alternate types entering midway between the mixing chambers, as shown in Fig. 2.

The focal length and aberration of the lens as a function of flow rates were measured using a modification of the Foucault knife-edge test mentioned in the accompanying B.S.T.J. Brief on thermal gas lenses.[1] The two gases were run through long parallel copper tubes, which had been soldered together, before they entered the gas lens. Water was circulated through a tube soldered to the copper gas tubes and through a tubular coil wrapped around the gas lens (see Fig. 1). This precaution insured the absence of any focusing due to thermal differences. At moderate flow rates no appreciable aberration was observed, but some spherical aberration appeared before turbulence set in.

Fig. 3 is a graph of the variation of focal length with rates of flow of argon and $CO_2$. The lower group of curves shows such variation in the simplest model, in which $CO_2$ flowed out the end of a $\frac{3}{8}$-inch ID tube or nozzle into a relatively large cavity surrounding the end of the nozzle. The cavity was supplied with argon from the opening opposite the nozzle. The upper group of curves shows the same parameters when the solid nozzle was replaced with a cylindrical tube of 50-mesh copper screen. The screen allowed mixing of the $CO_2$ with argon over a longer distance with greater radial variation in concentration. The result is

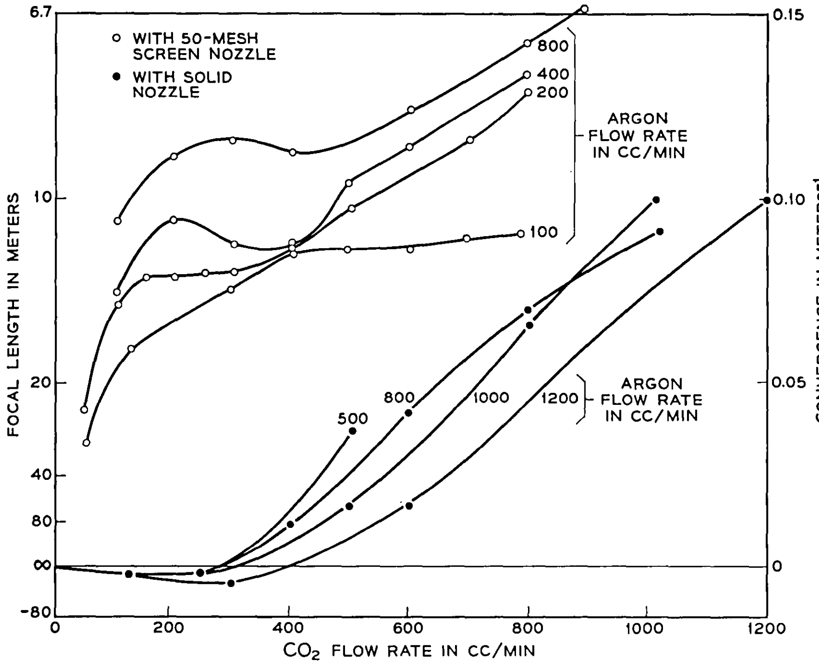


Fig. 3 — Graph showing variation of focal length and convergence with gas flow rates. Note increased efficiency using screen nozzle.

much greater curvature of the effective interface between the $CO_2$ and the argon, which gave a much shorter focal length at a given flow rate. Diffusion is certainly very important in the enhancement of focusing strength when the screen is used. A. R. Hutson was the first to suggest gas lenses utilizing refractive index gradients controlled by diffusion of gases of unequal refractive index into one another (private discussions with the author).

The curves stop at flow rates of about 1 liter per second of either gas because turbulence appeared at higher flow rates. Flow appeared to be completely free of turbulence at lesser flow rates.

The minimum power consumption, if the gases must be recycled, can be obtained using a simple thermodynamic argument due to K. B. McAfee.[2] If it were possible to find two semipermeable membranes, one for one gas and one for the other, the power required to separate the gases reversibly, neglecting small departures from ideal gas properties, would be

$$P = -fRT\left[\ln X + \frac{1 - X}{X}\ln(1 - X)\right]$$

where $f$ is the flow rate of one of the gases in moles per second, $R$ is the gas constant in joules/mole °K, $T$ is the absolute temperature, and $X$ is the mole fraction of that gas in the mixture. If the flow rate of each gas is 200 cc/minute, so that $X = 0.5$, the formula gives a power consumption

$$P = 0.50 \text{ watts.}$$

Tests showed that the focal length at such a flow rate was about 15 meters in the lens with a screen nozzle, using $CO_2$ and argon. The theoretical maximum "efficiency" of the lens is thus 0.13 diopters per watt at this flow rate. It may be of interest to note that this efficiency is the same order of magnitude as that of the convective helical gas lens reported in Ref. 2. However, it should be emphasized that scuh low power consumption is only a theoretical limit for a counter-flowing gas lens of these particular dimensions.

*Acknowledgments.* It is a pleasure to acknowledge many helpful discussions and much encouragement given by A. R. Hutson in the course of this work. D. E. Collins has been of great help in setting up and performing the experiments.

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