Cable Design and Manufacture for the Transatlantic Submarine Cable System

By A. W. LEBERT,* H. B. FISCHER* and M. C. BISKEBORN*

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The transatlantic cable project required that two repeatered cables be laid in the deep-water crossing between Newfoundland and Scotland, and one across the shallower waters of Cabot Strait. The same structure was adopted for the cables laid in the two locations.

This paper discusses the considerations leading to design of the cable and describes the method of manufacture, the means and equipment for control of cable quality, the process and final inspection procedures, the electrical characteristics of the cable, and factors relating to mechanical and electrical reliability of the final product.

DESCRIPTION OF CABLE

General features of the cable structure adopted for the transatlantic cable project[1] are illustrated in Fig. 1. The cable consists of two basic parts: (1) the coaxial, or the electrical transmission path, and (2) the armor or outer protection and strength members.

The coaxial is made up of three parts: (1) the central conductor, (2) the insulation, and (3) the outer or return conductor. The central conductor is composed of a copper center wire surrounded by three helically applied copper tapes. The insulation is a polyethylene compound which is extruded tightly over the central conductor. The insulated central conductor is called the cable core. The outer or return conductor is composed of six copper tapes applied helically over the insulation.

The protection and strength components shown in Fig. 1 for the type D deep water cable are provided by a teredo tape of thin copper applied over the outer coaxial conductor, a fabric tape binding, a layer of jute rove for armor bedding, the textile covered armor wires and finally, two layers of jute yarn flooded with an asphaltum-tar compound. This cable is characterized by the extra tensile strength of its armor wires and by the extra precautions taken to minimize corrosion of these wires.

* Bell Telephone Laboratories.

At the shallow water shore ends, the armor types are characterized by the use of mild steel wires which are increased in diameter in steps as the landing is approached. These types are designated A and B and will be described in greater detail later.

The transmission loss of this cable structure at the top operating frequency of 164 kc is 1.6 db per nautical mile and is 0.6 db per nautical mile at 20 kc, which is the lower end of the frequency band. The high frequency impedance of the cable is about 54 ohms.

BASIS OF DESIGN

A coaxial structure was first used for telephone and telegraph service in a submarine installation in 1921, between Key West and Havana, Cuba. Three coaxial cables with continuous magnetic loading and no submerged repeaters were laid. One telephone circuit and two telegraph circuits were provided in each cable for each direction of transmission.

In 1950, a pair of submarine coaxial cables,[2] which included flexible submerged repeaters, was laid between Key West and Havana, Cuba. Each cable furnished 24 voice circuits. One cable served as the "go" and the other as the "return" for the telephone conversations. The transatlantic telephone cable design is similar to this cable except that the nominal diameter of the insulation is 0.620″ instead of 0.460″. An outstanding difference between the transatlantic and Key West-Havana systems is cable length — about 2,000 nautical miles as compared with 125. This difference influenced significantly the permissible electrical and mechanical tolerances applying to the cable structure.

The installation of some 1,200 miles of cable with island based repeaters for a communication and data transmission system for the U. S. Air Force, between Florida and Puerto Rico,[3] followed the 1950 submarine cable system. The design of this cable is identical with that of the transatlantic cable, except for differences in the permissible dimensional tolerances on the components of the electrical transmission path. Data obtained on the electrical performance of the Air Force cable provided the transmission characteristic to which the repeaters for the transatlantic project were designed.

The design of this cable installation was the result of many years of cable development effort, which was guided by the successes and failures of the earlier submarine telegraph cables. The 1950 Key West-Havana and the Air Force cables differed from the earlier structures in one important respect, namely, the lay of the major components. A series of fundamental design studies during the 1930's and 1940's and extensive field tests in the Bahamas in 1948 demonstrated that having the same direction of lay of the major components of a cable was very important in minimizing kinking and knuckling. In addition, other laboratory tests pointed the direction for the adoption of new materials and techniques in the manufacture of these cables. These and subsequent improvements in materials and manufacturing techniques were included in the transatlantic cable design.

Since the electrical characteristics of a cable have a direct bearing on the overall system design and performance, considerable emphasis was placed on this phase of the design of the transatlantic cable. The size of

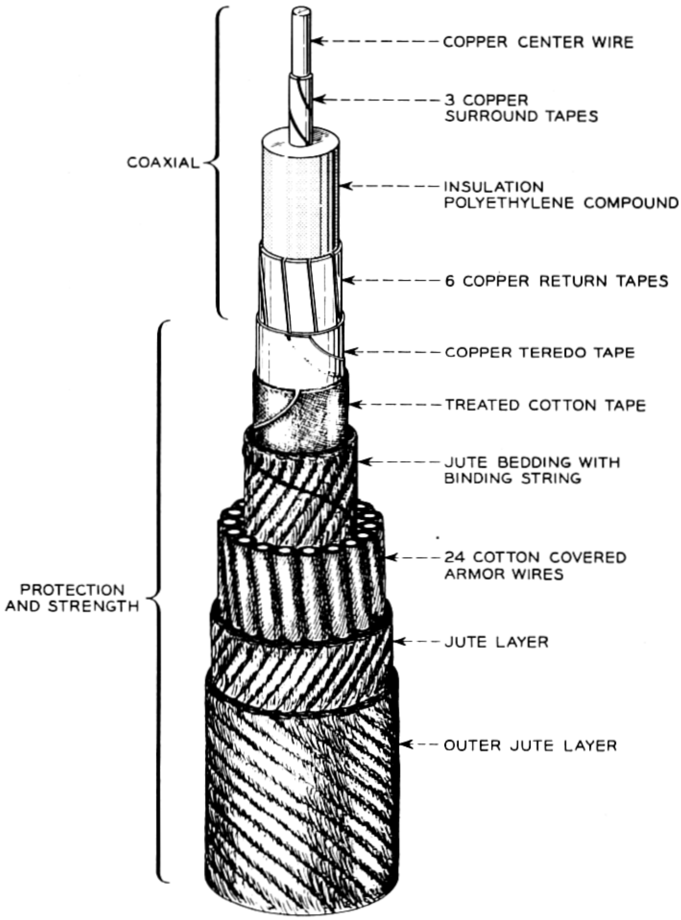
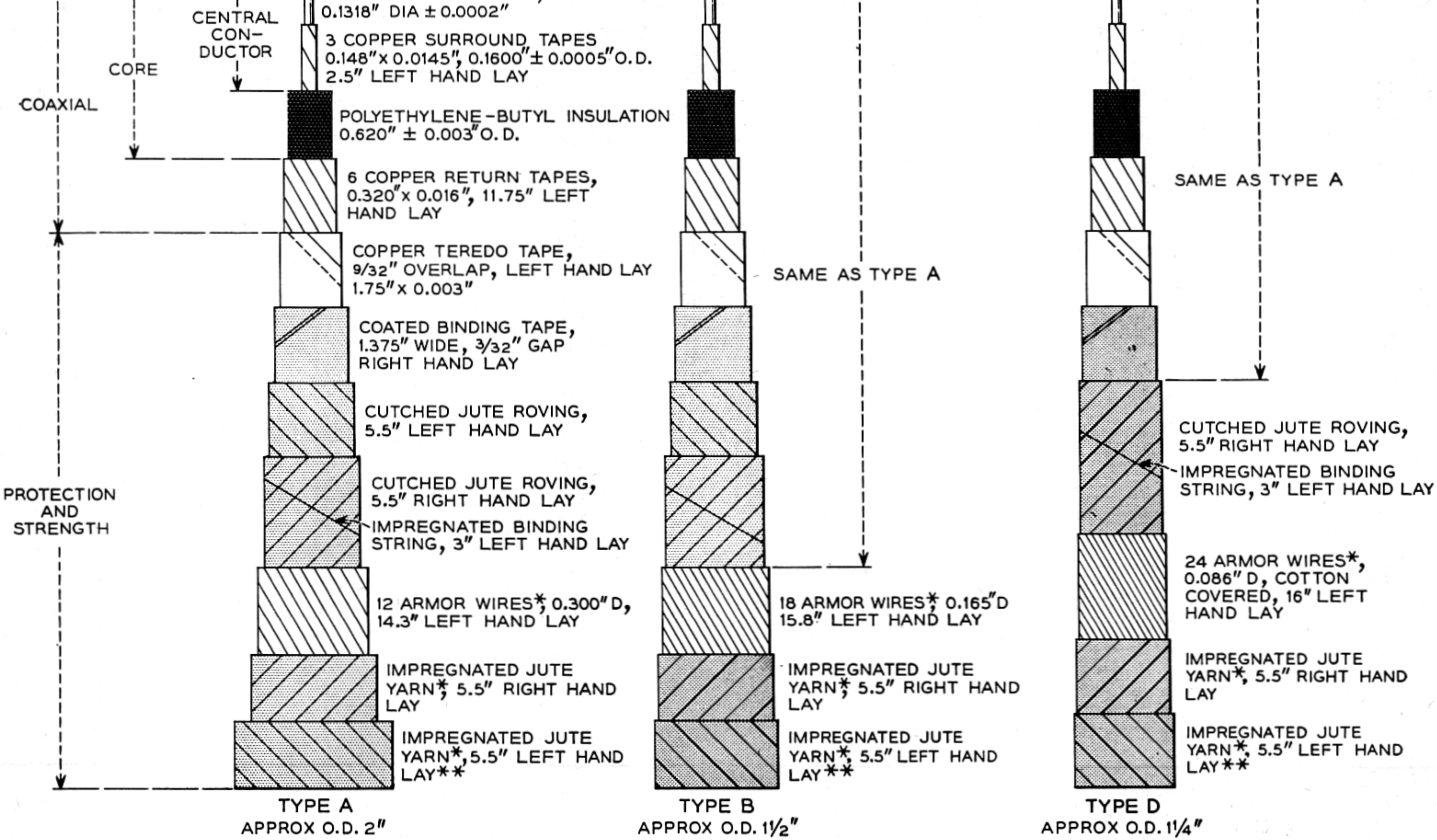


Fig. 1 — Structural features of the deep water type of cable.



*HOT FLOODING COMPOUND APPLIED DURING THESE OPERATIONS
**COATED WITH CALCIUM CARBONATE

Fig. 2 — Design details of the types of transatlantic telephone cable for different depths of water.

central conductor and core used in the Air Force cable resulted in low unit attenuation and low dc resistance. These advantages resulted in the adoption of this size of cable. However, the outside diameter of the core and the diameter of the central conductor of the coaxial do not fulfill the requirements generally described as optimum for minimum attenuation. Mathematical analysis shows that there is a preferred diameter ratio which results in minimum transmission loss. For the 0.620″ core diameter employed in the Air Force cable, the central conductor diameter chosen was smaller than the ideal central conductor required to satisfy the preferred diameter ratio. The diameter chosen retained the central conductor size which the Key West-Havana and Air Force cables proved to be satisfactory from a manufacturing standpoint. The choice was also compatible with the dc resistance requirement for transmission of power over the cable to each of the repeaters.

While production of the cable was proceeding, cable manufactured to the transatlantic specification was tested near Gibraltar in March, 1955. These tests provided a final evaluation of the mechanical and electrical characteristics of this cable before the actual laying of the transatlantic link.

DETAILS OF STRUCTURAL DESIGN OF CABLE

The structural features of the coaxial and of types A, B and D armor are summarized in Fig. 2.

A composite central conductor was chosen to provide a conductive bridge across a possible break in any one of its elements, due to a hidden defect, such as an inclusion of foreign material in the copper. The dimensions of the components of the central conductor were precisely controlled, and a light draw through a precision die was used to compact and size the assembly.

Use of high molecular weight polyethylene (grade 0.3) for core insulation is a major departure from the materials used in early submarine telephone and telegraph cables. The development of synthetic polymers such as polyethylene had led to the replacement of gutta percha as cable insulation, since polyethylene possesses better dielectric properties and mechanical characteristics and is lighter in weight.

Ordinary low molecular weight polyethylene is subject to environmental cracking, especially in the presence of soaps, detergents and certain oils. High molecular weight material is much less subject to cracking, and by adding 5 per cent butyl rubber, further improvement in crack resistance is obtained.

Six copper tapes applied helically over the core comprised the return conductor and thus completed the coaxial structure. The dimensions of these tapes were precisely controlled. The helical structure was chosen to impart flexibility to the coaxial.

Insulation of some of the early submarine telegraph cables suffered from attack by marine borers such as the teredo, pholads and limnoria. To protect against such attack, a thin metallic tape was placed over the insulation in the early submarine cables. The necessity for such protection for the transatlantic cables, especially in deep water, may be questioned, but the moderate cost of this protection was considered cheap insurance against trouble. The copper teredo tape was applied directly over the return conductor, as a helical serving with overlapped edges to completely seal the coaxial from attack by all but the smallest marine organisms.

A cotton tape treated with rubber and asphaltum-tar compound was applied over the teredo tape to impart mechanical stability to the coaxial during manufacture. A small gap between adjacent turns of the helix was specified to permit ready access of water to the return tape structure and to the surface of the core. The use of a gap was based on laboratory tests which showed that transmission loss was dependent to a modest extent on thorough wetting of the exterior of the coaxial. Since transmission loss measurements are made on repeater sections of cable shortly after manufacture to determine whether any length adjustments are required, it was essential that the wetting action be as rapid as possible.

The design of the protection and strength components of the cable was modified according to the depth of the water in which the cable was to be laid. To prevent damage to the coaxial by any cutting action of the armor wires during manufacture and laying, a resilient cushion of jute roving was placed between the armor wires and coaxial. For type-D cable, a single layer of jute was used; for types A and B cable, the bedding was made up of two layers of jute. To protect this jute from microbiological attack, a cutching treatment was employed. The traditional

TABLE I

Type	Armor Wire			Application
	Number of Wires	Diameter in Inches	Material	
A	12	0.300	Mild Steel	Up to 350 fath.
B	18	0.165	Mild Steel	350 to 700 fath.
D	24	0.086	High Strength Steel	Greater than 700 fath.

cutching process consists of treating the jute with a vegetable compound called catechu or cutch.

Armor wires were applied over the bedding jute. The use of heavy or intermediate weight near shore has been established by experience with ocean cable. This type of armor is generally employed where the cable may be exposed to wave action, bottom currents, rocks, icebergs, ship's anchors and fishing trawlers. A lighter weight structure having higher tensile armor wires is needed in deep water. Table I shows the essential differences between the armor types employed in the transatlantic cable and the approximate range of depths in application.

In addition to the above armor types, a shore length of 0.6 nautical mile was provided with an insulated lead sheath under Type A armor to facilitate preferred grounding arrangements and to provide signal to noise improvement.

Where the tensile strength of the armor wires is most important, as in the type D design, each of the wires was protected against corrosion by a zinc galvanize plus a knitted cotton serving or helically applied tape, the whole assembly being thoroughly saturated with an asphaltum-tar compound. The effectiveness of such protection is clearly apparent when early submarine cables, which used this protection, are recovered and examined. For the heavier armor types, the protection was similar to that of type D, except that the textile serving was replaced by a dip treatment to coat each wire with an asphaltic compound.

As the armor wires were applied to each type of cable additional protection was obtained by flooding the cable with a special asphaltum-tar compound and then applying two layers of jute yarn over the wires. The jute yarn was impregnated with an asphaltum-tar compound before application to the cable and then flooded with another asphaltum-tar compound after application. Formulation of cable flooding materials required the use of compounds having a relatively high coefficient of friction to avoid slippage of the cable on the ship's drum during laying.

To assure satisfactory handling characteristics during the laying operation, all of the metallic elements of the cable were applied with a left-hand direction of lay and the lengths of lay (except for the teredo tape) were chosen so that approximately the same helical length of material was used per unit length of cable. Since the teredo tape was relatively soft and ductile compared to that of the other metallic components, it was not necessary to equate its helical length to that of the other components. Width and lay of the teredo tape were selected to give a smooth, tight covering.

The choice of direction and length of lay of the jute layers was based on experience with cable in factory handling and laying trials. Experience, particularly with the direction of lay, has shown that improper choice of lays for the two outer layers of jute may result in a cable that is difficult to coil satisfactorily in factory and ship storage tanks. The combination of lays selected for the cable components provided good performance in all the handling operations, including the final laying across the Atlantic.

MANUFACTURE OF THE CABLE

Before considering the manufacture of the cable, it should be understood that the repeater gain characteristic was designed to compensate for the loss characteristic of the cable. Therefore, once this loss characteristic was established, it was essential that all cable manufactured conform with this characteristic.

To obtain the required high degree of conformance, close control had to be kept over all stages of manufacture and over the raw materials. Controls to guide the manufacture of the cable were set up with two broad objectives:

1. To produce a structure capable of meeting stringent transmission requirements.
2. To assure that the manufactured cable could be laid successfully and would not be materially affected by the ocean bottom environment for the expected life of the cable system.

Attainment of a final product capable of meeting the stringent transmission requirements is described in a later section of this paper. Process and raw material controls in manufacture were provided by an inspection team which checked the quality of the various raw materials and the functioning of the several processes during the manufacturing operations. This type of inspection coverage is somewhat unique with submarine cable. It assures the desired final quality by permitting each error or accident to be investigated and corrected on an individual basis.

Cable for the transatlantic crossing was manufactured in America by the Simplex Wire and Cable Company and in England by Submarine Cables, Limited. Differences in machinery and equipment in the plants of the two manufacturers necessitated minor differences in the sequence of the operations and in the processes. The sequence of operations in assembly of the cable was as follows:

Step No.	Operation
1	Stranding of central conductor
2	Extrusion of insulation
3	Runover examination, repair where necessary

4 Panning and testing of core
5 Jointing of core
6 Application of return tapes, teredo tape, fabric tape, jute bedding and binding string
7 Application of armor wire and outer jute layers
8 Storage in tanks, testing
9 Splicing in repeaters, testing

The only important difference in the sequence of the manufacturing operations at the two plants was the use of separate operations for steps 6 and 7 at Submarine Cables and the combination of these operations in one machine at Simplex.

Other minor differences in process methods related to raw materials. For example, the American supplier purchased polyethylene already compounded with butyl rubber and antioxidant in granule form, ready for use. The British supplier purchased polyethylene, butyl rubber and antioxidant separately, and performed the compounding in the cable factory.

STRANDING OF CENTRAL CONDUCTOR

The central conductor was stranded on a machine which included a revolving carriage with suitable arbors for the three surround tapes. It was equipped with brakes designed to assure equal pay-off tension among the tapes and with detectors to automatically stop the strander in case of a tape break. Each tape was guided through contoured forming rolls to shape the tape to the center wire.

The joints between successive reels of wire and tape used in fabrication of the central conductor were butt brazed. The brazes were staggered to avoid more than one braze in a given cross-section of the conductor. The quality of the brazes in these components was controlled by a qualification technique described below in the section on core jointing.

The strand was drawn through several forming dies to size the finished diameter of the central conductor accurately. No lubrication was used because the removal of the resultant residues, which could contaminate the polyethylene insulation, was difficult. The taper in the central conductor diameter due to the die wear was controlled by appropriate replacement of tungsten carbide dies, where used, or by the use of a diamond die where the rate of die wear is less than 1 or 2 micro-inches per mile.

The stranding area in both plants was enclosed and pressurized to guard against dirt and dust settling on the central conductor. A high standard of cleanliness was maintained for parts of the machine which touched the conductor or its components. Undue wear of the guide faces

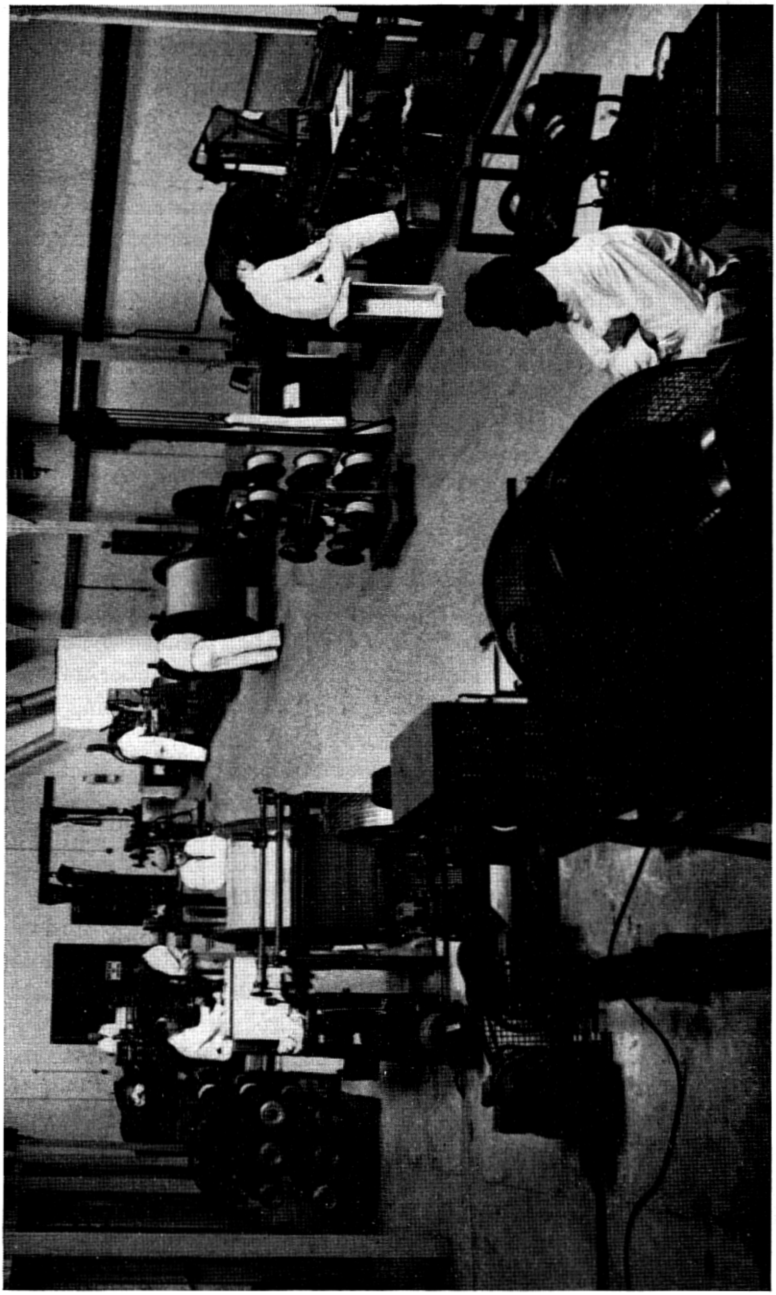


Fig. 3. — View of typical manufacturing area for stranding of central conductor.

or capstan sheaves was cause for replacement of the sheaves and adjustment of the machine. A photograph of the stranding area is shown in Fig. 3.

EXTRUSION OF INSULATION

To avoid possible contamination of the polyethylene insulating compound in the extruder-hopper loading area, a pressurized enclosure prevented entry of air-borne dust and dirt, and the containers of polyethylene compound were cleaned with a vacuum cleaner before being brought into the hopper area. A fine screen pack placed in the extruder reduced the possibility of contamination in the core.

In passing through the extruder, the central conductor was payed-off of a large reel with controlled tension, into the pay-out capstan, through an induction heater, through a vacuum chamber, and thence into the cross-head of the extruder. The induction unit heated the central conductor and provided means for controlling the shrinkback of the core insulation and the adhesion of the conductor to the insulation. Shrinkback is a measure of the contained stresses in the insulation.

On the output side of the extruder, the core was cooled in a long sectionalized trough containing progressively cooler water from the input to the output end. The annealing of the polyethylene in the cooling trough also served to hold the shrinkback of the core to a low value. The extrusion shop is shown in Fig. 4.

An important addition to the extrusion operation consisted of the use of an improved servo system to control the extruder automatically to attain constant capacitance per unit-length of coaxial. The system used is described in a subsequent section.

RUNOVER EXAMINATION

Following extrusion, the core was subjected to continuous visual and tactual examination in a rereeling operation called "runover". The purpose of the runover operation was the detection of inclusions of foreign material in the dielectric and the presence of abnormally large or small core diameters. Core not meeting specification requirements was cut out or repaired.

In addition to visual inspection of the cable, examination of short lengths of core was made at regular intervals with a shielded source of light arranged to illuminate the interior of the dielectric material. Provision of this internal illumination facilitated detection of particles of foreign material well beneath the surface of the core. Strip chart records

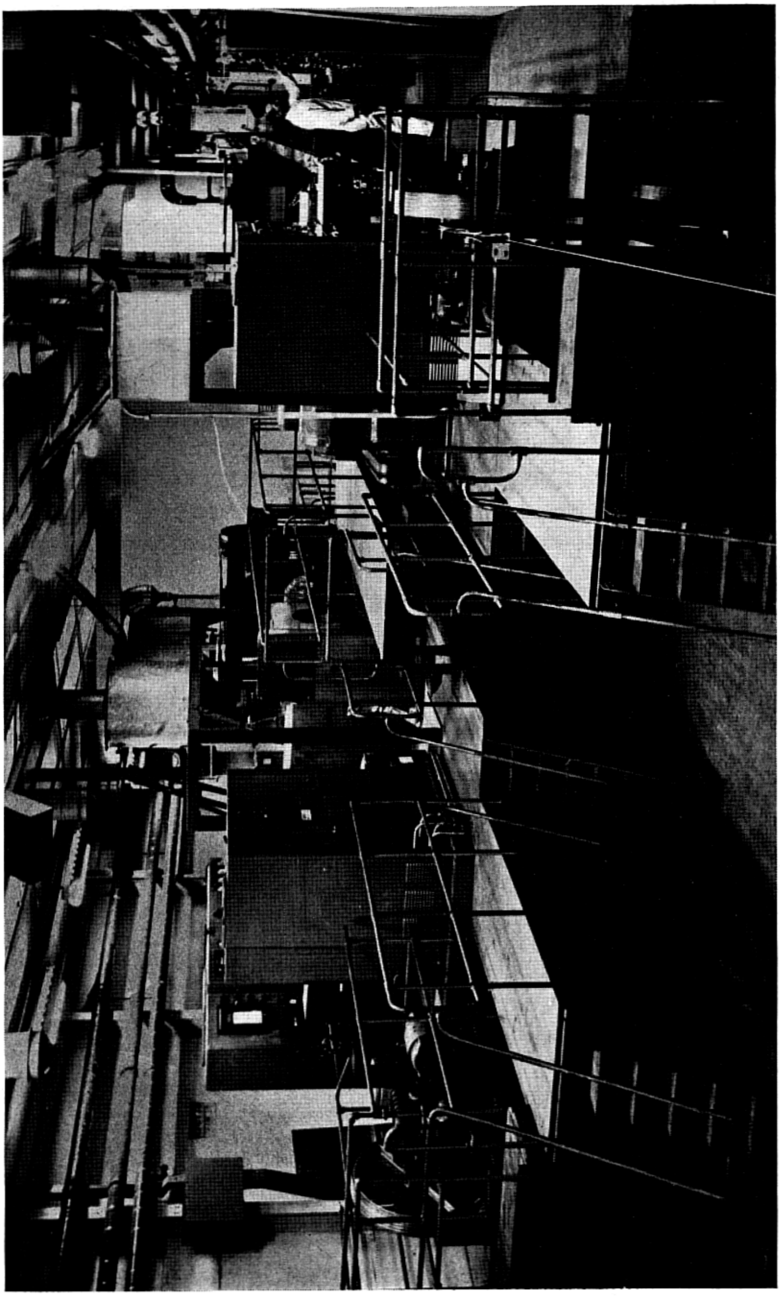


Fig. 4 — View of typical manufacturing area for extrusion of core insulation.

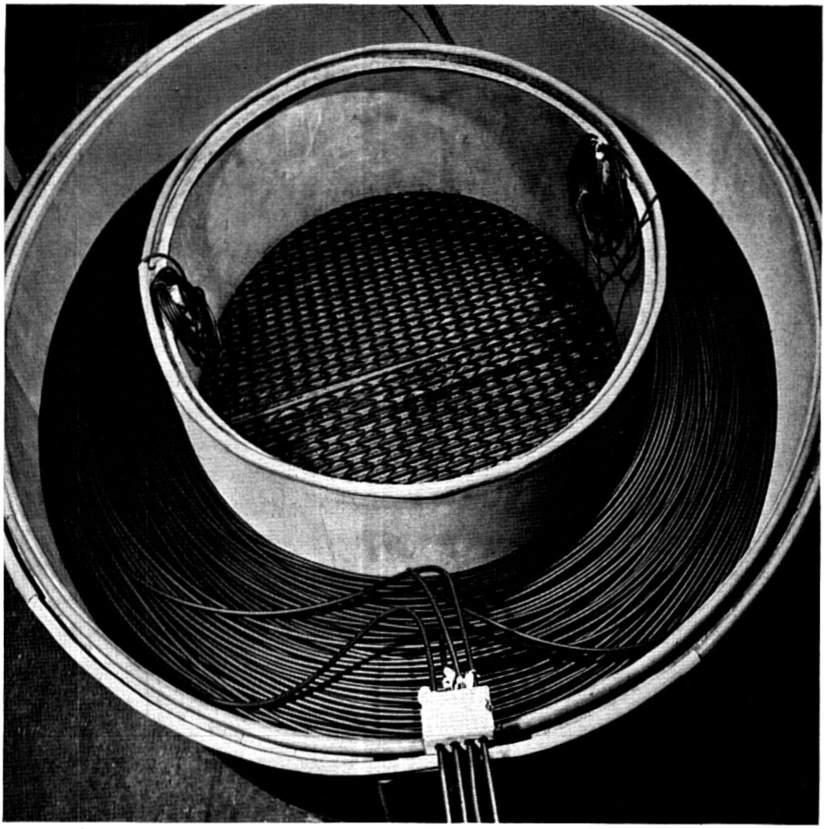


Fig. 5 — Special water tank or pan for tests on immersed cable core.

of the unit-length capacitance of the core obtained during extrusion were used as a guide in searching out regions of uncertainty.

PANNING AND TESTING

After runover, the core was coiled in tanks of water, as shown in Fig. 5. Precautions were taken to remove the air dissolved in the water and thus prevent the formation of bubbles on the surface of the core. The water was also temperature controlled and circulated to maintain uniform temperature throughout the tank. Thermocouples placed at different levels in the tank determined when the temperature was uniform. Measurements of dc conductor resistance, ac capacitance, insulation resistance, and dielectric strength were then made. These measurements are discussed in detail in a later section of this paper.

JOINTING OF CORE LENGTHS

The cable core was manufactured in lengths much shorter than a repeater section, which necessitated connecting the individual core lengths together. Jointing techniques consisted of brazing the central conductor with a vee-notch type of junction and of molding in a short section of the polyethylene insulation. After silver-soldering the vee-joint, a safety wire consisting of four fine gauge tinned copper wires was bridged across the junction in an open helix and soft soldered at the ends. Extreme care was taken to remove any excess rosin and to eliminate any sharp points on the ends of the safety wires. The safety wire is intended to maintain continuity of the electrical path in case the braze should fail.

Visual examination of brazes in the actual cable was the only means available for their final inspection. To assure a high degree of quality on these brazes, a system was devised for checking the performance of the operator and the brazing machine initially and at frequent intervals through the use of sample brazes in each of the components, which were tested to destruction. To control the uniformity of brazes, the brazing of the copper wire and tapes was made as automatic as possible by the use of controlled pressure on the components, appropriate sized wafers of silver solder, and an automatically timed heat cycle. The tests on the brazes used to qualify operators and machinery indicated that a high degree of braze performance was achieved.

Pressure and temperature were carefully controlled during the molding of the insulation over the conductor. Periodic checks similar to those described for brazes were made on operator and molding-machine to maintain a satisfactory level of performance. In addition, each molded joint placed in the actual cable was X-rayed and subjected to a high voltage test while immersed in water.

APPLICATION OF RETURN TAPES AND ARMOR WIRES

After the core lengths were joined together, they were pulled through the return taping and armoring operations. The machine for applying return tapes was designed specifically for the purpose and was similar in characteristics to the corresponding portion of the strander for the central conductor. Controlled pay-off tension, automatic breakage detectors, precision guides, and contoured forming rolls to shape the tape, were incorporated in the construction.

The return tape, teredo tape, and fabric tape were applied from taping heads, and the bedding jute and binding string were applied from serving heads in a tandem operation. Another set of tandem operations included the application of armor wires, outer jute layers and the appropriate asphaltum-tar flooding compounds. In the American suppliers plant, both sets of tandem operations were combined into one continuous production line. In the British plant, these operations were divided into two separate production lines. A view of the armoring machine area is shown in Fig. 6. Following the application of the flooding compounds, whiting is applied either at the take-up capstan on the armoring line or in the storage tanks as the cable is coiled.

To avoid core damage, the flow of hot flooding compound was stopped when the cable in the armoring line was stopped. One of the major sources of such stoppages was the reloading of the various applicating heads.

STORAGE AND TESTING

In a continuous haul-off operation, the cable was conveyed from the armoring machine to the tank house for storage. The cable was coiled in spiral layers, called flakes. Each flake started at the outside rim of the tank and worked toward the central cone. Several 37-nautical mile repeater sections were stored in each tank.

Water was circulated through the cable tanks to establish uniform temperature conditions throughout the mass of cable. When thermocouples located at appropriate points in the tank indicated that the cable temperature was uniform, measurements were made of attenuation, internal impedance irregularities and terminal impedances, dc resistance, dc capacitance, insulation resistance, and dielectric strength.

To facilitate these tests without interrupting production, successive repeater section lengths were placed in alternate tanks. By this procedure, a group of four or five sequential repeater section lengths, called an "ocean block", was stored in two tanks. The ends of each repeater section were brought out of the tank to a splicing location. After all tests were completed and the specification requirements met, the repeaters were spliced in. Testing of the ocean block for transmission performance completed the manufacturing operations.

RAW MATERIALS

Stringent requirements were placed on all raw materials used in the manufacture of the transatlantic cable. Detailed specifications covered

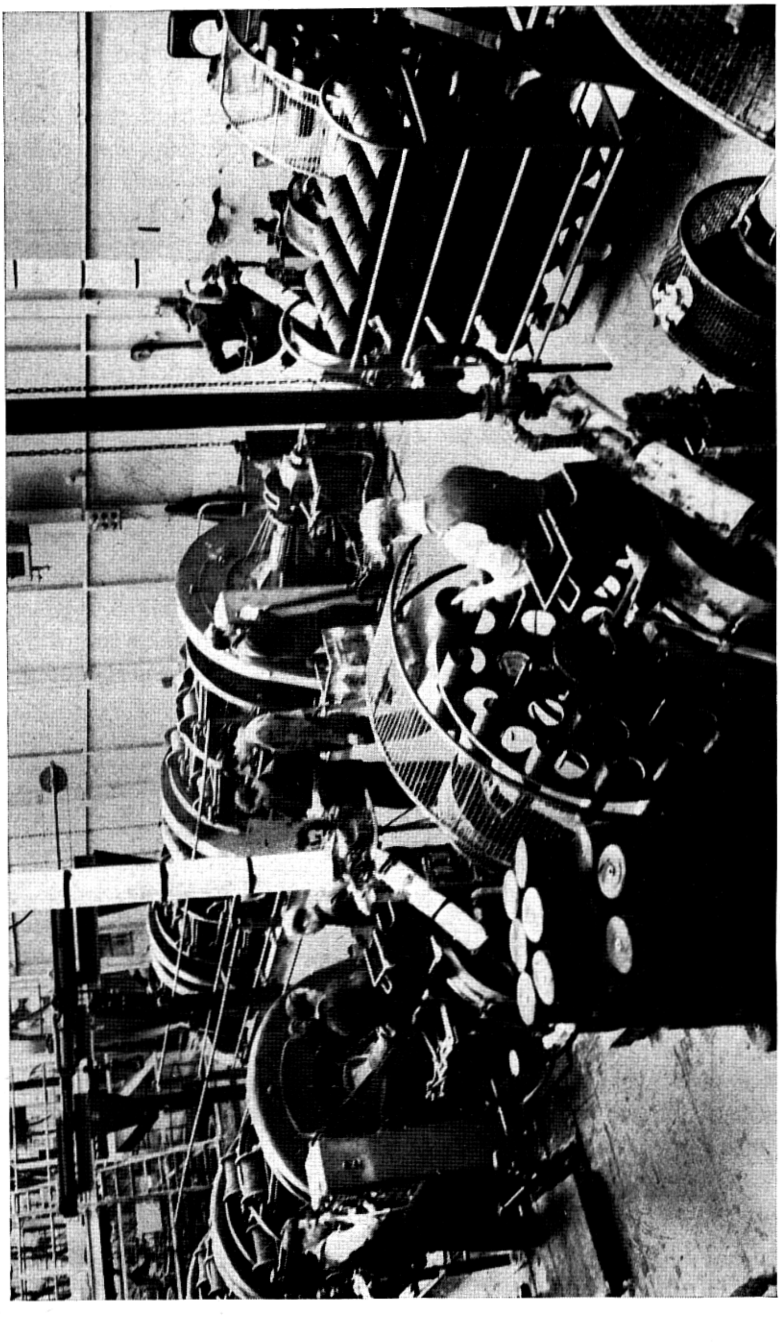


Fig. 6 — View of shop for application of cable armor.

the basic requirements and the methods of controlling their quality on a sampling inspection procedure. The requirements for the materials were established to insure that their use would not jeopardize the life of the cable. Since cable life is critically related to the integrity of the insulation, all materials had to be scrutinized for their tendency to cause environmental cracking. These tests were necessarily made on an accelerated basis. Since no correlation exists at present between accelerated tests and long term (20 year) life tests, only conservative design selections can be justified.

Close tolerances such as ± 0.0002 inch for the diameter of the solid center wire in the central conductor were specified for all copper components of the coaxial. In addition, these components had to be free from slag or other inclusions, and the wire drawing and rolling of the tape had to be controlled to assure smooth surfaces, edges of prescribed shape, and freedom from filamentary imperfections. Compounds used in drawing and rolling operations were selected to minimize the possibility of contaminating or causing cracking of the polyethylene. Residual quantities of compound on the wire or tapes were removed prior to annealing, which was controlled to prevent the formation of oxides and to assure clean and bright copper.

The dielectric constant range of the polyethylene-butyl compound was limited to 2.25 to 2.29. These limits were determined by the limited accuracy of the measuring equipment available at the time. Restrictions covered the allowable amount of contamination since its presence in other than minute quantities might reduce the dielectric strength or degrade the power factor of the compound.

In addition, the melt index (a factor related to molecular weight) of the final insulating compound composed of polytheylene resin, butyl rubber, and antioxidant, was held to 0.15 to 0.50. The melt index of ordinary polyethylene used for insulation generally, is 2.0 or higher. Choice of the low index assured the maximum resistance to environmental cracking.

The cutching and fixing processes used in the manufacture of bedding jute were adjusted to limit the alkalinity of the jute because of the adverse effect of alkaline materials on polyethylene compound. Oils used in the spinning of the jute were selected to obtain types which were not strong cracking agents for polyethylene, and the quantities used were reduced to the workable minimum. The presence of such impurities as bark and roots was restricted to provide the desired fiber strength. The impregnation of the jute was controlled to ensure adequate distribution of the coal tar throughout the fibers without having an excess that would make the jute difficult to handle during the armoring process.

The size, composition, and processing of the armor wires were also placed under close control. Purity, tensile strength, and twist requirements were designed to ensure that the wire could be applied to the cable, and welded, and that it could withstand the expected tensions during laying and pickup. Strength considerations made it mandatory that inclusions of slag or piping of the wire be eliminated. Piping is an unusual condition encountered during rolling or drawing which results in a hollow shell of steel which may be filled with slag.

CONTROL OF TRANSMISSION CHARACTERISTICS

From a broad point of view, the attainment of a final product capable of meeting the stringent transmission requirements was achieved by the following basic steps.

1. Precision control of the dimensions of the copper conductors, including the diameter of the fabricated central conductor.
2. Automatic control of the insulating process to maintain a constant capacitance, thus compensating for deviations in central conductor diameter and dielectric constant of the insulation.
3. Factory process control, by means of a running average of the measured attenuation characteristic of current production, to guide the adjustment of suitable parameters when necessary.

As indicated in the sections above on the method of manufacture and the control of raw materials, precautions were taken to obtain a central conductor that had predictable electrical performance, and a controlled taper in overall diameter along its length. The need for such effort is explained by consideration of the factors that determine the attenuation of a coaxial structure.

The attenuation, α, of the cable is directly proportional to the ac resistance, R, and inversely proportional to the characteristic impedance, Z_0, as a satisfactory approximation. That is,

$$\alpha = \frac{\mathrm{a}R}{Z_0}\, db/nm$$

where "a" is a coefficient depending on the units. It is thus clear that control of α may be attained by control of R and Z_0. Since the resistance is a function largely of the diameter of the central conductor, and since it is held to close tolerances, the constancy of impedance completes the requirement for attenuation control.

The characteristic impedance of a transmission line is determined by:

$$Z_0 = b\sqrt{\epsilon}\log\frac{D}{d}\text{ ohms}$$

where ϵ is the dielectric constant of the insulating material, D is the inside diameter of the outer conductor, d is the diameter of the inner conductor, and b is a numerical coefficient. If the dielectric constant of the insulating material (polyethylene) does not vary, control of characteristic impedance reduces to control of capacitance. This follows from the fact that the capacitance, C, is related to the D/d ratio as follows:

$$\frac{D}{d} = \text{antilog}\frac{k\epsilon}{C}$$

where k is a numerical coefficient.

Precision control of capacitance during the insulating process is achieved by a double-loop linear servo system, as shown in a simplified block diagram, Fig. 7. The two loops consist, respectively, of one capable of introducing relatively fast capacitance corrections of only modest accuracy and of one capable of highly precise capacitance control on a relatively long time basis. The servo system controls the capstan payout

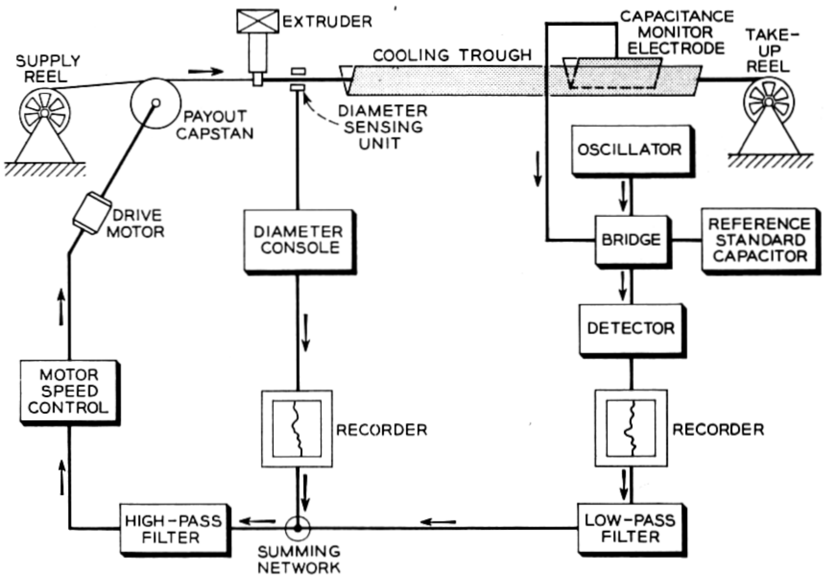


Fig. 7 — Simplified block diagram of capacitance monitor servocontrol system.

speed of the central conductor feeding into the extruder applying the core insulation, as shown in the block diagram. Since the extruder delivers insulating material at a constant rate, an increase in central conductor speed results in a thinner than normal wall of insulation and thus causes an increase in capacitance.

The sensing element for the control loop consists of a capacitance monitor. This is a device capable of measuring the unit length coaxial capacitance of the cable core continuously as it moves through the water in the trough. Since the capacitance of a polyethylene insulated core is temperature sensitive, the monitoring electrode must be located at a point in the cooling trough where the temperature of the core is stable and known to a degree commensurate with the overall accuracy objectives. The distance from the extruder to the electrode corresponds to about 10 minutes of cooling time; hence, a servo system based on this loop would be necessarily slow, due to the 10-minute delay in detecting a drift in capacitance.

Analysis shows that fast capacitance information of only moderate accuracy may be used in combination with the slow loop to speed up the response of the overall system to a satisfactory degree, without sacrifice of precision of the slow loop. The sensing element used for the fast loop consisted of a light-ray diameter gauge, which measures the diameter (changes in diameter are the approximate inverse of the capacitance) of the hot core close to the extruder. The slow and fast data are combined to control the extruder, as shown in the block diagram.

The servo constants were chosen to minimize the deviations in unit length capacitance occurring in core lengths corresponding to less than $\frac{1}{4}$ wave length of the top operating frequency. Stated in other words, the objective for choice of servo loop constants was to assure equality in the capacitance of all $\frac{1}{4}$ wave sections of core. Echo measurements indicated that a highly satisfactory degree of control was achieved. Overall servo system performance was such that the standard deviation of the capacitance of the core lengths manufactured for the two crossings was ± 0.1 per cent. The capacitance monitor electrode and the servo console is illustrated in Fig. 8.

ADJUSTMENT OF CONCENTRICITY

Means for setup and adjustment of the extrusion process to achieve relatively accurate centering of the conductor in its sheath of insulation was provided by a device called a concentricity gauge. This device operates on the principle that two small, plane electrodes on opposite

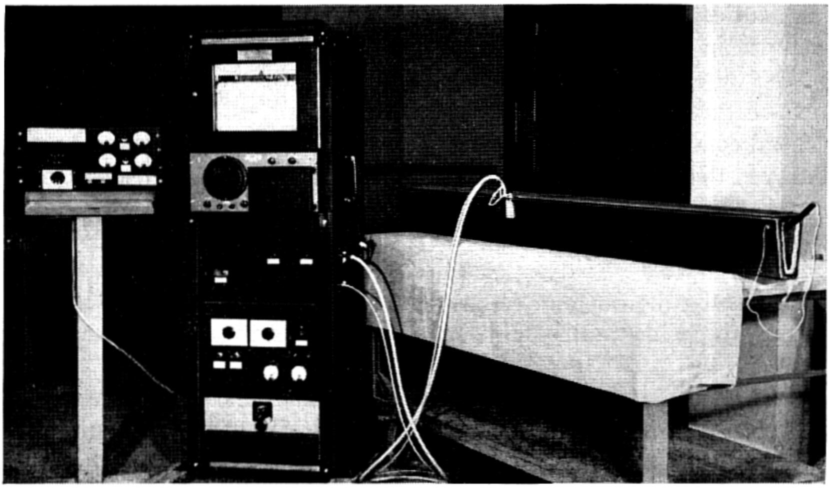


Fig. 8 — Photograph of capacitance monitor electrode and servo-controller console in laboratory setup.

sides of the core will have different direct capacitances to the central conductor, when the conductor is not properly centered.

A simplified block diagram of the concentricity gauge is shown in Fig. 9. Data obtained with two sets of electrodes displaced 90° were recorded on a strip chart recorder, with the output of the two sets of electrodes being displayed alternately. A satisfactory degree of centering was moderately easy to maintain.

ELECTRICAL MEASUREMENTS

To assist in achieving the goal of matching the cable and the repeater characteristics with a minimum of deviations, electrical measurements were made throughout the process and close tolerances were placed on the electrical parameters in each stage of production. Measurements on the repeater section lengths of cable were used as a final check to determine the extent to which all of the controls had been successful. The primary standards used were calibrated by the Bureau of Standards in the United States or the National Physical Laboratories in England. These precision standards were used to calibrate the bridges frequently.

The dc resistance of the central conductor was measured under constant temperature conditions with a precision type of Wheatstone bridge. The permissible range of resistance was 2.514 and 2.573 ohms per nautical mile at 75°F. In practice, the spread of resistance values was well within these limits.

The 20-cycle core capacitance was also measured under constant-temperature conditions. For this measurement, the two ends of the central conductor were connected together and the measurements made between the central conductor and ground, which was provided by the water. A capacitance-conductance bridge was used for this purpose. The capacitance limits set initially were from 0.1726 to 0.1740 microfarads per mile at 75°F. Analysis of the core measurements indicates that at each factory the range of capacitance was held more closely than indicated, which illustrates the benefits of servo control to the insulating process.

The dc insulation resistance of the core was also measured by applying 500 volts for one minute. A minimum insulation resistance requirement of 100,000 megohm-miles at 75°F was established, but any lengths that had less than 500,000 megohm-miles were scrutinized for possible sources of trouble and were subject to rejection. As a general rule, insulation resistances considerably in excess of 500,000 megohm-miles were obtained.

The core was tested also at a voltage of 90,000 volts dc for a period of one minute. This test was designed to catch any gross faults in the

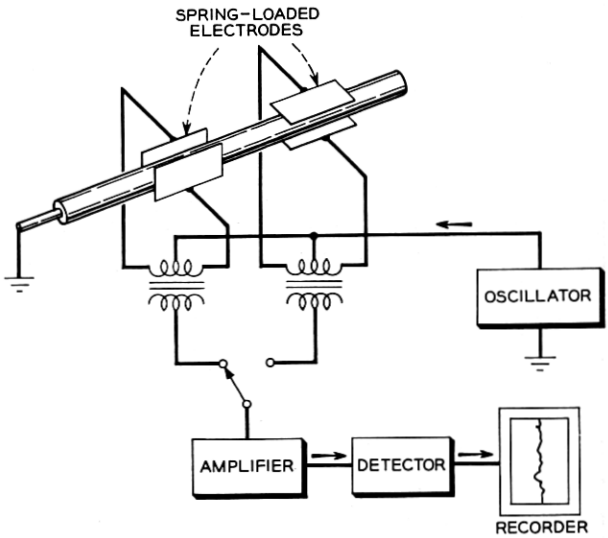


Fig. 9 — Simplified block diagram of concentricity gauge for continuous measurement of centering of central conductor.

core caused by foreign particles which escaped detection by the other mechanical and electrical tests made on the core.

As discussed under the section on jointing, the core lengths were assembled and joined together to form a repeater section of cable. In general, an effort was made to produce the core for a repeater section of cable on a particular strander, extruder, and armoring line, and to join the lengths together in the order of manufacture. Practical difficulties such as the fact that the outputs of two standers were required to supply one extruder made it impossible to achieve this objective in all cases.

Capacitance deviations from the desired nominal resulted from a variety of causes, such as inaccurate control of the temperature of the water in the core cooling troughs and improper adjustment of the control apparatus. To minimize the reflection which would result from joining together two lengths of core of widely different capacitances, cores were not joined together if their measured ac capacitances differed by more than 0.3 per cent. When such capacitance differences did exist, the core length involved was removed from its normal sequence and placed in a position near the middle of the repeater section.

Because the taping and armoring processes were combined in one

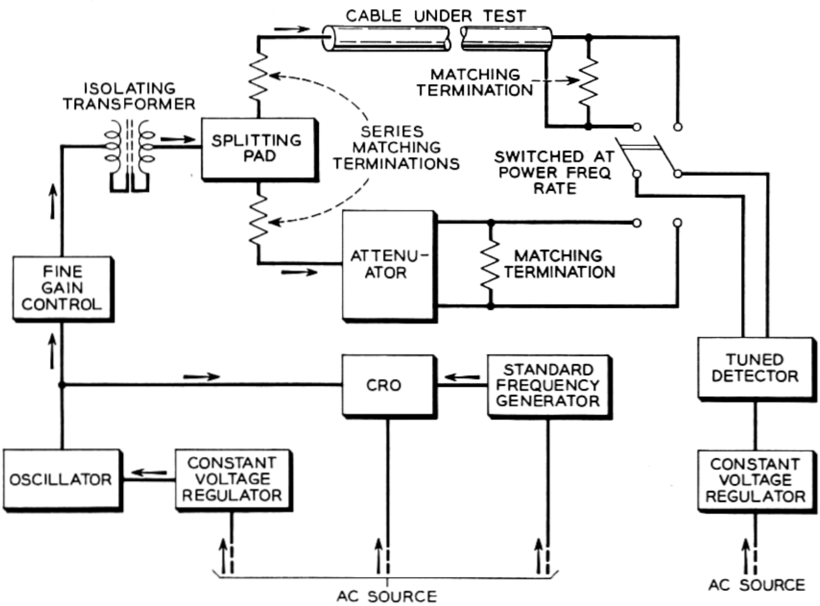


Fig. 10 — Simplified block diagram of cable attenuation measuring set.

production line in the American factory, no other electrical measurements could be made on the components of the cable until it was completely armored. In the British factory, tests for information purposes only were made on the cable in the coaxial stage. These tests included measurements of attenuation, internal impedance irregularities, and terminal impedances. They served as a means of evaluating the changes in the electrical performance during armoring.

The insulation resistance requirement after armoring and storage under water for at least 24 hours was 100,000 megohm-miles. The cable had to withstand 50,000 volts for a period of one minute without failure.

ATTENUATION MEASUREMENTS

As an aid in achieving the desired uniformity of product, new measuring equipment of improved accuracy was provided. A block schematic of this equipment is shown in Fig. 10. The requirements for this equipment were that it should be capable of measuring a 37 to 44 mile section of cable with an absolute accuracy of 0.04 db and a precision of 0.01 db in the frequency range from 1 to 250 kc.

The attenuation of the cable was measured at 10 kc intervals from 10 kc to 210 kc and measured values were corrected to 37°F, using the changes in attenuation owing to temperature, shown in Fig. 11. By comparing the corrected values with the design characteristic shown in Fig. 12, the deviations were determined. Both the attenuation charac-

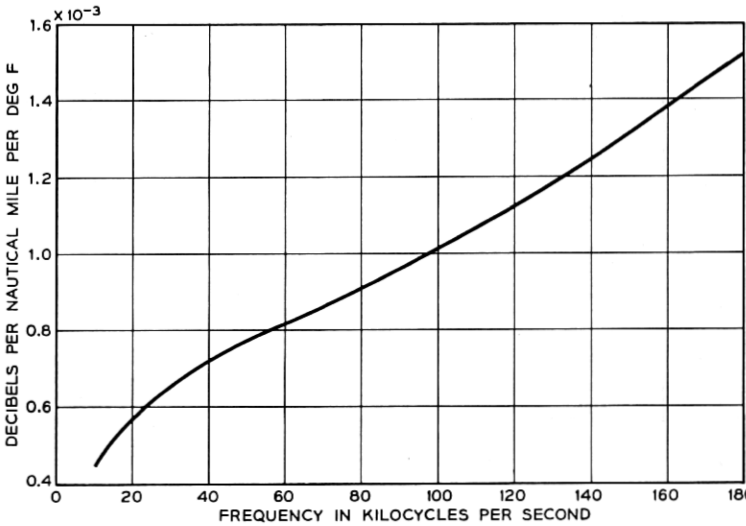


Fig. 11 — Change in cable attentuation due to temperature as a function of frequency.

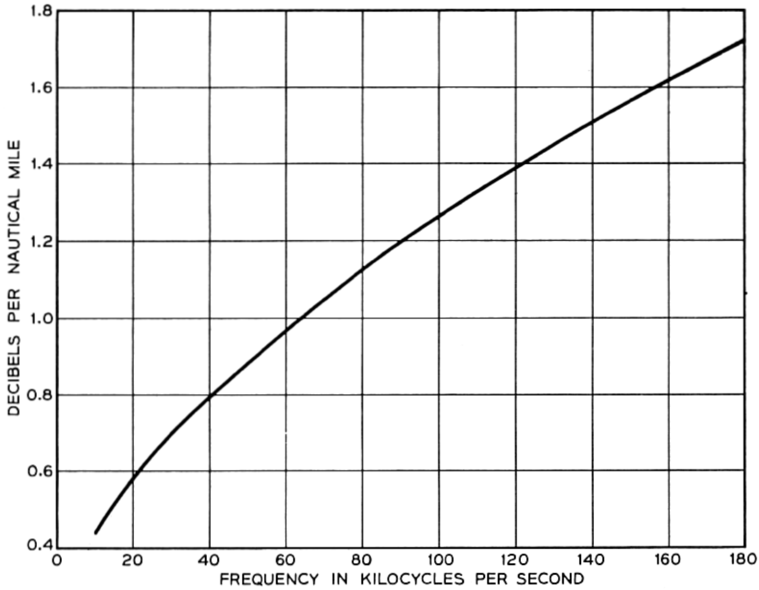


Fig. 12 — Design characteristic of cable attentuation as a function of frequency for 37°F and atmospheric pressure.

teristic and the changes in attenuation owing to temperature were derived from factory measurements of attenuation made on the Florida-Puerto Rico cable.

By comparing the running average and spread of these deviations with the design requirements, it was possible to assess the performance of the cable and, if required, to make any necessary adjustments in parameters for subsequent sections. In addition, these deviations were used to determine the length adjustment required for each repeater section to keep the sum of the deviations at each frequency in any one ocean block to a minimum. Typical average attenuation deviation characteristics are shown in Fig. 13.

TEMPERATURE AND PRESSURE COEFFICIENTS

Measurements of primary constants were made on 20-foot lengths of cable and core placed in a temperature and pressure controlled tank. These measurements were used to compute the temperature coefficients of attenuation in order to check the values derived from measurements made on the Florida-Puerto Rico cable section. Additional attenuation measurements were made on several repeater section lengths of cable over a range of temperature from approximately 40° to 70°F, to establish further the magnitude of the changes in attenuation with tempera-

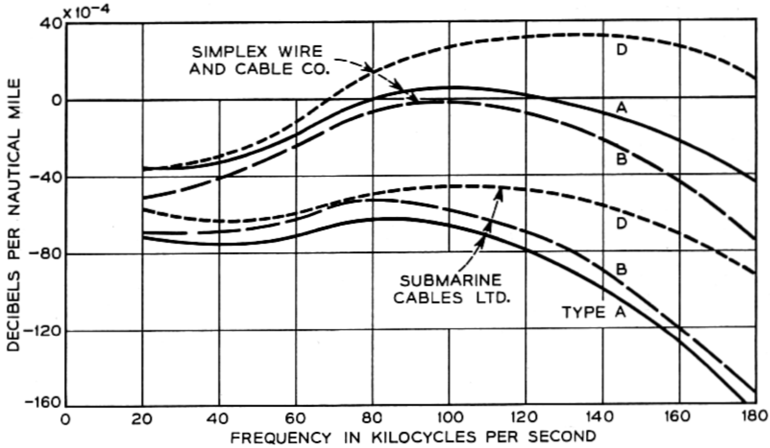


Fig. 13 — Deviation of measured cable attentuation from design characteristic as a function of frequency. Typical average values for Types A, B, and D for 37°F and atmospheric pressure.

ture. The measurements indicated that the derived temperature coefficients were accurate to within ±10 percent.

Measurements also were made to determine the effect of pressure on the primary constants of the cable. These measurements indicated that capacitance was the only parameter affected by pressure. The capacitance increased linearly 0.1 percent for each 500 pounds per square inch of applied pressure. Since the attenuation, α, is inversely proportional to the impedance, it is evident that if C is the only parameter affected by pressure, α will also be affected by pressure to an amount equal to approximately one half the pressure effect on C. The pressure coefficient of α was therefore established as 0.05 percent per 500 pounds per square inch of pressure.

LAVING EFFECT

Analysis of the Florida-Puerto Rico cable data indicated that the measured ocean bottom attenuation was less than the attenuation predicted from factory measurements. The differences were large enough to warrant study and indicated that the measurements were in doubt or sea bottom conditions were not known accurately or that some unexplained phenomenon was taking place.

In March of 1955, approximately 22 miles of cable of the transatlantic design were laid in 300 fathoms of water off the coast of Spain in the Bay of Cadiz, and another equivalent length was laid in 2,300 fathoms off Casablanca. Precise measurements of attenuation were made in both cases, and it was established that a difference did in fact exist

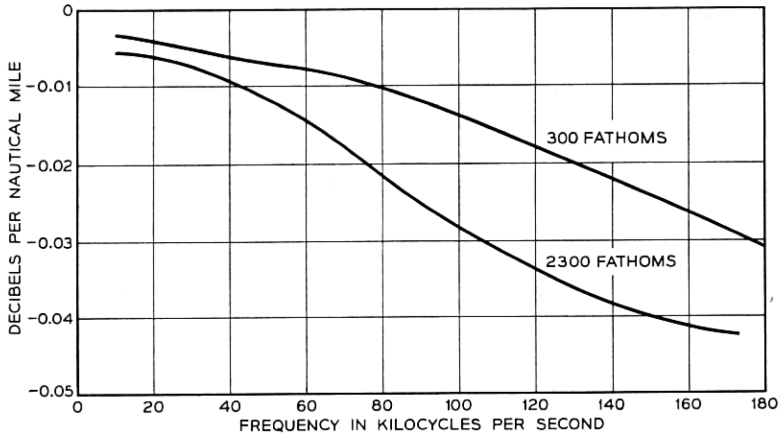


Fig. 14 — Laying effect or deviation of measured attenuation from predicted attenuation as a function of frequency, as observed in Gibraltar trials.

between measured values of attenuation at the ocean bottom and values predicted from factory measurements. It was further established that the difference in 2,300 fathoms was about twice that in 300 fathoms. The measured differences are shown in Fig. 14.

It was established during these trials that the difference increased slightly with time. Measurements made on the cable in 300 fathoms immediately, 18 hours, 48 hours, and 86 hours after laying indicated that measurable changes in attenuation were taking place. However, the change between 48 and 86 hours was so small that it was concluded only very small changes would occur in a moderate interval of time. The tests also indicated that the attenuation of the two lengths of cable decreased somewhat during loading of the cable ship.

The total difference between the attenuation at the ocean bottom and the values predicted from factory measurements, taking the temperature and pressure coefficients into account, was designated "laying effect". Various theories, such as the consolidation of the central conductor, consolidation of return structure, and changes in the dielectric material have been advanced to explain these differences. Each of these has been under study, but at the time of writing this paper, no conclusive explanation has been established.

The shape of the "laying effect" versus frequency characteristic was such that the adjustment of repeater section lengths in conjunction with several fixed equalizers, which had approximately 4 db loss at 160 kc and 0.6 db loss at 100 kc, would provide a good system characteristic. The matter of equalization is covered in greater detail in the article[4] on the overall system. The magnitude of the laying effect observed during the laying of the two transatlantic cables substantiated the trial results.

PULSE ECHO MEASUREMENTS

Process controls, such as the use of a capacitance monitor and the jointing of the core in manufacturing sequence provided the means for controlling the magnitude of reflections due to impedance mis-matches. However, to insure that the final product met these requirements, measurements of terminal impedance and internal irregularities were made using pulse equipment.

A block schematic of the circuit of the echo set is shown in Fig. 15. For the submarine cable tests, a 1.5-microsecond raised cosine pulse

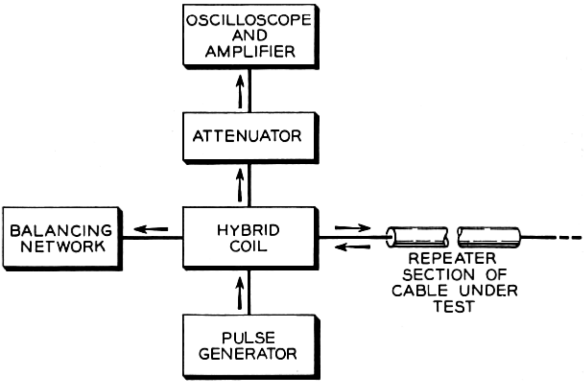


Fig. 15 — Simplified block diagram of pulse echo set for measurement of terminal impedance and internal impedance irregularities.

was used, and the impedance of the balancing network was calibrated at 165 kc. The 165-kc impedance of the repeater sections was maintained well within a range of 54.8 ± 1 ohm. The internal irregularities at the point of irregularity were maintained at least 50 db below the magnitude of the measuring pulse. The requirement was 45 db.

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