Armorless Cable Manufacture

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

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

I. MANUFACTURING BACKGROUND

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

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

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

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

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

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

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

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

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

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

II. RAW MATERIAL PROCUREMENT AND INSPECTION CONTROL

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

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

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

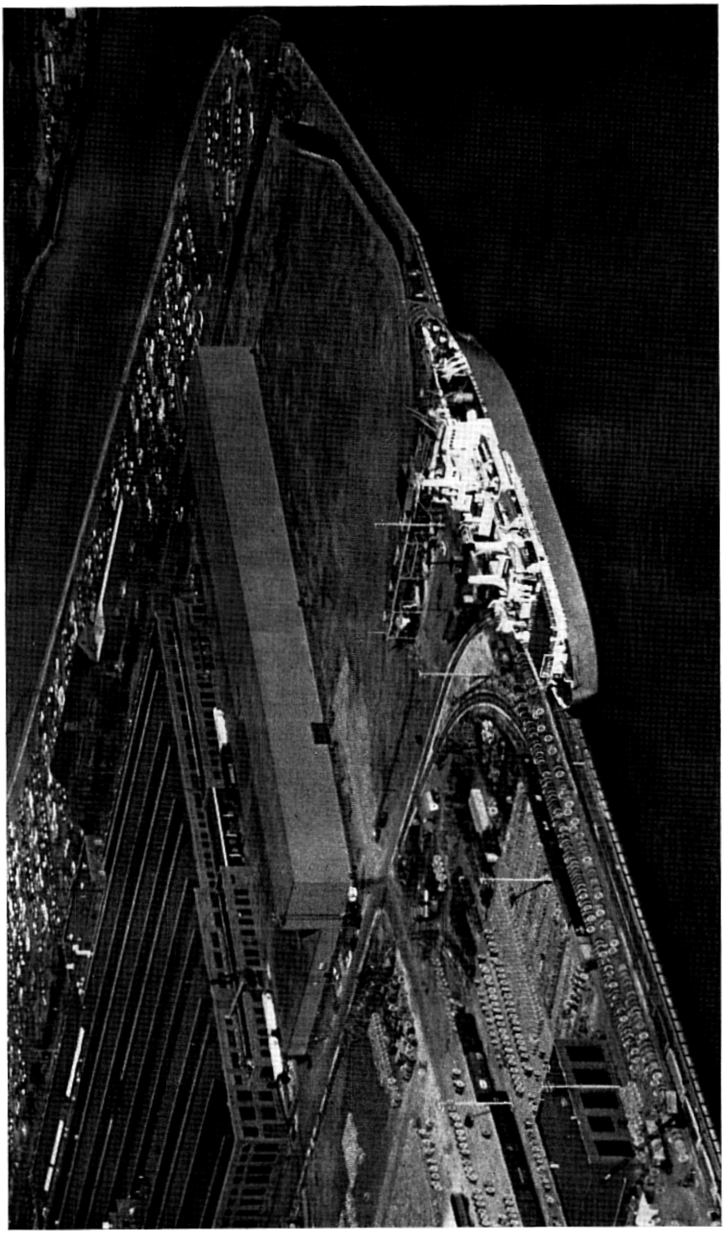

Fig. 1 — Cable factory and loading facilities, with C.S. *Long Lines*.

2.1 *Steel Wire*

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

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

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

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

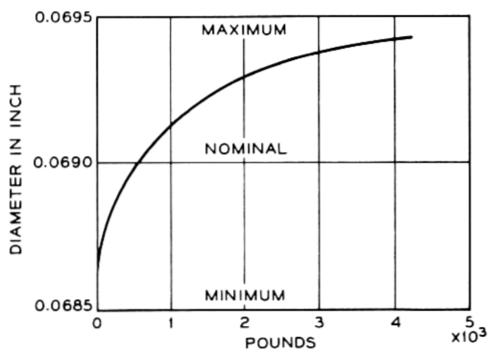

Fig. 2 — Wire diameter changes due to die wear.

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

2.2 *Inner Conductor Copper Strip*

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

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

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

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

Typical charts are shown in Fig. 3.

2.3 *Polyethylene Dielectric*

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

2.4 *Outer Conductor Copper Strip*

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

2.5 *Ethylene Plastic Jacket*

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

III. CABLE FABRICATION AND STORAGE

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

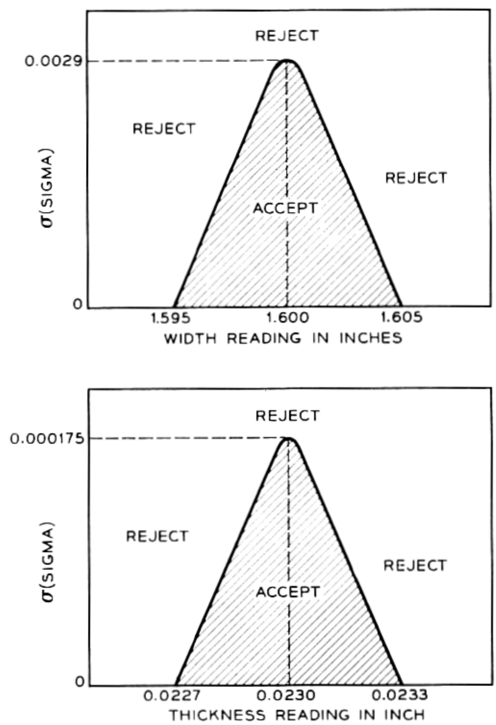

Fig. 3 — Copper strip quality control — acceptance ranges for width and thickness variations.

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

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

3.1 *Formation of Inner Conductor*

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

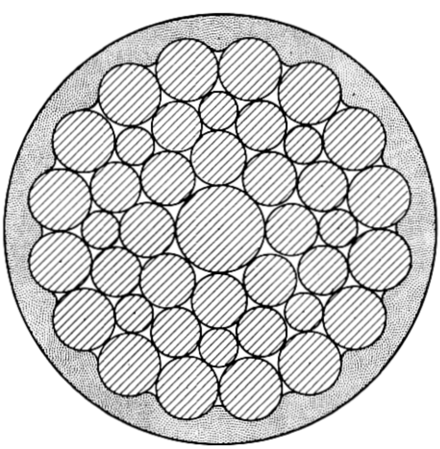

Fig. 4 — Cross section of finished conductor.

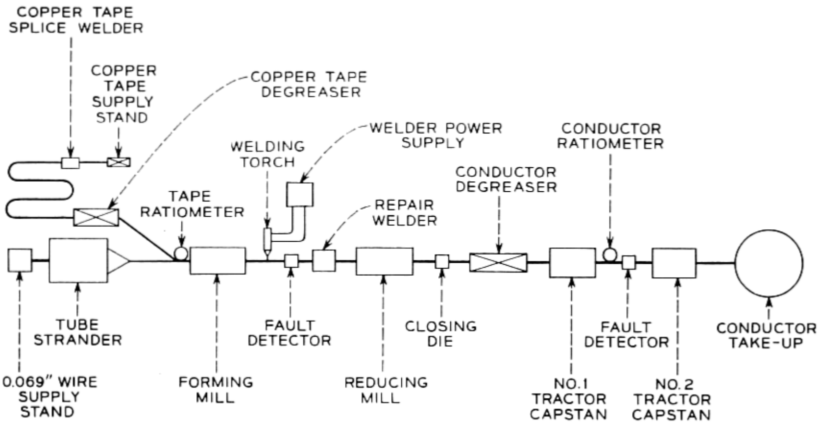

Fig. 5 — Inner conductor line.

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

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

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

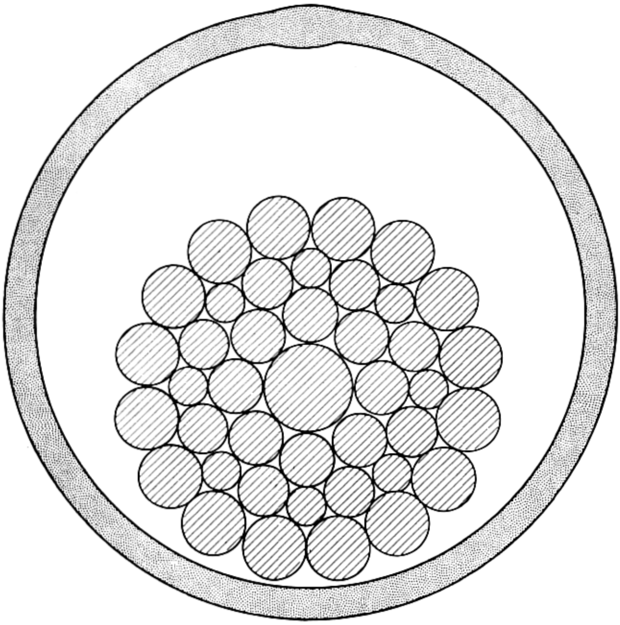

Fig. 6 — Steel strand and welded tube.

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

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

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

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

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

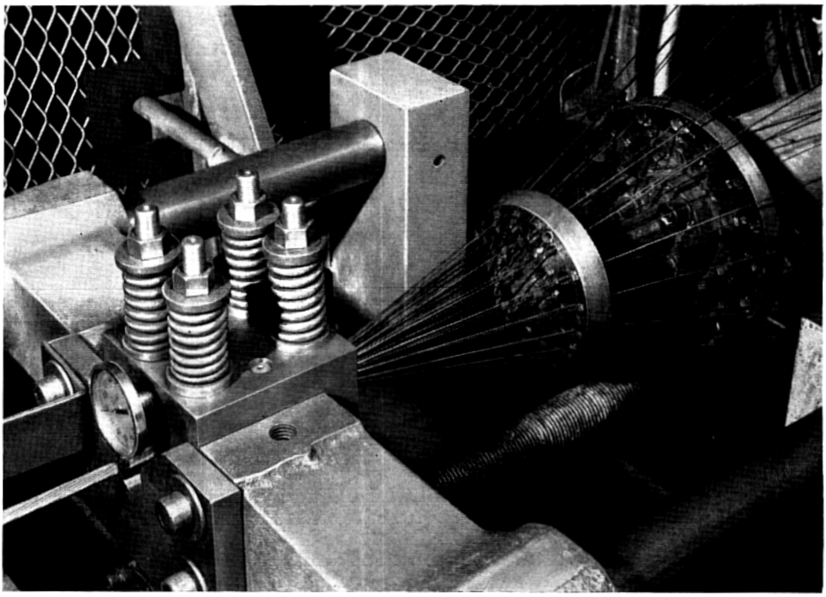

Fig. 7 — Strander point and closing die.

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

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

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

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

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

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

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

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

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

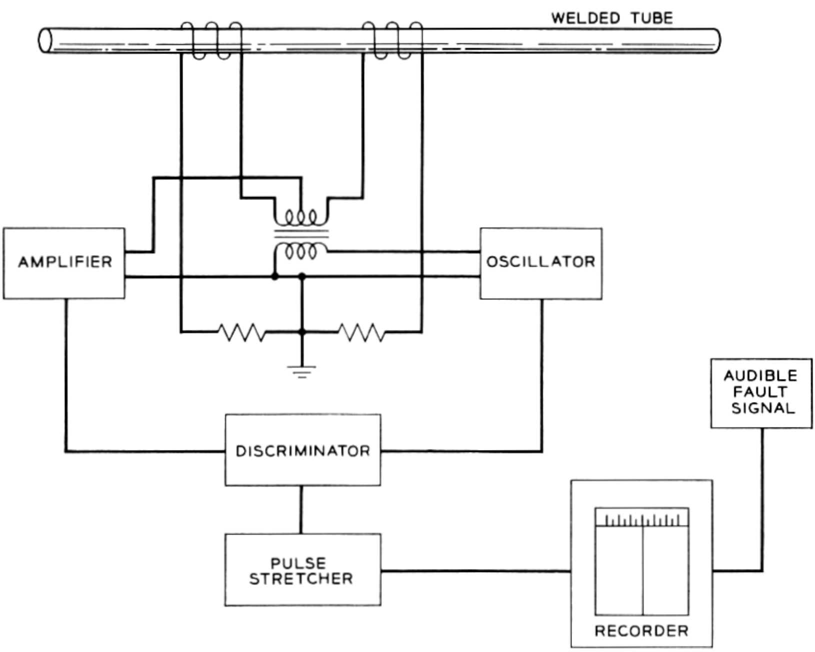

Fig. 8 — Weld integrity test set.

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

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

3.2 *Extrusion of Dielectric*

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

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

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

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

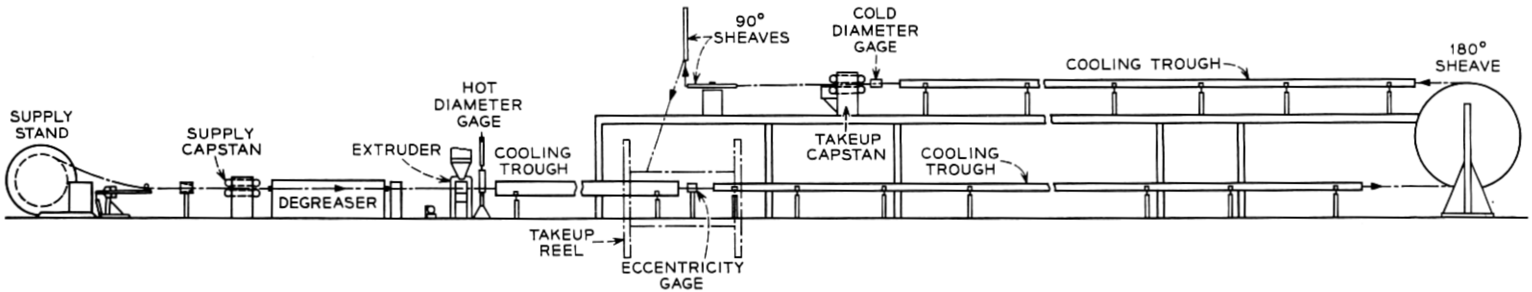

Fig. 9 — Elevation of ocean cable dielectric line.

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

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

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

3.3 *Dielectric Repair*

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

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

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

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

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

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

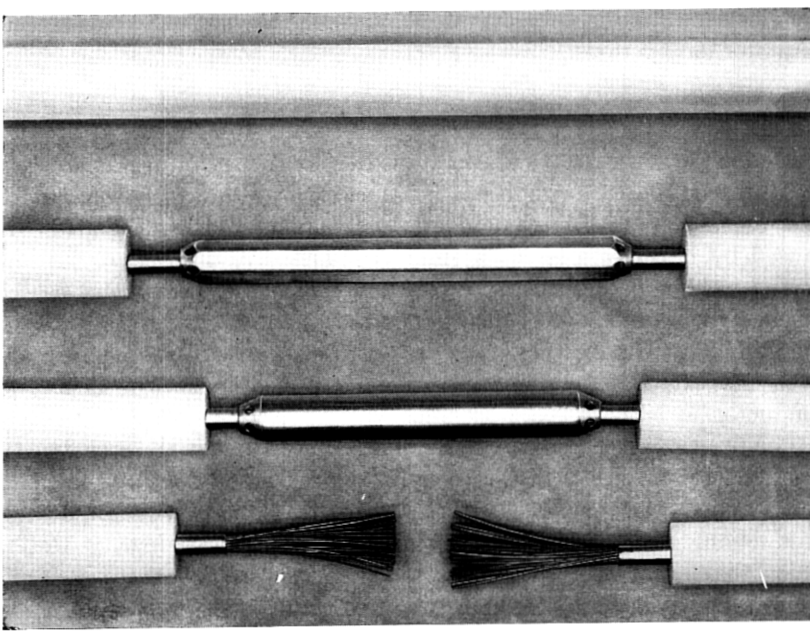

Fig. 10 — Steps in repair of inner conductor, and dielectric remolding.

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

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

3.4 *Dielectric Sizing*

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

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

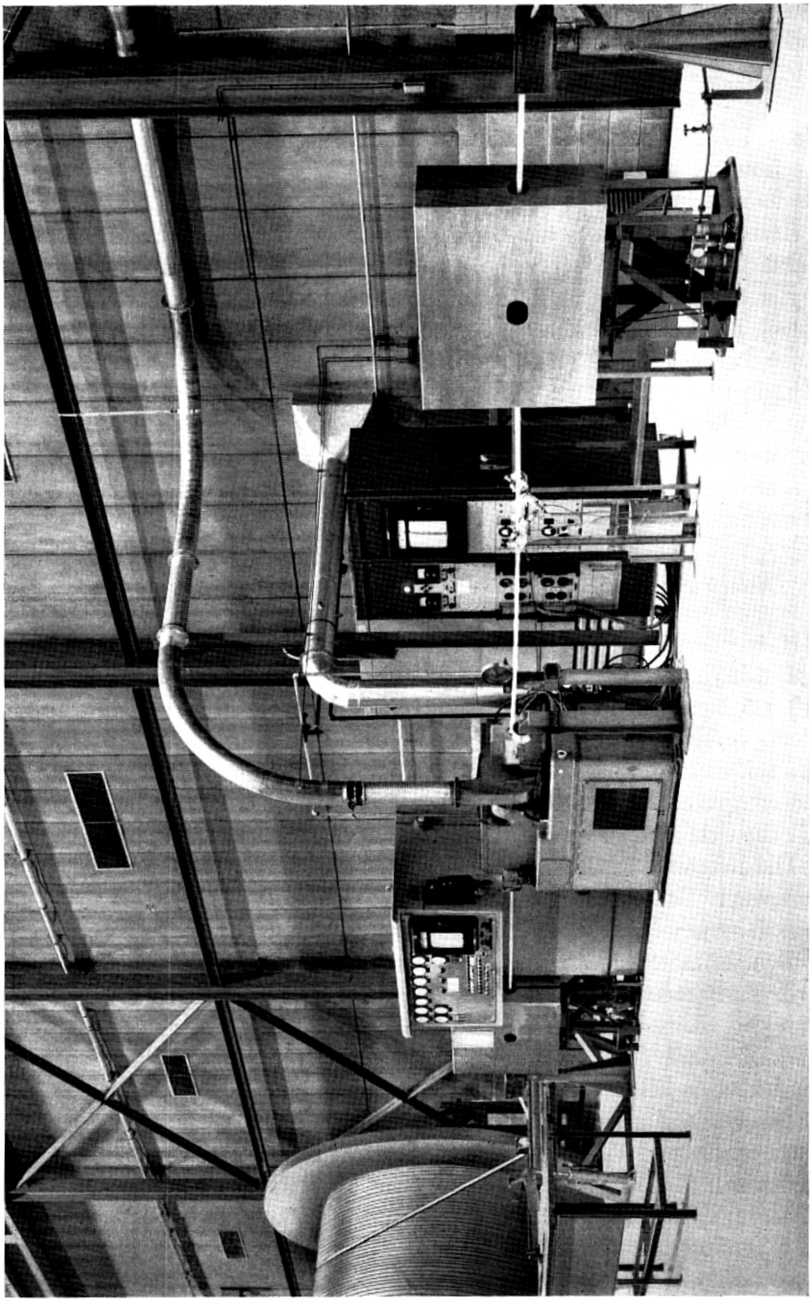

Fig. 11 — Dielectric sizing machine.

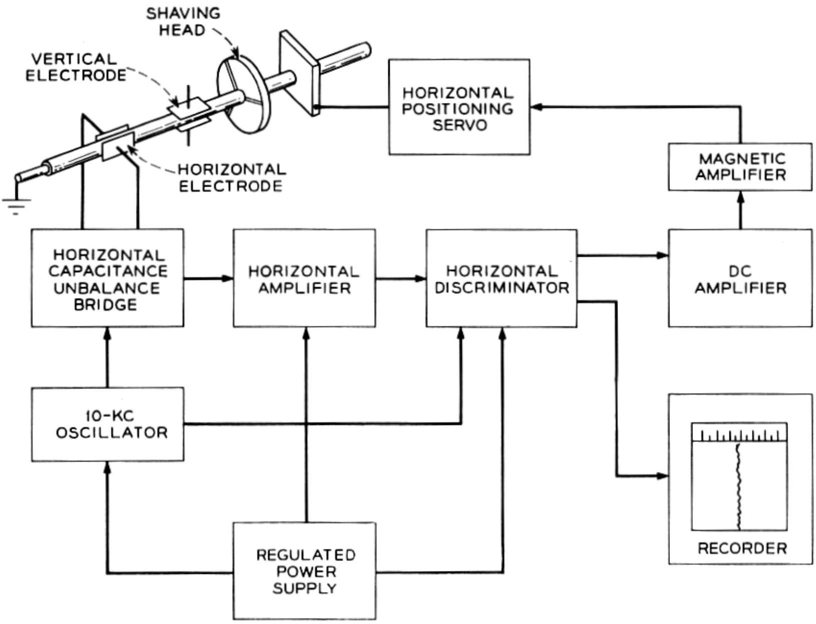

Fig. 12 — Shaver eccentricity control system — horizontal half.

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

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

3.5 *Application of Outer Conductor*

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

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

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

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

3.6 *Extrusion of Jacket*

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

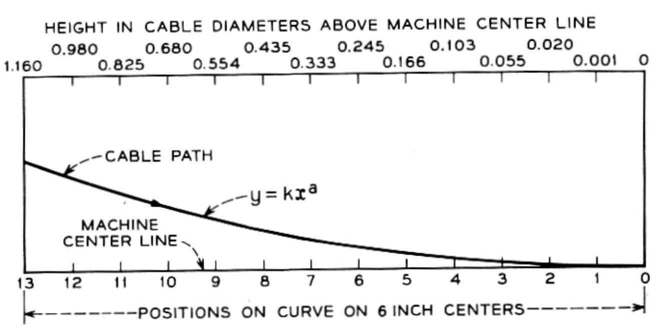

Fig. 13 — Path of cable through forming mill.

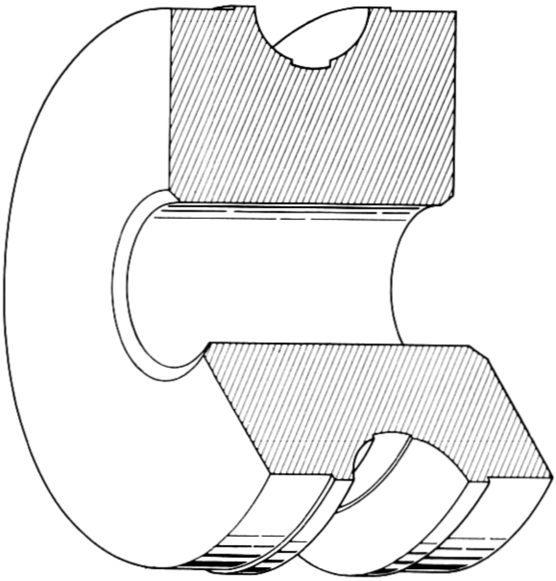

Fig. 14 — Last-pass forming roll.

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

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

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

IV. ELECTRICAL TESTING

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

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

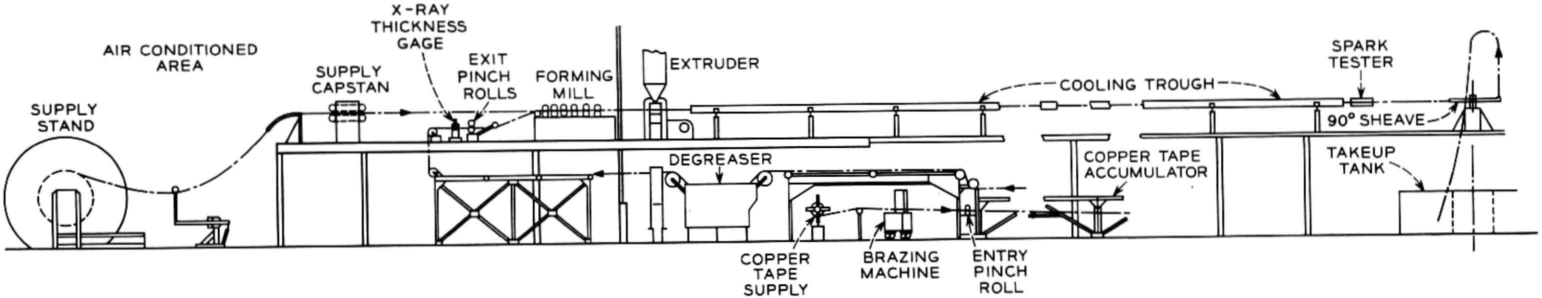

Fig. 15 — Elevation of outer conductor forming and jacketing line.

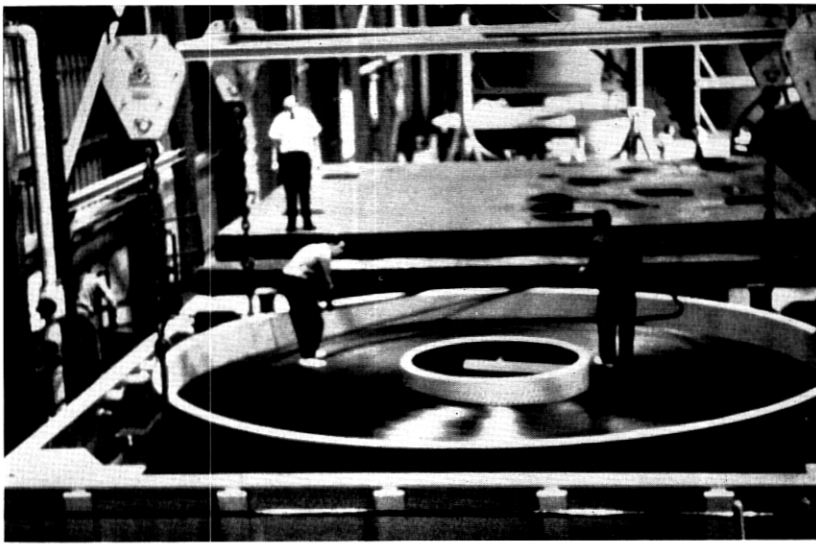

Fig. 16 — Test tank.

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

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

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

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

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

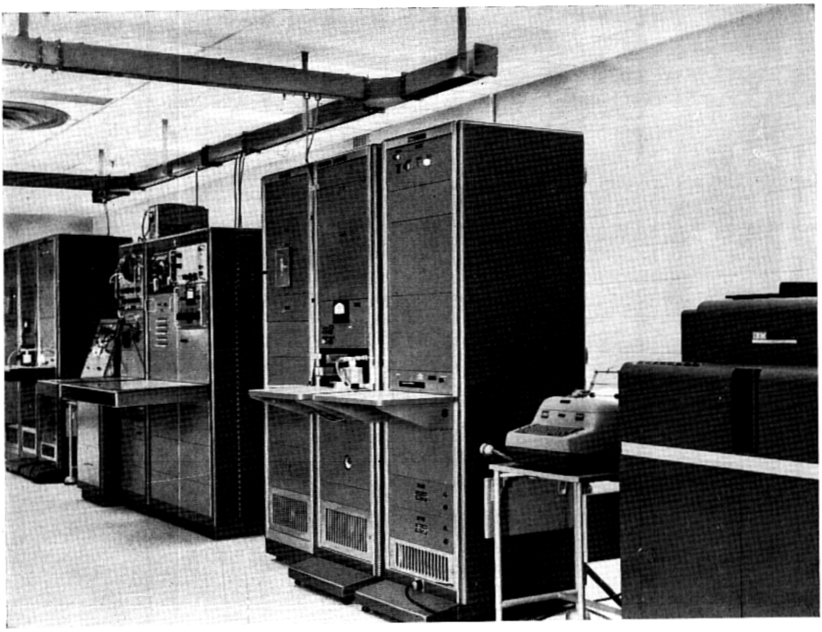

Fig. 17 — Test room.

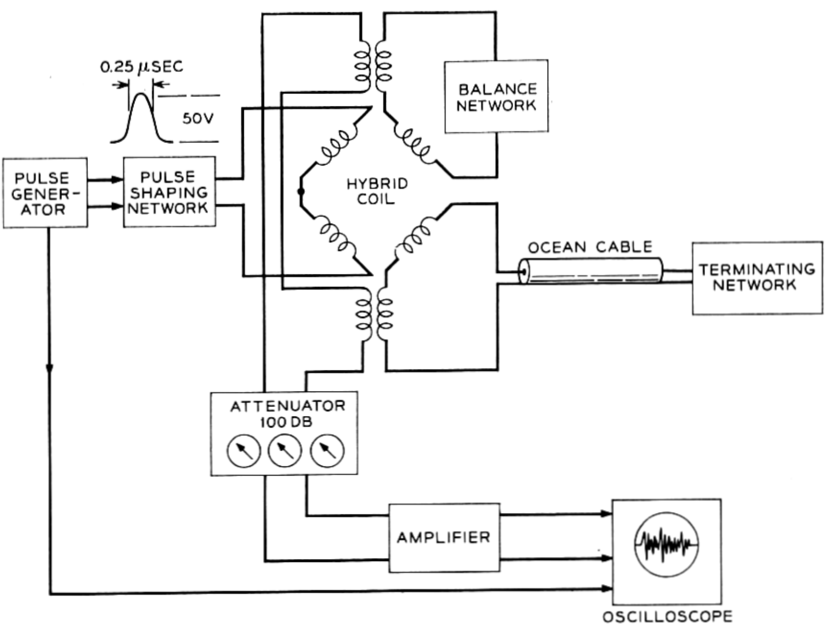

Fig. 18 — Pulse echo set.

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

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

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

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

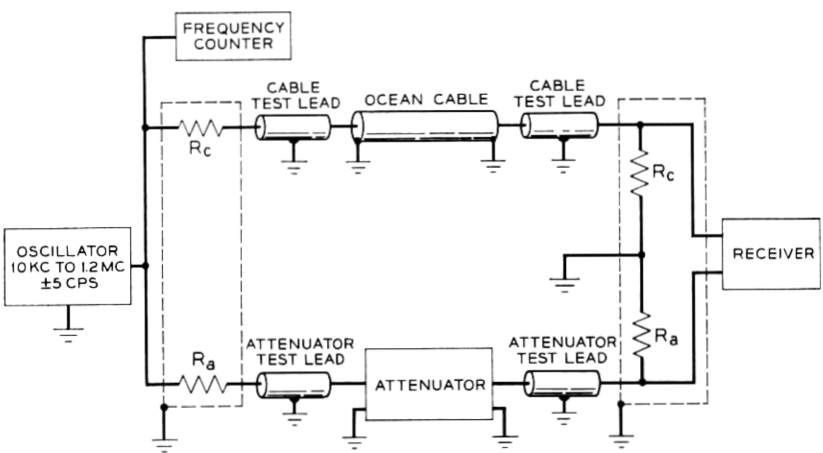

Fig. 19 — Delay set.

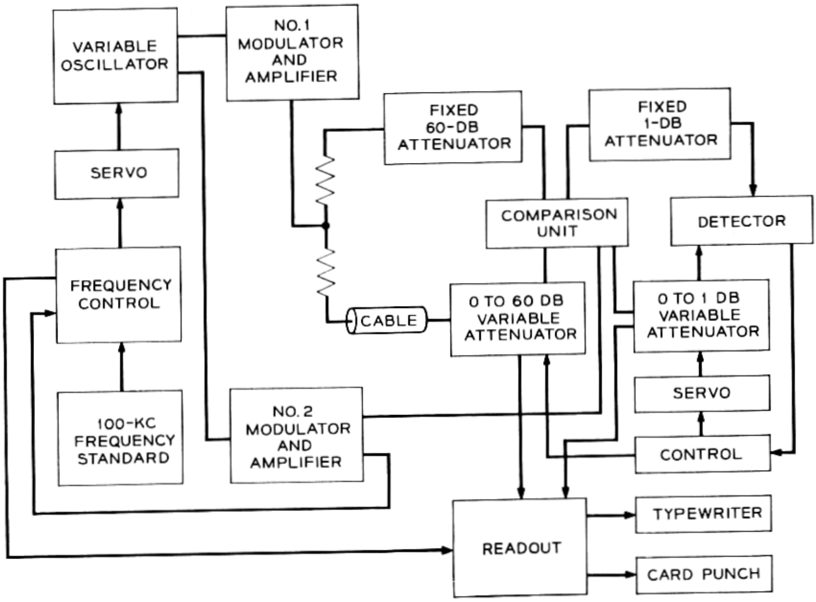

Fig. 20 — Auto-balance attenuation test set.

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

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

V. CABLE TERMINATING

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

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

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

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

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

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

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

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

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

VI. ARMORED CABLE

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

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

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

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

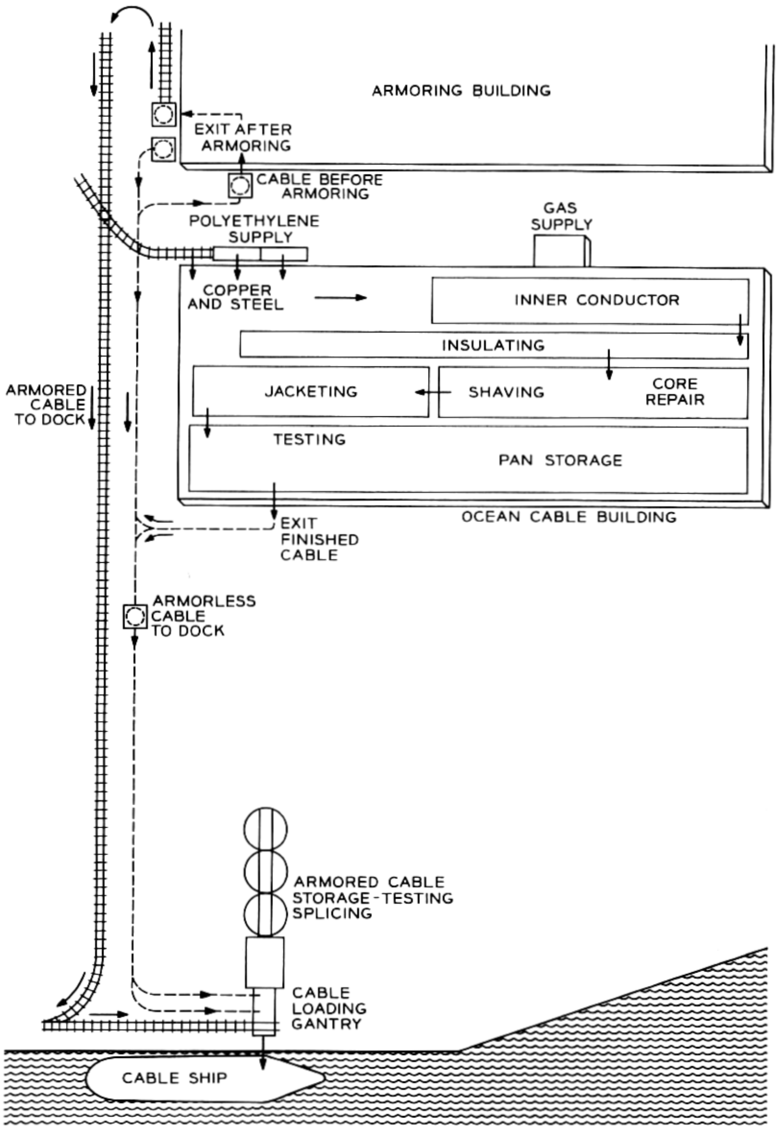

Fig. 21 — Ocean cable manufacturing facility, Baltimore, Md.

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

VII. TRANSPORT AND HANDLING OF CABLE

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

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

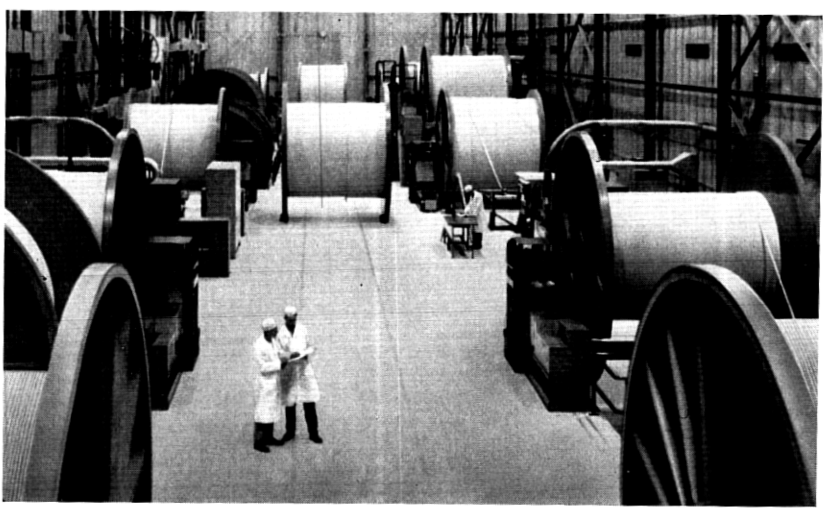

Fig. 22 — Controlled-temperature clean room.

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

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

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

VIII. PROCESS INSPECTION

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

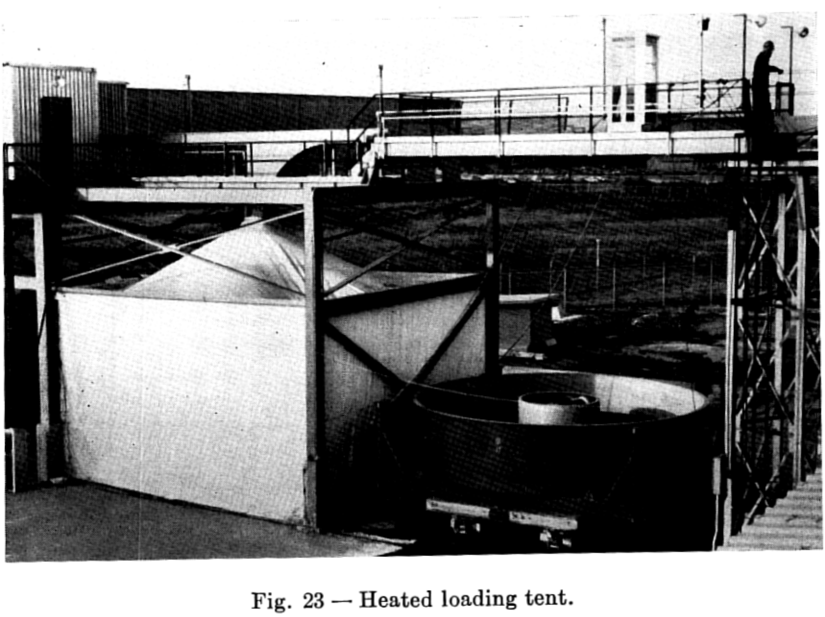

Fig. 23 — Heated loading tent.

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

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

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

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

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

IX. PROCESS RESULTS

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

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

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

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

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

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