Design of Armorless Ocean Cable

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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-

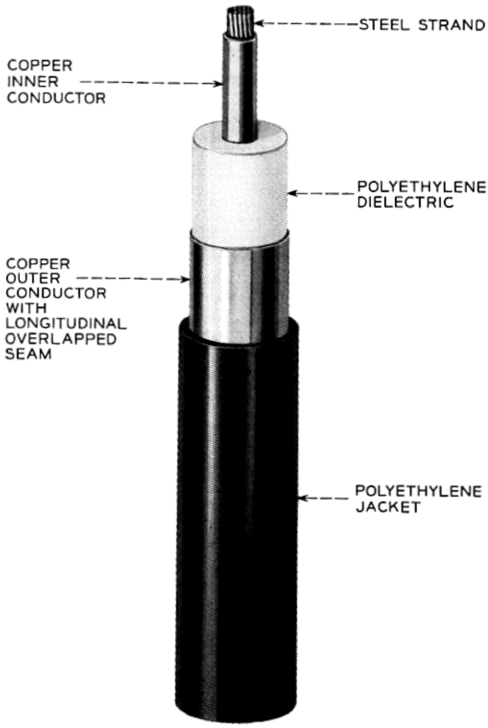

Fig. 1 — Armorless ocean cable.

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

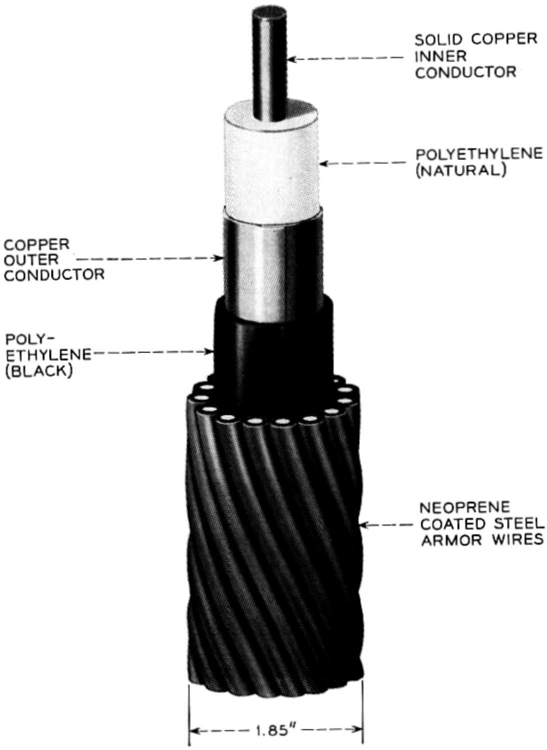

Fig. 2 — SD cable for shallow water.

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.

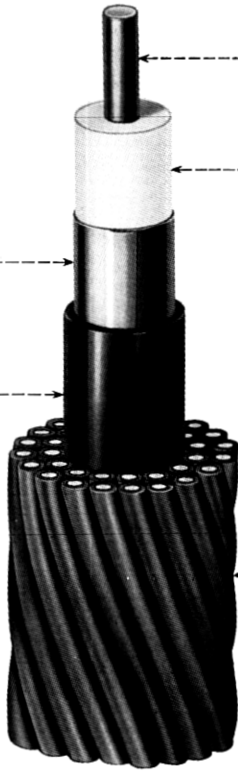

Fig. 3 — SD cable for shallow water, maximum protection.

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]

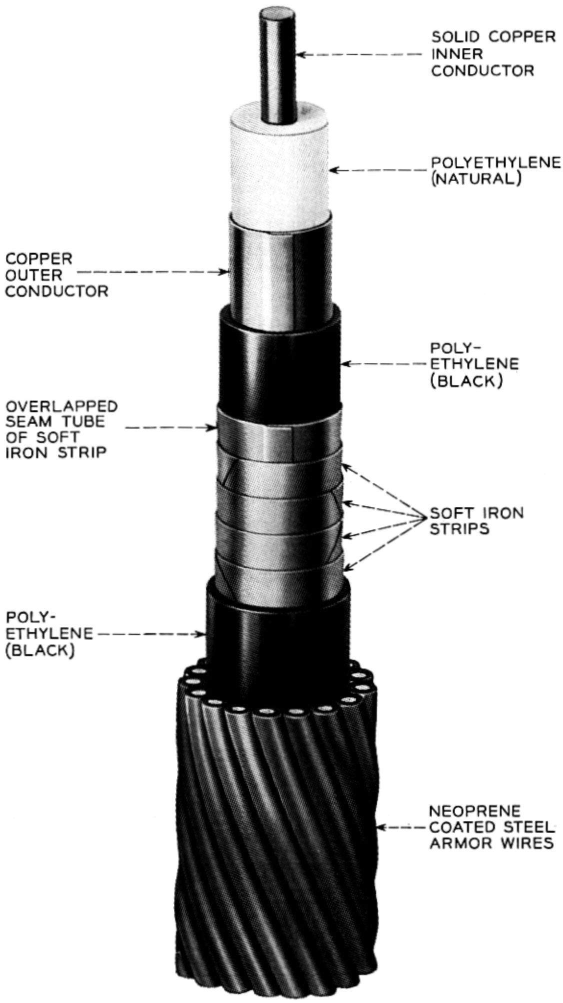

Fig. 4 — SD cable for shore ends.

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-

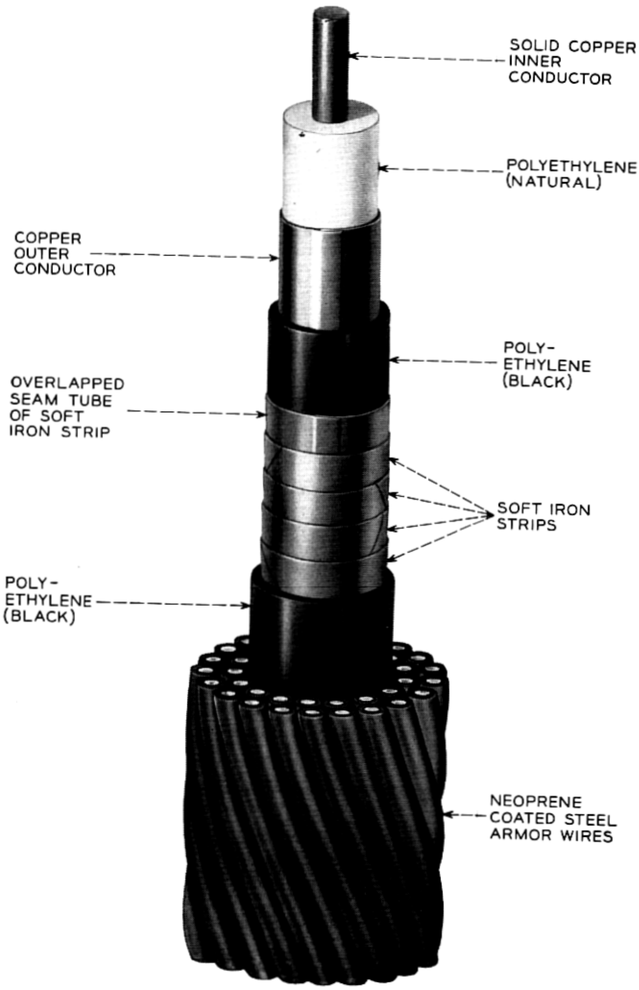

Fig. 5 — SD cable for shore ends, maximum protection.

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-

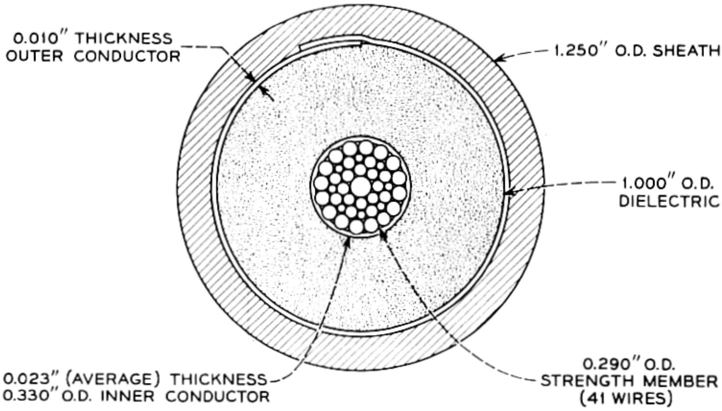

Fig. 6 — Cross section of armorless ocean cable.

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

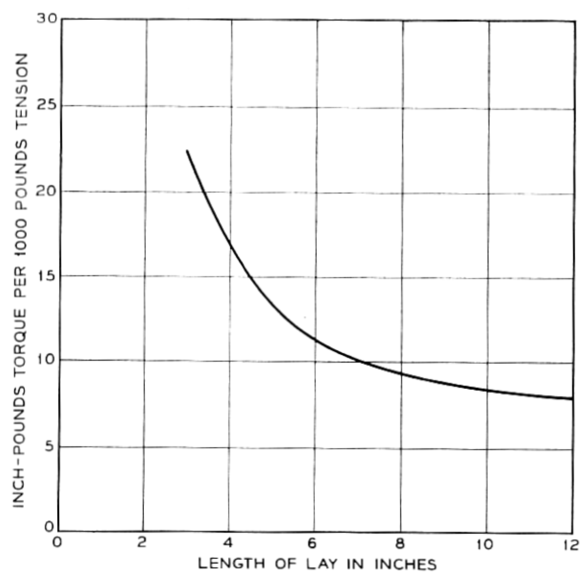

Fig. 7 — Torque vs length of lay for steel strand.

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 ±7 per cent and a diameter tolerance of ±0.5 mil. Additional requirements are imposed on the selection of combinations of wires to insure

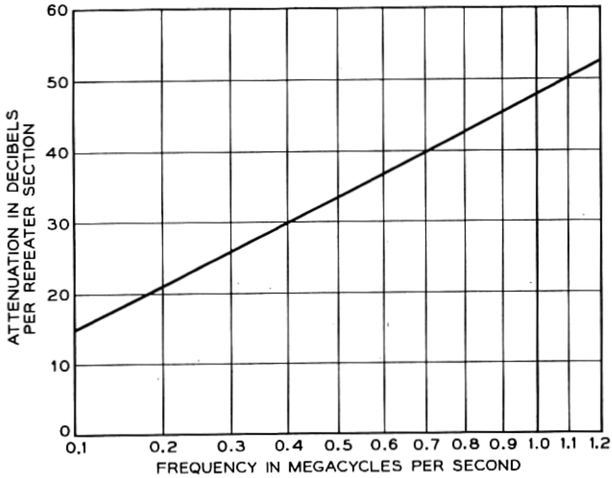

Fig. 8 — Nominal attenuation characteristic.

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 ±2 db, which is ±1.2 per cent at 0.1 mc and ±0.4 per cent at 1.0 mc. The ±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 ±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
ϵ = dielectric constant
σ_i, σ_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 ± 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]

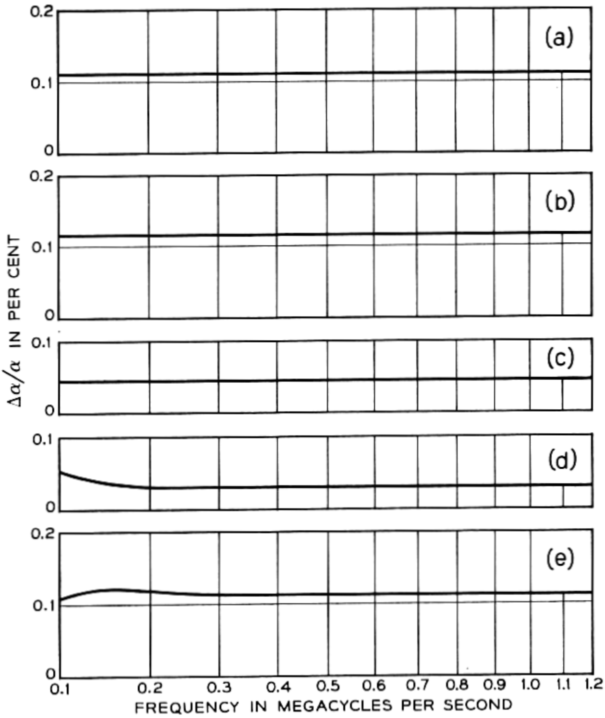

Fig. 9 — Tolerances having approximately cable shape: (a) per cent change in attenuation due to an increase in the dielectric constant of 0.005; (b) per cent change in attenuation due to a decrease in the diameter of the dielectric of one mil; (c) per cent change in attenuation due to an increase in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

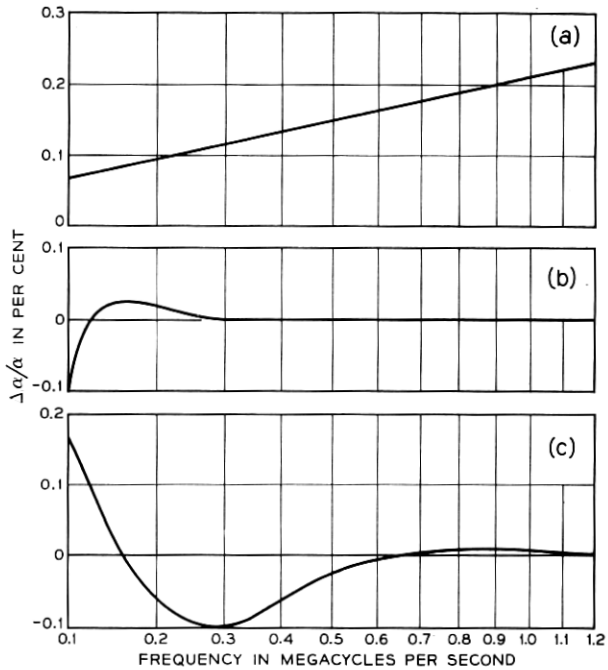

Fig. 10 — Tolerances not having cable shape: (a) per cent change in attenuation due to an increase in dissipation factor of 0.00002; (b) per cent change in attenuation due to a decrease in thickness of the inner conductor of 0.5 mil; (c) per cent change in attenuation due to a decrease in thickness of 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 ±1.2 db at 0.1 mc and ±3.0 db at 1.0 mc. Random combination of the tolerances would result in attenuation deviations of ±0.5 db at 0.1 mc and ±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 ±1.0 db. As a result of favorable experience with the design, the present objective at the manufacturing locations is ±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.

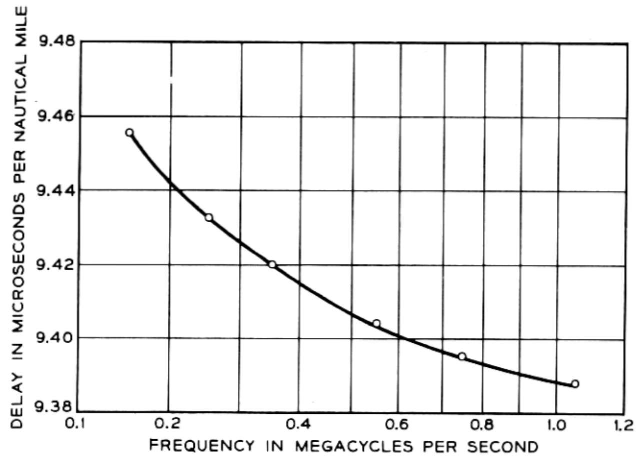

Fig. 11 — Measured phase delay (open circles) compared to theoretical (curve).

measured on an absolute basis to an accuracy of ±0.00002 db, temperature maintained at 3°C and measured to ±0.01°C and pressure was maintained at 5000 psi and measured to ±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

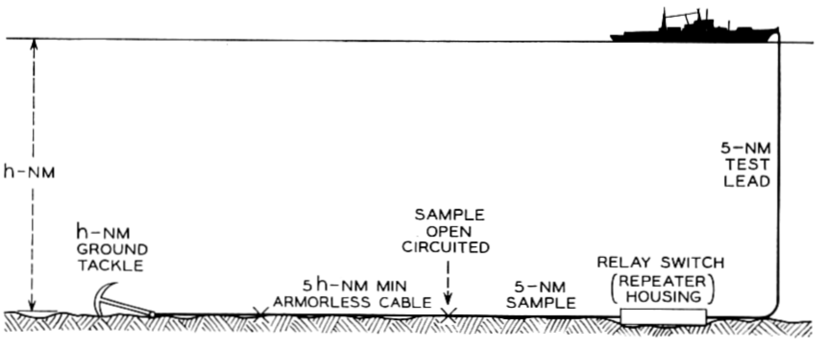

Fig. 12 — Cable arrangement for sea trial.

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.

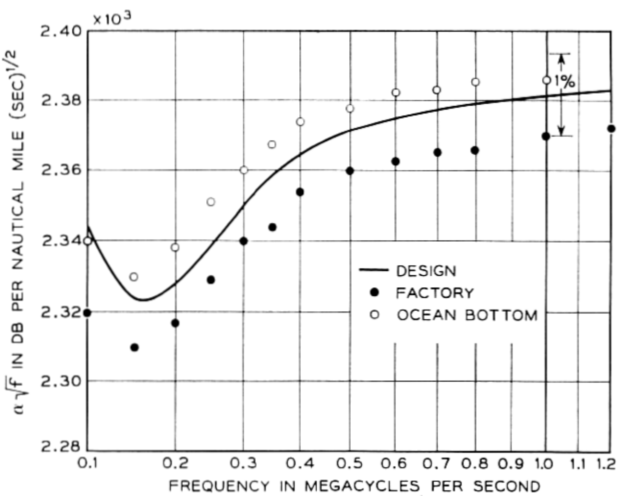

Fig. 13 — Attenuation of sea-trial cable design, as manufactured and on ocean bottom.

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 α is in radians per foot per pound of tension; the constant β is in radians per foot per inch-pound of torque. Both α and β 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 α and β would have values of 2×10^{-6} and 3.3×10^{-4}, respectively.

Values of α and β 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 α and β were 1.2×10^{-6} and 2.5×10^{-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

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