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SG Undersea Cable System:

Installation and Maintenance of the Undersea System

By J. E. H. COSIER, A. P. DAVIES, S. W. DAWSON, Jr., R. F. GLEASON, F. E. KIRKLAND, and T. A. MCKENZIE

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Many changes were made in Cable Ship Long Lines *to facilitate installation and maintenance of* SG *cable and repeaters. This paper describes new equipment provided for the ship and modifications made to existing equipment. Both transmission equipment and cable and repeater handling facilities are discussed.*

I. BACKGROUND

A significant part of the development of a new undersea cable system is involved with the equipment required to install and maintain the system. Much of the basic work concerning cable payout and repeater handling was done as part of the earlier SD Submarine Cable System and the design of Cable Ship *Long Lines*.[1] Even so, for the SG system, many specific changes were necessary. This paper describes the most important ones. The areas or conditions that called for revision or new design can be summarized as follows:

(*i*) *Electrical*
- (*a*) Test sets
- (*b*) Power feeding equipment
- (*c*) Transmission equipment
- (*d*) Computer facility
- (*e*) Repeater monitoring set

(*ii*) *Environmental*
- (*a*) Repeater temperature control and measurement
- (*b*) Cable temperature control and measurement

(*iii*) *Physical and Mechanical*
- (*a*) Increased cable tensions and cable size

(*b*) Large number of repeaters and equalizers
(*c*) Burying of cable and repeaters
(*d*) Grapnels.

II. TEST SETS AND PROCEDURES

Installation of a system requires a continuous program of testing beginning when the cable, repeaters, and equalizers are loaded aboard ship and ending with the final splice completing the undersea link. The test equipment, test procedures, and computations are designed to ensure the proper performance of the system, to optimize equalizer settings, and to preserve the acquired data for future use.

2.1 Test set philosophy and design

New test equipment was designed to facilitate the installation of SG submarine cable systems. The design allows the use of identical test equipment on the ship and at shore terminals. The new installation test equipment designs include the cable laying test set, the repeater monitoring set, the SG high frequency line equipment, the shipboard power-feeding equipment, and a new shipboard computer facility.

2.1.1 Cable laying test sets

The cable laying test set (CLTS) was developed for the purpose of making automatic, simultaneous, two-way transmission measurements on SG and SF cable systems during installation and commissioning.[2] As shown in Fig. 1, the cable laying test set has a transmit section and a receive section. The transmit section consists of an oscillator with precision output level control and a digital control unit, while the receive section consists of a selective detector, a digital control unit, and signal monitor unit. Signaling to achieve automatic control between the transmit section and the receive section is accomplished by set command tones. By using a patching arrangement, this signaling scheme allows the transmit and receive sections of the same CLTS to work either directly with each other or with the receive and transmit sections of another CLTS at the other end of a cable system. In the latter case, control is via an order wire channel over the link being installed.

Each section of the CLTS has one manual and five automatic modes of operation. In the manual mode, the transmit and receive digital control units are disabled. The transmit section simply becomes a manually tuned oscillator, and the receive section becomes a manually tuned selective detector with a signal monitoring capability. The signal monitor unit detects the signal power received by the selective detector and provides an audible and visible alarm when the received power level varies by more than ±1.5 dB.

The five automatic modes of operation are: SF low band, SF high band,

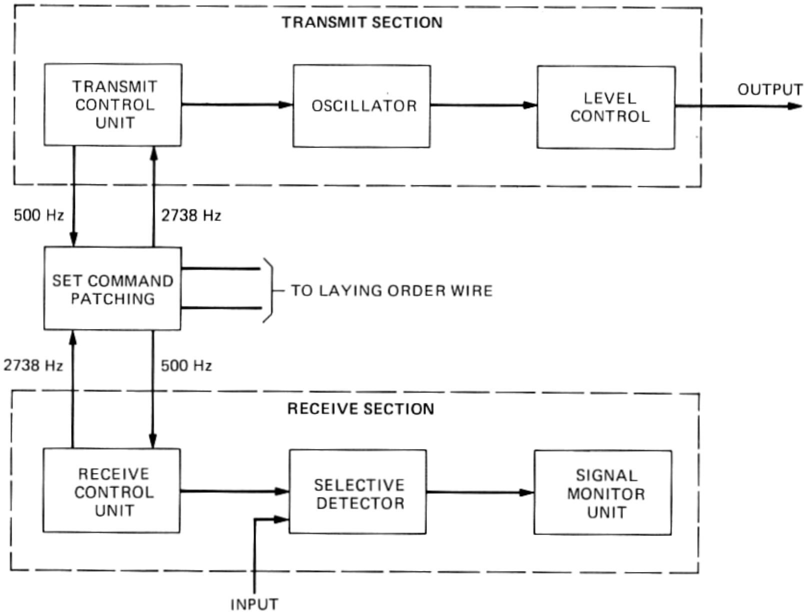

Fig. 1—Cable laying test set.

SG low band, SG high band, and RIPPLE. The RIPPLE mode is the most flexible, and all other modes are special cases of it. In the RIPPLE mode, the transmit and receive operator(s) choose a start frequency, stop frequency, and step frequency interval by setting thumbwheel switches on the front panels of the control units. When the transmit control unit is initialized, it causes the transmit section to begin sending a test tone at the start frequency and also sends a set command tone to the receive section, causing it to measure the received power at the start frequency. When the measurement is complete, the frequency and measured power are recorded via the data translator and teletypewriter (TTY). The receive control unit then sends a set command tone back to the transmit control unit, causing it to step to the next test frequency. To step to the next test frequency, the transmit control unit increments the oscillator frequency in 1-kHz steps at 10,000 steps per second until the next test frequency is reached. The receive control unit increments the measurement frequency in a similar fashion and begins a new cycle. This process continues until the measurement at the stop frequency has been completed and the data have been recorded.

All other automatic modes of operation are similar, except that the start and stop frequencies are fixed, standard values and the step frequency intervals vary in size between the standard frequencies. For these modes of operation, the start, stop, and step frequency intervals are stored in read-only memory (ROM) in the control units.

The oscillator and selective detector units used in the CLTS are standard Western Electric transmission measuring sets, and thus the basic measurement capability of the CLTS is determined by these units. Both the oscillator and the selective detector are designed to cover the frequency range from 10 kHz to 60 MHz. The level control unit in the transmit section provides an output of 0.00 ± 0.02 dBm (into 75 ohms), which can be attenuated to −99.9 dBm in 0.1-dB increments. The selective detector has a measurement range from 0 to −129.9 dBm. In all automatic modes, measurements can be made over a range from zero to −109 dBm with a readout resolution and repeatability of ±0.01 dB.

All the equipment associated with a CLTS, including power supplies and a blower for cooling, is packaged in one bay. Two complete CLTS bays are installed aboard ship, and two additional CLTS bays are installed (on a temporary basis) at the shore terminal from which cable is being laid, thus providing redundancy at both ends of the cable.

2.1.2 Power feeding equipment

New shipboard power feeding equipment was designed for the installation of SG submarine cables.[3]

2.1.3 Transmission equipment

The SG high-frequency line equipment was developed for the installation of SG cable systems. It is permanently installed aboard the Cable Ship *Long Lines* and temporarily installed at cable stations from which cable is laid. This allows the undersea cable system to be installed independent of the installation of the terminal wideband line equipment. The high-frequency line serves as the interface between all the transmission test facilities and the cable system.

The major function of the transmit high-frequency line is to provide level adjustment capability for transmission test tones and the 12-channel laying orderwire signal to obtain acceptable signal-to-noise ratios for each. At the same time, the broadband power transmitted must be limited to a value such that no repeater is overloaded. These functions are achieved for the conditions of transmitting into an inboard- or outboard-end section of cable (whose length can range from essentially zero to a full repeater section) or into the test lead of an ocean block equalizer.[4]

The receive high-frequency line provides three paths of independently adjustable gain for the broadband signal received from the cable system. First, the gain of the transmission test tone path is adjustable to allow for as much gain as possible while limiting the signal level applied to the receive cable laying test set to less than 0 dBm. Second, the gain of the orderwire path is adjustable to achieve the proper transmission level at the input to the multiplex equipment. Finally, the gain of the supervisory tone path is adjustable so that the power of the supervisory tones at the input to the repeater monitoring set will lie between −40 and −100 dBm. Again, the implementation of the high-frequency line allows all these requirements to be met for receiving at an inboard or outboard cable end section or at an ocean block equalizer test lead.

Two high-frequency line units, regular and spare, are included in each high-frequency line bay. Each unit consists of a directional filter for separating transmit and receive signals, fixed-gain broadband amplifiers, variable attenuators, and hybrid transformers. Regular and spare SG laying orderwire multiplex equipment is also included in each high-frequency line bay. The multiplex units contain the stages of modulation necessary to translate the existing SF laying orderwire spectrum into the SG bands. In addition, the high-frequency line bay contains a patch panel to facilitate the convenient patching of all signals and test equipment used for transmission testing during the installation.

Because of the many different situations that can arise during laying, flexibility of patching the high-frequency line equipment received considerable attention. For example, the use of broadband amplifiers and attenuators throughout the high-frequency line having essentially flat response over the frequency range from 500 kHz to 60 MHz allows the transmit and receive bands to be determined simply by patching the directional filter. The design of the directional filter requires a large band-to-band rejection to preclude leakage from the relatively high-level transmitted signal from overloading the low-level receive section of the high-frequency line. The SG high-frequency line directional filter has an in-band loss of less than 1 dB in each band and a band-to-band rejection of greater than 65 dB.

2.1.4 Computer facility equipment

The advantages of a shipboard computing facility have been described previously.[5] Figure 2 is a block diagram of the new computing facility aboard Cable Ship *Long Lines*. It consists of a programmable calculator with 15,000-word memory and an internal cassette memory, two additional cassette memory units for program and data storage, a thermal page printer, a plotter, and an optical paper tape reader.

During a cable lay, a detailed record-keeping procedure is employed which consists of entering data and performing computations on a specially prepared set of printed forms. Both the shore terminal and the ship maintain a complete set of all data and computations. The computer software is designed to replace the manual record-keeping procedure

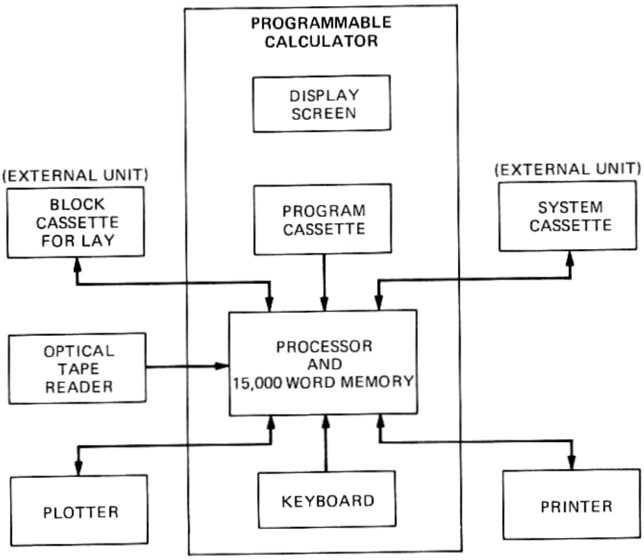

Fig. 2—Shipboard computer facility.

aboard ship. For this reason, it prints out data and computations on pages which replace the forms which would have been filled out manually. Thus, in the event of a computer failure, the manual computations can easily be resumed. In addition, a software package allows operator-controlled manipulation of various data for special calculations during a cable lay.

2.1.5 Repeater monitoring set

The repeater monitoring set is designed to be used on the SG system to measure supervisory tones from repeaters as well as to measure the intermodulation performance of repeaters.[4] Unlike the equipment described above, which is used only during installation and commissioning,[6] the repeater monitoring set is a permanent piece of terminal station equipment which is also used during installation. The supervisory tone measurements allow for data acquisition necessary for system administration and for fault localization. Intermodulation tests, which are normally performed on an out-of-service basis, are helpful in localizing a wide variety of faults.

The repeater monitoring set can be operated in a manual mode or in a semi-automatic mode. In the manual mode, input parameters are set on thumbwheel switches by an operator. In the automatic mode, input parameters are entered from mark-sense cards by a card reader. The repeater monitoring set has a visual output of measured data as well as an output suitable for driving a TTY. The set can also be used to measure supervisory tones on the SF system.

For supervisory tone measurements, the repeater monitoring set uses a phase-locked selective detector technique. The measurement bandwidth is 5 Hz, and all the conversion carriers in the selective detector are phase-locked to a highly precise common reference frequency, allowing accurate frequency measurement of the received tones.

The receiver, whose automatic frequency control loop contains a 50-Hz bandwidth IF filter, has an acquisition range of ±25 Hz for signals above −110 dBm. Once phase lock is achieved, the frequency and power of the received signal are measured automatically over the range of −100 to −40 dBm. Input bandpass filters, used to prevent overload of the detector by the broadband message signal, can be bypassed, enabling the set to be used as a general-purpose selective detector over the 10-kHz to 60-MHz range.

Because the SG repeaters are highly linear, a special technique was required to obtain accurate intermodulation measurements of individual repeaters on an installed system. This particular measurement is made possible by the common-amplifier repeater configuration and by the different distance and hence different round-trip delay to each repeater. Chirp radar and matched-filter techniques are used to obtain the necessary signal-to-noise ratio under the peak power constraints of the repeaters.

A linear FM (chirp) signal 100 kHz wide with a 10-Hz repetition rate is transmitted together with a single frequency tone. In the low band, an 8.6- to 8.7-MHz chirp and a 12-MHz tone are transmitted. Each repeater produces a second-order intermodulation product whose frequency sweeps from 20.6 to 20.7 MHz and is received in the high band. The return from a given repeater is recovered by demodulating the received signals with a swept carrier identical to the transmitted chirp but translated in frequency by an amount corresponding to the round-trip delay to the given repeater. A single IF signal results (in this case, 20 MHz) which is measured by the 5-Hz bandwidth selective detector. Returns from adjacent repeaters are separated by approximately 100-Hz intervals and are rejected by the detector. The effects of delay distortion on the signal are minimized by choosing the transmit and receive frequencies such that the round-trip delay over the 100-kHz chirp band is constant.

Successful implementation of this method requires precise phase control of two synchronized frequency generators.

2.2 Test procedures

2.2.1 Tests during loading

Repeaters, ocean-block equalizers, and shore-controlled equalizers are individually tested during manufacture and then transported to the dock for loading aboard ship. Following loading and prior to splicing, resistance checks are made to determine that all repeater housings have a high dc resistance to ground and that all equalizer housings are solidly grounded to the ship's hull. The purpose of these pre-checks is to ensure the validity of the outer-conductor dc resistance tests which are used later to determine cable temperature. The cable, repeaters, and equalizers are then spliced together to form an assembled shipload.

2.2.2 Assembled shipload tests

The assembled shipload is subjected to a series of tests to ensure proper operation. The diagram in Fig. 3 shows the equipment and connections used to perform these tests on a block-by-block basis. Individual block testing is necessary because the differences in temperature and pressure between shipboard and ocean bottom environment can result in large temporary end-to-end misalignment which makes a single measurement of an entire shipload impractical. Block-by-block measurements have some useful benefits. Testing procedures and computations can be mechanized in a generally repetitive manner, and single block tests automatically localize faults to a block.

Each end of the assembled shipload is terminated at a power separation filter. The power separation filters allow high voltage to be applied to the center conductor at one end and dc ground at the other. A broadband connection is also provided for test signals. Transmission tests are performed on each of the blocks (including the partial end blocks) at a selected set of standard frequencies in each band.

For discussion of the actual transmission tests, refer again to Fig. 3. All transmission measurements are made by either the cable laying test sets (CLTSs) or the repeater monitoring set (RMS). For these tests, the CLTSs transmit and receive signals at a standard list of stored frequencies. All the test equipment as well as the orderwire is connected to the assembled cable system through the high-frequency line equipment. The CLTSs are used to measure the transmission response of each block. The measurement starts at the first test frequency and automatically sequences through the standard frequency list. The measured data are automatically recorded by means of the data translator and the teletypewriter in both printed page and punched-paper-tape form. The data translator also causes the TTY to print out heading information which identifies the type of measurement made, the date and time of day, the direction of transmission, the test sets used to make the measurement, the run number, and the block number. The CLTSs are also used to measure all the losses and gains associated with the test configuration (e.g., patch cords and power separation filter). The punched paper tapes allow automatic loading of test data into the shipboard test room computer facility.

Computations are performed using the measurement data described

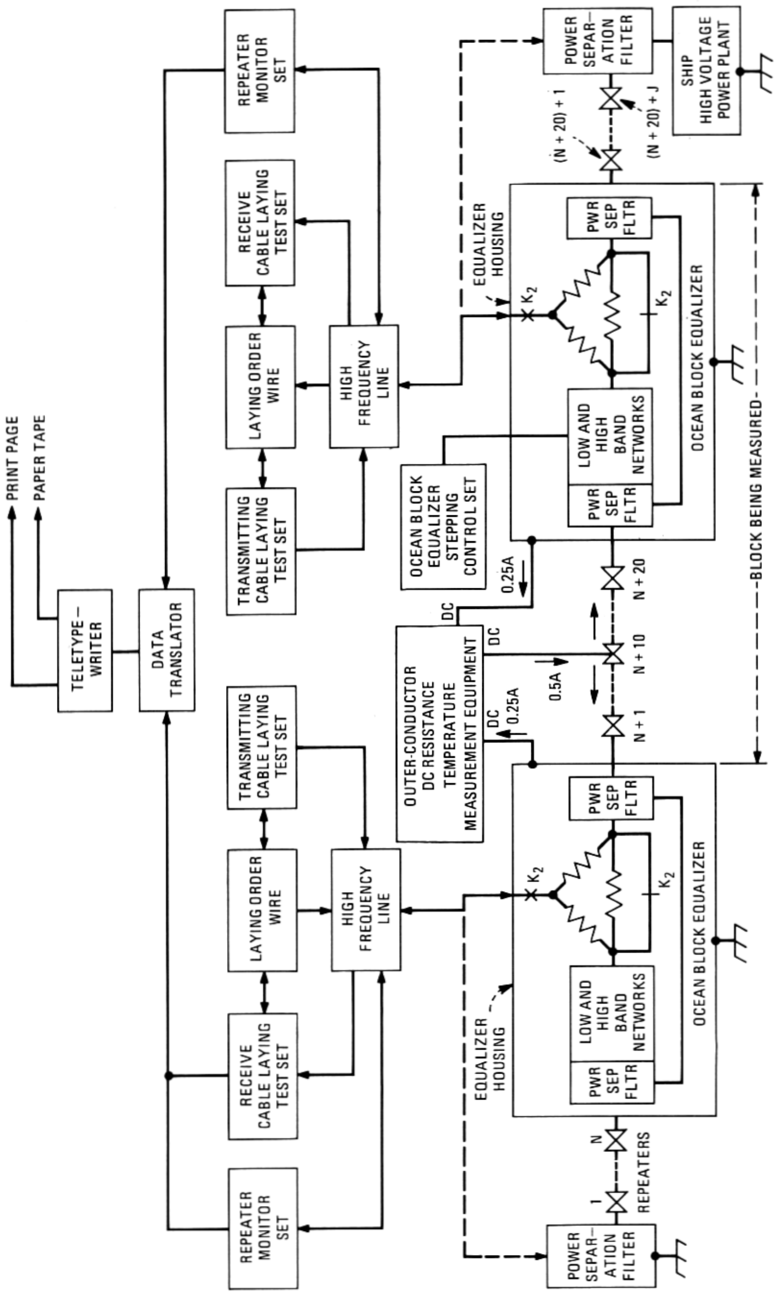

Fig. 3—Assembled shipload transmission test.

above. The primary intent of these calculations is to verify that the assembled shipload is operating properly. To accomplish this, one must be able to predict the expected transmission response. Factory measurements on the actual repeaters, cable sections, and equalizers in each block, which are loaded into the computer memory prior to testing, are used to compute a transmission response to be compared with the shipboard measurements. The computed transmission response must correct for the actual temperature of the repeaters and cable aboard ship, because these are generally not the same as during factory measurements.

2.2.3 Tests during laying

Many of the tests during laying are similar to the assembled shipload tests except that the test path is between ship and shore rather than only within the shipload.

The beginning of a cable lay starts with a cable splice. Before the splice is made, a transmission reconciliation test is made to verify the performance of the previously installed portion of the system. If this reconciliation (comparison with measurements made earlier) is satisfactory, the splice is made. After the splice, another reconciliation transmission test is performed between the shore terminal and the test lead of the most outboard ocean-block equalizer in the shipload. Again, the data are analyzed using the shipboard computer to determine if the measurement is consistent with the previous reconciliation and the assembled shipload measurements.

The primary reasons for transmission tests during laying are to confirm proper operation of the system and to obtain data necessary to choose the optimum ocean-block equalizer settings. Using the test configuration shown in Fig. 4, transmission tests are made at regular intervals. At the end of a standard frequency measurement run, each station has only the measurement data for its receive band. These data are then exchanged via the laying orderwire by using the TTY with a paper tape reader and the data sets. Thus the shore terminal and ship obtain measurement data for both bands.

Between standard frequency runs, while the cable is being payed out, the cable laying test sets are used to send and monitor a single tone in each direction of transmission. The receive cable laying test sets give an automatic alarm when the received power of this tone varies by more than 1.5 dB. Also, the supervisory tone power from each repeater is measured and recorded using the repeater monitoring set, data translator, and TTY. Because adjacent repeaters transmit supervisory tones in opposite directions, the data must be exchanged between the ship and shore terminal. Additional tests performed during laying include (*i*) a transmission test through the next-to-be-laid block to ensure that its

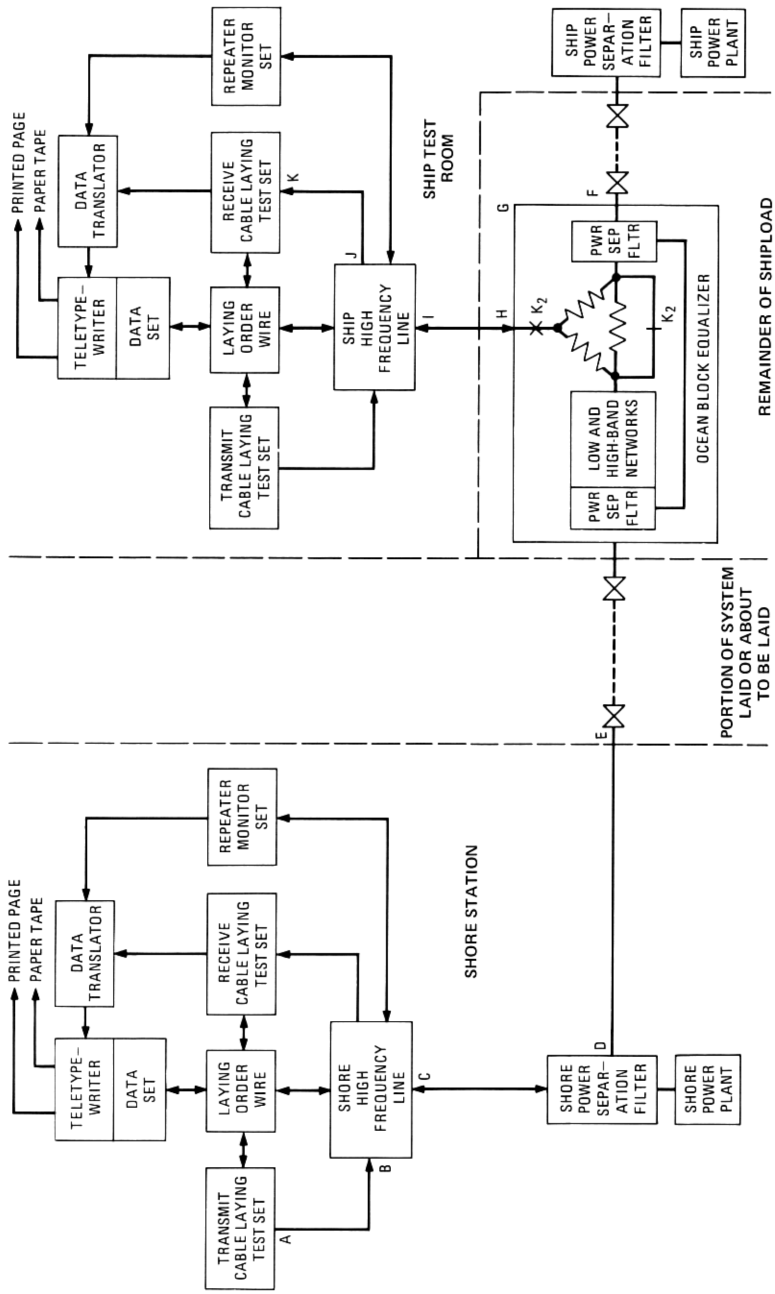

Fig. 4—Transmission tests during laying.

transmission has not changed since the assembled shipload tests, (*ii*) transmission tests at closely spaced frequency intervals, called ripple runs, and (*iii*) monitoring the power plant voltage and current.

The process of choosing the optimum equalizer setting typically starts about three hours before the equalizer is scheduled to go overboard. This interval allows time for the equalizer decision to be made and for the test and stepping leads to be sealed by overmolding. First, a transmission objective is computed using the shipboard computer. The transmission objective is the expected test tone power which would be measured at the input to the receive cable laying test set, assuming that the only misalignment in the system is the planned misalignment.* All the components of this calculation are known either by calculation or by direct measurement with the cable laying test set.

At the time of any standard frequency run, the misalignment of the system consists of the sum of residual misalignment and temporary misalignment. The temporary misalignment is due to the fact that not all the block being laid has stabilized at ocean bottom conditions. Nevertheless, the temporary misalignment must be removed from the measurement data since the equalizer should compensate for only the residual misalignment. This is accomplished as follows. Under steady-state conditions (i.e., constant ship speed, cable payout rate, and shipboard cable and repeater temperature), which are normally closely approximated during laying, temporary misalignment decreases linearly with time (and thus distance) until the equalizer is overboarded. The shipboard computer sorts the standard frequency run data and extrapolates to the expected value corresponding to the time that the equalizer would go overboard. The amount of remaining temporary misalignment due to the cable suspended between the ship and the ocean bottom and due to the thermal inertia of the cable and repeaters is calculated from theoretical considerations and used to correct the extrapolated data.

Direct comparison of the corrected extrapolated data to the transmission objective yields the residual misalignment to be compensated for by the equalizer, which is referred to as block deviation. The computer equalization program then compares the block deviation to the loss shapes available in the equalizer and orders the various setting choices based on a weighted-sum-of-squared-error criterion. The equalizer setting that is selected is typically the one with minimum sum-of-squared-error. The transmission engineers, however, examine the top several choices, taking into account auxiliary information (e.g., anticipated misalignment in the next block), and occasionally choose a different setting.

Once the choice of equalizer setting has been made, four standard

* An example of planned misalignment is gain provided at time of cable installation to precompensate for anticipated increased cable loss with time, i.e., cable aging.

frequency runs are performed. The first two are made immediately before and after the equalizer is switched. A comparison of these two standard frequency runs is made to verify that the correct change in loss has been achieved. Second, the shipboard transmission test lead is moved to the next inboard equalizer, adding the next ocean block to the measurement path. The next two runs are performed before and after the transmission test pad is switched out of the equalizer about to be laid. A comparison of these two standard frequency runs is made to verify that the test pad has, in fact, been switched out. At this point, the equalizer stepping and transmission test leads are sealed, and the equalizer is ready for overboarding. Transmission testing then continues through the next inboard equalizer.

III. ENVIRONMENTAL CONSIDERATIONS AND MEASUREMENTS

3.1 Repeater temperature control

In previous undersea cable systems, no special effort was made to control the temperature of repeaters and equalizers on the cable laying ship. For SG, however, reasonably precise control is required.

3.1.1 Control requirements

Even though repeaters and equalizers are vacuum-dried during manufacture, some water remains, much of it dissolved in polymeric materials. At high storage temperatures a significant amount of water exists as vapor within the free volume of the repeater. If such a repeater were launched into the ocean, where the bottom temperature is typically 2.5°C, there is a possibility that the water would condense on surfaces within the repeater before it could be reabsorbed by the polymers. Condensed water on and between conducting surfaces can cause repeater failure. A careful experimental investigation showed that condensation would not occur if the ambient storage temperature were less than 32°C for unpowered repeaters and 27°C for powered repeaters. The lower of these two values is controlling, since repeaters are powered when they are laid.

If temperature-controlled repeaters[4] are included in a shipload, it is necessary to know their temperature in order to predict what their transmission characteristics should be. To limit positive misalignment in blocks containing temperature-controlled repeaters, the difference between repeater and cable temperature must be controlled. Because the thermal mass of the cable is much greater than that of the repeaters, it is more efficient to control repeater temperature than cable temperature. Thus it is necessary not only to limit the maximum value of repeater temperature but to be able to set it and maintain it with reasonable precision.

Temperature control is also needed for other repeaters, but the requirements are less stringent because temperature changes produce a much smaller change in transmission. Table I summarizes repeater temperature setability, stability, and measurement accuracy objectives.

3.1.2 Temperature-control facilities

To achieve the required setability of repeater temperature, it was decided to use air-conditioning units in each repeater bay and to build tents over each repeater stack. The air-conditioning units are located along the port bulkhead of each repeater bay. The chilled air is piped into a 4-inch-high (102 mm) rectangular telescoping duct located beneath the repeater stack.

When a full load of repeaters is in place, the duct is extended to its full length, spanning the entire stack. As repeaters are payed out during a cable-laying operation, the duct can be shortened ultimately to approximately one-third of its fully extended length. The telescoping feature was provided to keep the incoming air flow concentrated around the remaining repeaters. The return duct for the air flow is on the deck next to the telescoping inlet duct. It contains a series of holes on the top and the side opposite the inlet duct to receive the air. Each hole is fitted with a swivel plate which can be moved to open or close the hole. As repeaters are payed out, the unused holes are sequentially closed.

The repeater stack is covered by an insulating tent with openings on the sides to pass the cable bights. The tent is made in sections so that, as repeaters are payed out, sections can be removed to allow the size of the tent to conform approximately to the size of the stack of remaining repeaters.

Under unusual conditions of very high humidity, condensation can occur on the repeater and equalizer housings in the tent. Drains have been provided to remove this water.

Table I — Shipboard repeater temperature objectives

	Temperature-Controlled Repeaters	Non-Temperature-Controlled Repeaters and Equalizers
Setability	<27°C*	<27°C
Stability in 12 hours	±0.2°C	±2.0°C
Measurement accuracy	±0.2°C	±0.5°C

* The maximum temperature for the temperature-controlled repeaters is determined in part by the cable temperature. The specific requirement depends on a number of factors. In the worst case, it is sufficient to keep the repeater temperature at or below that of the cable.

3.1.3 Repeater temperature measurement

An automatic temperature measurement and recording system has been installed on Cable Ship *Long Lines*. Twenty-one thermocouples can be placed in each of the three repeater stacks. The thermocouples are attached to the periphery of holes in the end cones of the repeaters using clamps which can be removed readily before the repeater is payed out.

The thermocouple identifying number, the indicated temperature, and the time of measurement are printed out on paper tape. The equipment can be programmed to scan and print data from all of the thermocouples at set intervals, e.g., every eight hours. When calibration and correction procedures are used, the temperature measurement accuracy is about 0.05°C.

3.2 Cable temperature control

With previous cable systems, there was no need to control cable temperature. The temperature was measured with thermocouples at 15 points in each tank, giving adequate information for transmission measurements. For SG, cable temperature stability in each tank has to be maintained.

3.2.1 Control requirements

As discussed above, temperature setability requirements have been applied to repeaters rather than to cable. Measurements to determine equalizer setting, however, require that the cable temperature remain stable for the measurement period. Specifically, the stability objective is ±0.2°C over a 12-hour period. Similarly, the measurement accuracy objective is ±0.2°C.

3.2.2 Temperature-control facilities

Measurement of cable temperature during installation of the TRANSPAC-2 SF system showed that the bottom aft portion of the Tank 3 wall was warmer than the rest of the tank. This was traced to the proximity of that area to the ship's main boilers. To improve the uniformity of temperature distribution in the cable, the cable was isolated from the warm area by spacers approximately two inches thick and a sheet of fiberglass to provide a smooth surface adjacent to the cable.

As a further means to provide a uniform cable temperature, the tanks are flooded with water during cable-laying operations. The water level is maintained about two feet below the top of the cable to protect people working in the tank. The water in each tank can be circulated by draining it from drains in the bottom of the tank and pumping it into the top of the tank along the walls. While the tank water temperature does change slowly in response to sea temperature, the circulating water arrangement provides adequate stability.

3.2.3 Cable temperature measurement

Two means are now provided for measuring cable temperature. The first, similar to that used previously, consists of 12 thermocouples in each tank which are connected to the temperature recording system discussed above for the repeater stacks. The thermocouples are taped to the cable during loading so that they are distributed throughout the tank. Thermocouples have the advantages of simplicity and accuracy but the disadvantage that they provide only point measurements. If the cable temperature is not uniform, it is not possible to determine precisely the average temperature of a cable section or a block from the thermocouple readings.

For transmission measurements, the average temperature of the cable in a block is the most important item of cable temperature data. To provide this information directly, the second cable temperature measurement system was developed. This method consists of measuring the dc resistance of the outer conductor of the cable and inferring from this and factory test data the average temperature.

The repeater and equalizer high-pressure housings are connected in series with the cable outer conductors but contribute negligible resistance. The conductivity of the copper used for the outer conductor of undersea cable is carefully controlled. Since the temperature coefficient of resistivity is directly related to the conductivity,[7] it is thus also carefully controlled. During cable manufacture, the factory determines the dc resistance of the outer conductor of each cable section at 10.0°C. This reference reading and the known temperature coefficient are then sufficient to relate temperature to dc resistance throughout the range of interest. Working the outer conductor during cable handling in the factory and from the factory to the ship increases the resistance by an amount equivalent to approximately 0.25°C temperature change on the average. A correction for this is made in the temperature calculation.

If the ship is stationary, a satisfactory measurement can be made as described above. If the ship is pitching or rolling, however, motion of the coiled cable in the earth's magnetic field induces voltages which can cause errors in the measurement. To overcome this problem, instead of measuring a block directly, the two halves of the block are measured in parallel. In this way, the voltages induced by ship motion in the two halves tend to cancel. As an added precaution, high measuring currents (up to 500 mA) are used to make the voltage drop from measuring current much larger than the motion-induced voltages.

The correlation under carefully controlled conditions between thermocouple and direct current resistance (DCR) measurements has been quite satisfactory. The high-current DCR method is regarded as the primary cable temperature measurement. The thermocouple results are used for check and backup.

IV. CABLE LAYING FACILITIES—C. S. LONG LINES

References 8 to 11 discuss the construction and operation of the Bell System Cable Ship *Long Lines,* first used for installing SD cable systems. This section discusses the extensive changes made to the ship to permit handling of SG cable and repeaters.

4.1 Reasons for modifications

Cable used in the SG system is larger, heavier, and stronger than the cable used in previous systems. Table II compares the size, strength, and weight of SG armorless cable and SF armorless cable. The larger diameter of SG cable limits a single shipload to approximately 770 nautical miles (1429 km). With 5.1-nmi (9.46 km) repeater spacing, one equalizer for each 30 repeaters and one-half mile of cable between the equalizer and each adjacent repeater, there is an average of 4.8 nmi of cable for each repeater and equalizer. Thus, it is necessary to stow approximately 160 repeater plus equalizer "bodies" on the ship.

4.2 Linear cable engine

The greater weight and resultant greater laying loads for SG cable required extensive modifications to the linear cable engine. In its original configuration, it had one drive power unit (electric motor and hydraulic pump combination), one main brake, and one hydraulic motor each for payout and pickup operation.

4.2.1 New drive motor and drive power unit

To increase the laying tension capability at 8 knots payout speed from 8000 to 16,000 pounds (3629 to 7257 kg), a new hydraulic motor was added and connected, through a gear box, to the upper forward sprocket shaft. The new motor operates only in the payout (hold-back) mode. A second drive power unit was then added to provide sufficient high pressure oil flow to drive both the old and the new motors simulta-

Table II — Comparison of physical properties of SF and SG armorless cable

	SG	SF
Outer diameter (inches/mm)	2.07/52.6	1.75/44.5
Strength (pounds/kg)	37,000/16,783	16,000/7257
Weight per nautical mile, in sea water (pounds/kg)	3,500/1588	2,000/907
Expected laying tension in 3 miles of water (pounds/kg)	10,500/4763	6,000/2722

neously. Isolation and cross-connection features are provided so that the engine can be run with both motors and both power units or, for lower laying loads, in the original one-motor configuration with either power unit. The engine cannot be operated with the new motor only since the old motor cannot readily be disconnected.

4.2.2 Track modification

The shear-limiting feature of the linear cable engine[10] was modified for the SG laying loads. Since the extensional elastic properties of the cable, as well as the weight in water, are determined primarily by the steel center strand as in previous cable designs, the maximum required shear limiter travel remained unchanged at one-half inch. This allowed the modification to be made without major redesign of the roller carriages. The higher loads were accommodated by using higher modulus springs in the roller carriage assemblies and by preloading the springs to approximately twice the load used previously.

New gripper blocks were designed for the larger diameter of SG cable. These blocks will handle SF and SG cable satisfactorily, but not SD cable.

4.2.3 New brake

Increased braking capability is required for the higher SG strength and loads. To provide this, a new hydraulically operated, spring-release brake unit was added on the upper forward sprocket shaft. This provides enough capacity so that, in an emergency, the cable will part before the brakes slip.

4.2.4 Tension displays

The original aft tension displays used a linear scale from 0 to 16,000 pounds (0 to 7257 kg). The system was changed to provide a quasi-logarithmic* scale from 0 to 50,000 pounds (0 to 22,680 kg). The scaling gives 0- to 10,000-pound (0 to 4536 kg) indication on the lower half of a 330-degree display, allowing greater resolution in the most commonly used range.

The forward tension displays were similarly changed. The dual 0- to 16,000- and 0- to 100,000-pound (0 to 45,360 kg) linear displays were replaced by 0- to 100,000-pound quasi-logarithmic displays with 0 to 20,000 pounds (0 to 9072 kg) on the lower half.

* The pointer motion is proportional to $\log(1 + bT)$, with T the tension and b a scaling factor.

4.3 Repeater stowage

In each of bays two and three, repeaters and equalizers are stacked in a rectangular array 16 wide by 4 high, allowing storage of 64 bodies. This is adequate for the 300 nautical miles (557 km) of cable which can be held in each of tanks 2 and 3. Tank 1 can hold 170 nautical miles (315 km). To accommodate this, the repeater stack in bay one is nine repeaters wide by four high. Thus a total of 164 repeaters and equalizers can be carried. For an SF shipload, 116 repeaters and equalizers are required.

4.4 Cable stowage

Figure 5 shows the stowage configuration for cable and repeaters typical of tanks 2 or 3. The arrangement for tank 1 is similar except for the different repeater stack orientation.

The cable is coiled in the tanks in the same way it has been for previous systems. The ends of the cable sections which feed from the tank up to the repeater stack on deck are called up-and-down runners, the up-runner being the end payed out ahead of a repeater, the down-runner the end payed out after the repeater. To prevent crossovers and kinking of the cable, these runners are neatly dressed into slots which lie on the forward wall of the cable tank. They are held in the slots with thick rubber flaps which deform to let the cable come out of the slot during payout.

Because of the larger diameter of SG cable, the slots had to be modified. In tank 1, there are now six up- and six down-runner slots, each deep enough to hold seven runners. This is sufficient to accommodate 41 repeaters, two runners being reserved to lead to the test room or to other cable tanks. In tanks 2 and 3, there are ten up- and ten down-runner slots, each seven runners deep, so 69 repeaters can be accommodated in each of these tanks.

4.5 Grapnels

The SG system uses larger and stronger cables, and closer repeater spacing than earlier systems. These changes led to a need for improved grapnels for repair operations in both shallow and deep water. Three areas of development were undertaken: (*i*) the design of conventional grapnels with increased strength, with dimensions changed for SG cable, (*ii*) the design of a powered cut-and-hold grapnel for deep-sea use, and (*iii*) the design of a simple detrenching grapnel for recovering buried cable.

4.5.1 Conventional grapnels

Stronger versions of three standard grapnels, the Gifford, the Rennie, and the Flatfish, have been designed and manufactured. These grapnels are illustrated in Figs. 6 and 7.

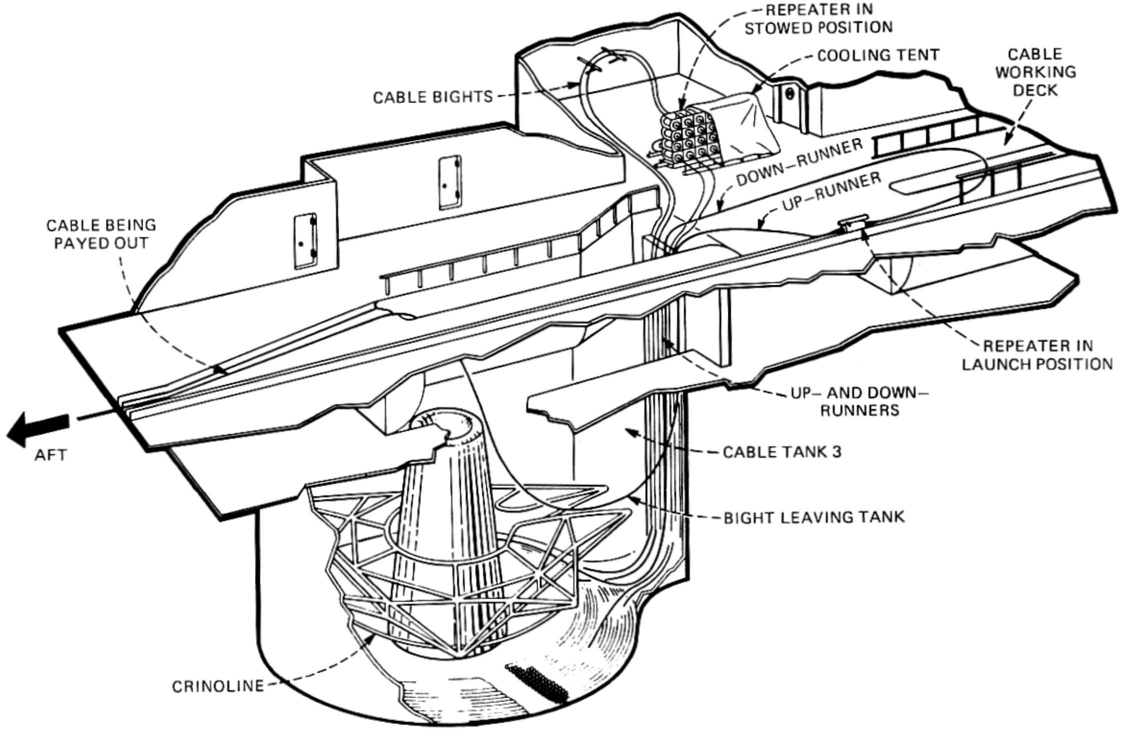

Fig. 5—SG cable and repeater stowage on C. S. *Long Lines*.

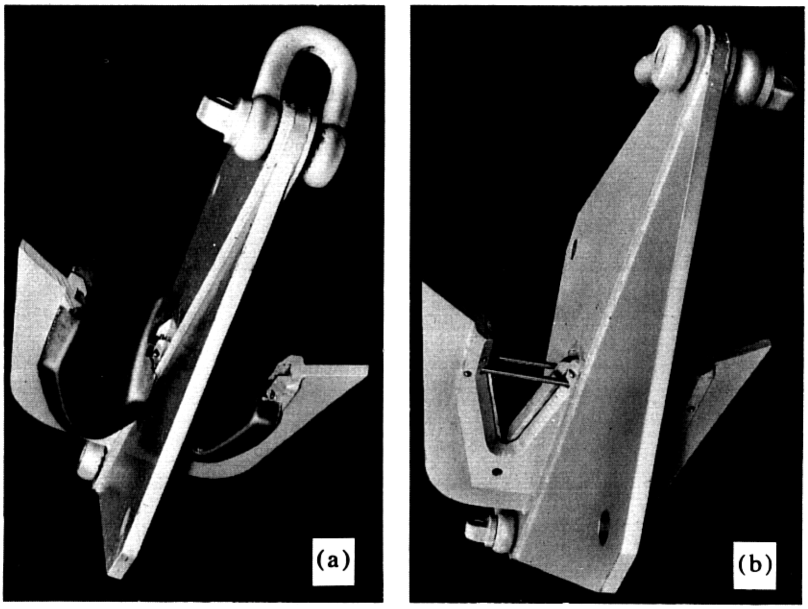

Fig. 6—Flatfish grapnel for SG cable: (a) fitted with "gloves"; (b) fitted with breakaway bars.

The Flatfish grapnel, Fig. 6, has been designed to cut or to hold all types of SG cable. If the grapnel is required for recovering cable, "gloves" are fitted over the blades at their base. For use in the cutting mode, two types of cutting blades have been produced, curved blades for armorless cable and conventional straight blades in a V-formation for armored cable. In addition, the grapnel can be fitted with bars located either side of the open end of the blades. As the cable tension increases, the bars suddenly break, and the cable impacts against the cutting blade, thus increasing the cutting action.

The Rennie grapnel, Fig. 7a, is conventional except for the use of replaceable prongs. The Gifford, Fig. 7b, is also conventional in design except for the inner surface of the "hook"; this has a V-formation, which reduces cable slip through the grapnel.

The new designs were tension-tested to 67,000 pounds (30,390 kg) and proved to be suitable by use during the TAT-6 laying operation.

4.5.2 Cut-and-hold grapnel

When carrying out a deep-sea repair, the cable must be cut before the ends can be brought to the surface. To prevent damage to the repeaters, they should not be dragged along the sea bed during this operation. The cut-and-hold grapnel is designed to cut the cable and also to hold onto

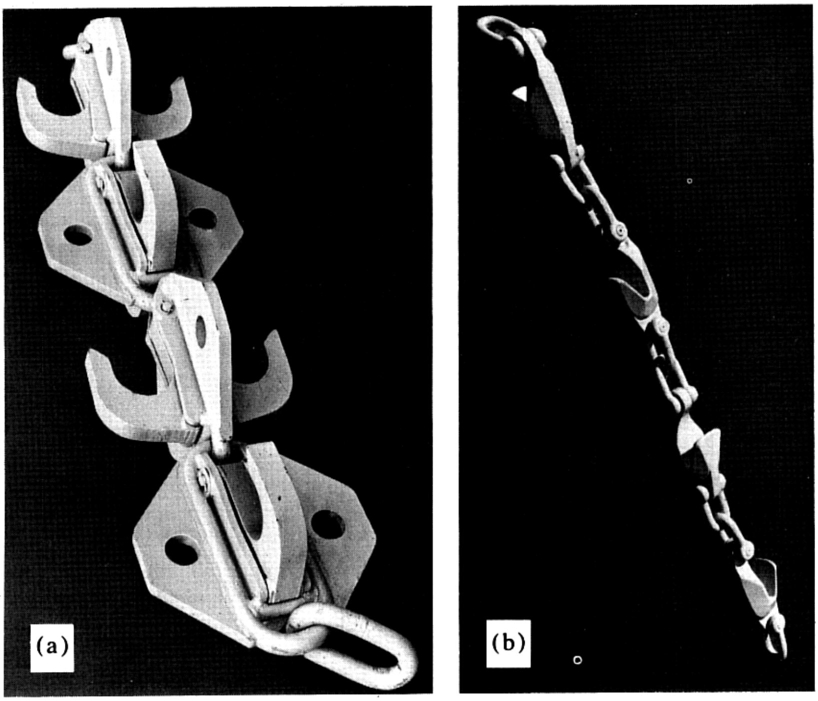

Fig. 7—Rennie and Gifford grapnels.

one end without applying a large tension which would displace the cable from its route.

The grapnel is powered by stored compressed nitrogen, and is hydraulically actuated. When the cable is engaged, a valve is operated which switches oil at 5,000 psi to a large ram with a six-start thread on the periphery of the cylinder. The ramrod is fixed, so the cylinder advances and, as it passes through a fixed nut, it rotates. Protruding horns are fixed to the cylinder and, when one of the horns catches the cable, a bight (loop) is belayed (wound) around the cylinder. At the end of the ram stroke, a second valve is operated which drives two guillotines whose blades can be positioned so that a predetermined side of the cable can be cut away, no matter which side is up when the grapnel lands on the sea bed, while the other cable end is left belayed around the cylinder. Thus one grapnel run cuts the cable and recovers one end.

A sonar surveillance system is built into the grapnel. The rate of transmitted pulses indicates the progress of the operation. The grapnel is suitable for operation to depths of 5000 fathoms.

4.5.3 Detrenching grapnel

An anchor-shaped detrenching grapnel was developed for the recovery of those sections buried by the cable plow. A prototype grapnel designed for a 36-inch (0.914 m) penetration in a granular sea-bed was successfully tried at sea in June 1976. Towing forces, although manageable, were high, and therefore a reduced penetration of 26 inches (0.660 m) has been chosen for the production grapnels. These should require towing forces of no more than 18,000 pounds (8165 kg).

V. CABLE PLOW

A new Bell System cable plow, designated Sea Plow IV,[12,13] was used to bury cable on both ends of TAT-6. The new plow is capable of burying cable and repeaters to a depth of 24 inches and of working in water depths up to 500 fathoms.

VI. CONCLUSION

This paper summarizes the electrical and mechanical designs and design modifications which were needed to lay, measure, and maintain an SG undersea cable link. The new automated laying test sets and shipboard computer facility were powerful and versatile tools which lifted the pressure of routine chores from test room personnel. The repeater monitoring set proved to be a highly useful and sensitive source of performance information on the undersea system. Modifications of the cable and repeater stowage and handling arrangements served well in the TAT-6 installation. The modified linear cable engine handled the large diameter SG cable smoothly.

The success of these numerous designs, involving several technical disciplines, is due to the expertise, dedication, and teamwork of many contributors, on both sides of the Atlantic. The authors humbly acknowledge their vital contributions.

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