Continuous Incremental Thickness Measurements of Non-Conductive Cable Sheath

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A method has been recently developed for measuring thickness variations of a non-conductive cable sheathing, extruded over a grounded metal jacket. The method translates direct capacitance increments, sensed by probes sliding on the surface of the sheath, into thickness increments. The accuracy of the system based on this method is sufficiently high that the electrical error, which is of the order of a few thousandths of a μμF, can be disregarded. Experimental data indicate that accuracy of the new system for absolute thickness measurements of homogeneous samples in stationary conditions is of the order of 0.002″.

The error caused by translating capacitance to thickness depends on manufacturing elements and process tolerances, and can be evaluated on a statistical basis. Thus incremental measurements of the cable sheath thickness on the production line yield accuracies of the order of 0.003″.

Application of this method to absolute sheath thickness measurements involves assumptions directly related to calibration and manufacturing process control. These aspects are rather extraneous to a measuring system per se, and, therefore, are not within the scope of this paper.

1 INTRODUCTION

1.1 The New Cable

A type of telephone cable has been developed in which lead is replaced with a polyethylene sheath extruded over a metal jacket. Since description of various aspects of this development can be found in the technical literature,[1, 2, 3, 4] only some details of the cable construction and production that are pertinent to the understanding of the new measuring system, will be briefly outlined here.

The cable core, Fig. 1, is covered with a thin layer of a highly conductive metal, such as aluminum,[1] or two layers of different metals, such as aluminum and steel,[2, 5] sealed longitudinally. To achieve the desired mechanical properties, the metal jacket is corrugated circumferentially. Between the metal layer and the plastic sheathing, a bonding viscous thermoplastic compound is applied (Fig. 2). Normally, this compound fills the depressions of the corrugations on the metal surface adjacent to the surrounding polyethylene jacket.

The sheathed cable leaves the extruder with an essentially uniform speed, under pulling force of a capstan. For various sizes of cables and production settings, this speed may range from 30 to 80 feet per minute. After leaving the extruder, the cable is cooled in a trough of water and, before reaching the testing position, dried with compressed air.

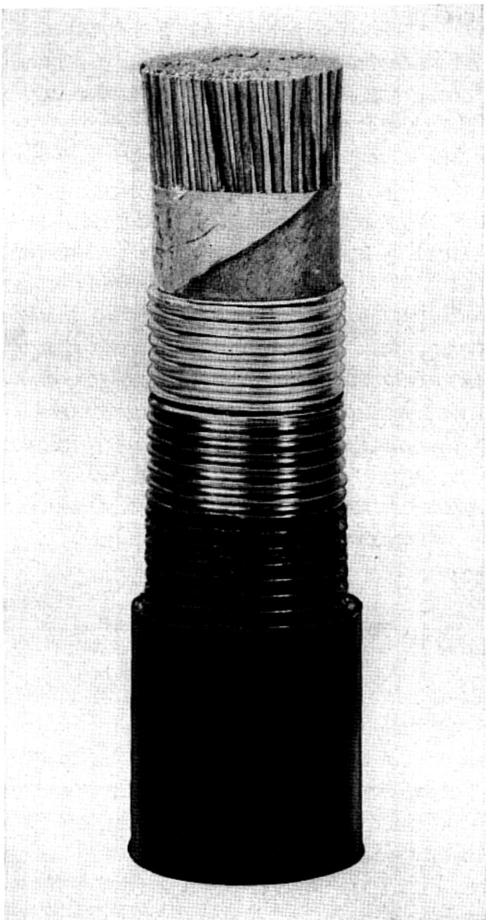


FIG. 1 — Polyethylene sheath telephone cable.

1.2 Measurement Difficulties

Some of the problems encountered in the manufacture of the new cable were related directly to the lack of reliable methods for measuring thickness of the plastic sheathing. Under manufacturing conditions, where sheath thickness cannot be adequately controlled, excess material must be used to assure meeting minimum thickness requirements.

Before the new method was developed, measurements were made by destructive testing of end samples. One or two circumferential strips were taken from each cable length and micrometer measurements were performed on each strip, at four to eight points. Unfortunately, the actual sheath thickness varies in a random way along the cable length, even between points only a few inches apart. It was evident that a method, based on a few point measurements, extrapolating long-cable properties which are describable rather in statistical terms only, left much to be desired.

1.3 Preliminary Considerations

The following methods of cable sheath measurements were considered:

A. Use of an X-ray machine.
B. Ultrasonic echo method (radar techniques).
C. Capacitance measurements.

For practical reasons as well as for anticipated lack of accuracy, the first of these methods was rejected. The success of the second method was judged doubtful, the main reason being the presence of corrugations and of an irregular layer of the filling compound under the polyethylene sheathing, obscuring delimitation of the reflecting boundary surface. The third method, at first, also had discouraging aspects. In the case under discussion only grounded capacitance measurements are involved, since the metal core cannot possibly be insulated from the corrugating and forming machinery. The required long-time capacitance-to-ground stability and accuracy of the measuring system were estimated to be of the

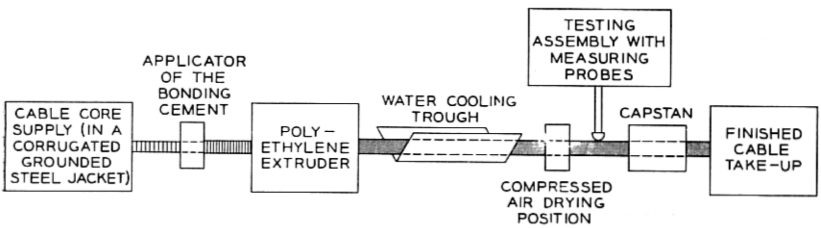


FIG. 2 — Block diagram of the polyethylene extruding process.

order of 0.001 $\mu\mu$F and 0.003 $\mu\mu$F, respectively. Meeting requirements of this order, even under controlled laboratory conditions, presents some difficulties — and yet these requirements had to be met on a production line, on moving cable in the climatic and operational conditions prevailing in a large cable plant.

It was evident, therefore, that conventional grounded-capacitance measurements would not be practical. For instance, a shielded cable connecting the probes with the bridge circuit alone could produce wider random capacitance variations than the capacitance increments under measurement. Thus a new system which would meet all the necessary requirements had to be developed.

2 CIRCUIT DESCRIPTION

The measuring system which was developed consists of an impedance bridge, a phase sensitive detector, an unbalance indicator (recorder), capacitance probes and associated auxiliary equipment (See Figure 3).

2.1 The Impedance Bridge for Grounded Direct Capacitance Measurements.

The circuit shown on Fig. 4 employs a bridge having ratio arms[6] magnetically coupled. An application of this type of circuit for capacitance measurements has been known for some time.[7] Such a circuit is capable of performing in one balancing operation direct capacitance measurements while the center point (B) of the transformer ratio-arms winding is grounded. In our case, the "D" corner of the bridge consists of the metal covering of the cable core, which, as was mentioned above, is necessarily at the ground potential. Therefore, the "B" corner cannot be grounded. However, by connecting to this "B"-corner a shielding,[8] surrounding the "A-D" and "C-D" measuring arms, including cables and probes, the following results can be achieved:

(a) Admittances from the measuring electrodes to the "B"-shielding are not critical. These admittances appear across the transformer-arms and, as a result of a close magnetic coupling realizable between these arms, any loading effects across any one of them are symmetrically reflected at the "A" and "C" corners of the bridge, thus essentially not affecting its balance.

(b) Stray admittances from the "B" shielding to ground appear across the opposite corners of the bridge (detector diagonal). Therefore, they also have no essential effects on the circuit balance.

(c) As a result of the "B"-shielding, stray admittances-to-ground

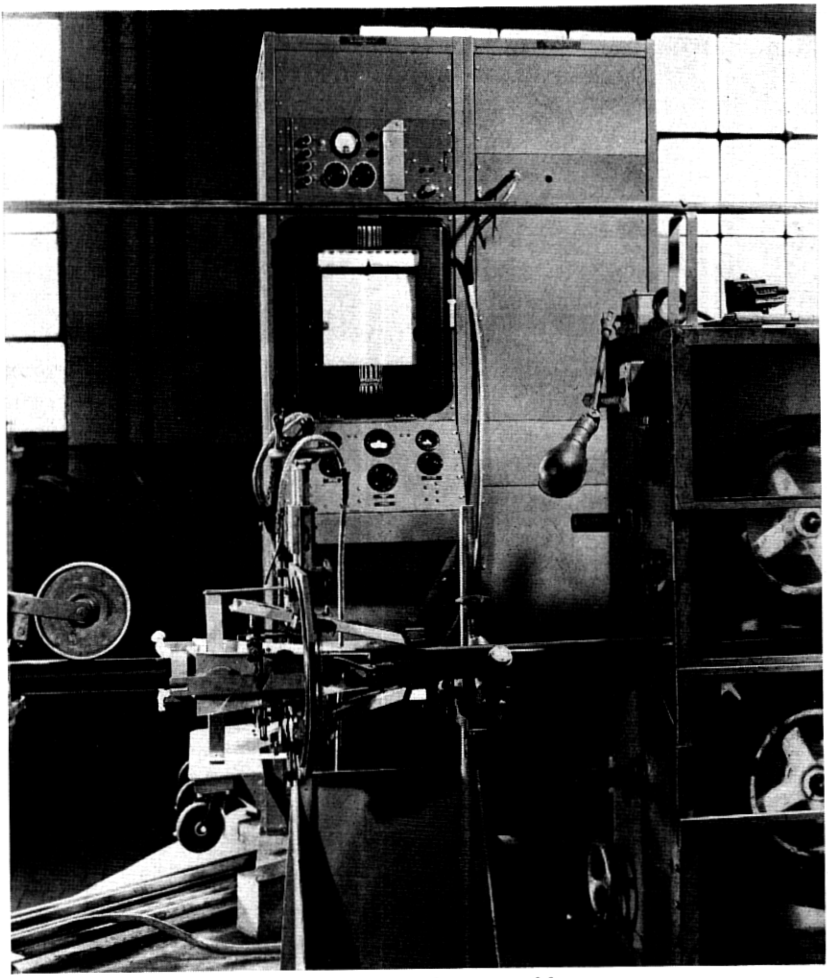


FIG. 3 — Measuring assembly.

from the measuring electrodes and from the connecting leads can be reduced to insignificant quantities.

As a result of the described circuit configuration, the bridge measures capacitance quantities equivalent to direct capacitance, in a particular case where one of two measuring electrodes is grounded. Realization of the grounded direct capacitance measurements is made possible by having within the measuring arrangement a three-electrode system in which stray admittances from the third (ungrounded) electrode to either of the measuring electrodes do not affect the fundamental balance condition of the bridge network.

By the arrangement described not only are the residual effective capacitances between the measuring electrodes and ground reduced to a desirable minimum (actually below one $\mu\mu$F, including calibrating capacitor and balancing networks), but also any adverse capacitance effects of the cables connecting the bridge to the measuring probes are practically eliminated, even though these cables are several feet long.

The calibrated grounded direct capacitance range of the bridge extends over 0.32 $\mu\mu$F in either direction off balance center position. Any unbalances within the $\pm$ 0.25 $\mu\mu$F range can be read in increments of 0.005 $\mu\mu$F per division on a recorder. Since covering such a limited capacitance range directly by an adjustable capacitor could present various practical difficulties, a network, dividing electrically the range of a 100 $\mu\mu$F differential capacitor by the ratio of 150 (approximately), has been applied. Using such a network facilitates calibration and adjustability and greatly reduces effects of the mechanical instability of the variable capacitor. (Similar networks are applied for capacitance and conductance residual balance controls.)

Stationary unbalances of the bridge network can be measured directly in a conventional manner by rebalancing the circuit with the calibrated capacitor. For unbalances rapidly varying in time, however, this null method could not be applied simply. Therefore, a proportional off-balance deflection method had to be used and various means to ascertain overall linearity between incremental capacitance unbalances and indicator deflections were provided, so that eventually variations in linearity no larger than 0.4 db over periods of several days and 0.2 db over several hours have been observed in the actual operating conditions.

Measurements with the bridge depend essentially on the calibrated capacitor. To avoid necessity for frequent and quite elaborate calibration checking (within a few one-thousandths of a $\mu\mu$F) of this capacitor in a laboratory, a set of supplementary, high stability auxiliary standards has been provided in the test set assembly. The capacitance values (1.05 $\mu\mu$F; 1.20 $\mu\mu$F; 1.35 $\mu\mu$F) of these capacitors are so chosen that differences between any pair of them can be compared directly with the calibrated capacitor in the bridge circuit. Reliability of this system is based on a reasonably high probability that change in the calibrated value of any single capacitor will be revealed in the process of mutually comparing all four capacitors. It was felt that this method of ascertaining calibration accuracy at the operating position was particularly recommended in the case of this circuit as its sensitivity to incremental capacitance unbalances is actually higher than the sensitivity of the usually available laboratory equipment.

The bridge network is supplied by a 10-kc ac power source.

2.2 Phase Sensitive Detector

For eccentricity measurements and control of the sheathing process it is essential to register the direction of incremental deviations from an arbitrary level. For this purpose a phase sensitive detector[9, 10] has been provided. Its simplified version is shown on Fig. 4.

By proper adjustment of the phase-shifter, the reactive component of the bridge unbalance signal can be oriented to be in-phase with the reference potential (b-a). In this condition, the capacitance unbalance sensitivity of the discriminator is at its maximum, and for a certain range of capacitance unbalances, linearity of the indicator may be assured. Also, when the above phase condition is fulfilled, the circuit is not sensitive to limited conductance unbalances (this fact also renders the circuit remarkably more stable than a similar circuit using a conventional null detector).

The dc output from the discriminator is fed through a balanced output stage (V2a and V2b), and an attenuator to a Leeds & Northrup zero-centered recorder. At the operating sensitivity level, each of the 100 divisions of the recorder scale corresponds to 0.005 $\mu\mu$F, or approximately to 0.001 inch of the incremental sheath thickness. The rôle of the attenuator is two-fold: it provides control of the over-all sensitivity of the measurements (in steps of 0.2 db), and it introduces more than 20 db attenuation into the dc output signal path. This loss is compensated by an added gain within the feedback-controlled ac amplifier (AC-A) preceding the phase discriminator. The net result of this "ac for dc gain-trading" is a considerable improvement of the over-all circuit stability since the range of random drifts, such as usually generated within the phase-discriminator and its direct-coupled output stage, are materially reduced.

2.3 Measuring Probes

As has been mentioned above, two arms of the bridge circuit consist of a pair of admittances between the grounded metal core of the cable (D corner) and the probes sliding on the surface of the plastic cable sheathing. These probes are connected to the "A" and "C" corners of the bridge, respectively, with two shielded flexible conductors (each

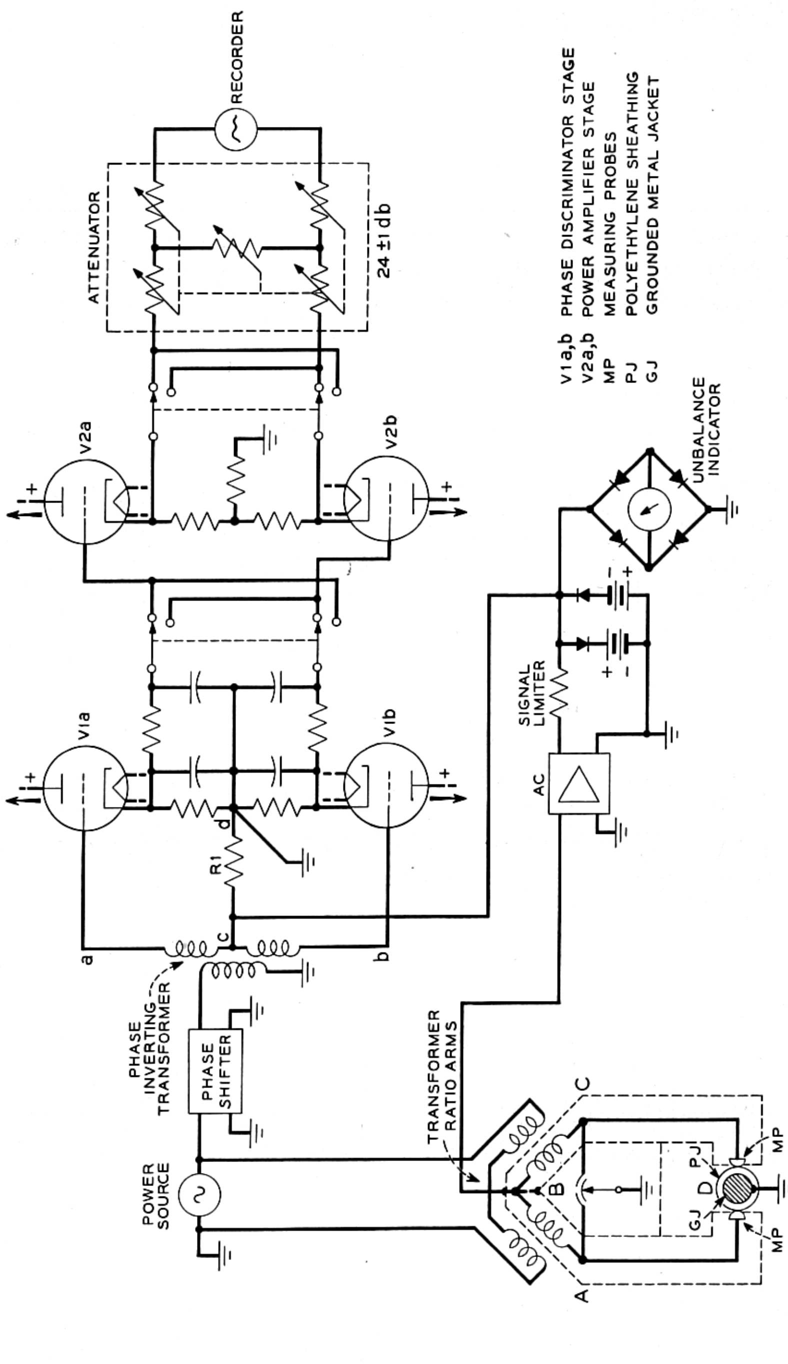


FIG. 4 — Bridge and discriminator circuit.

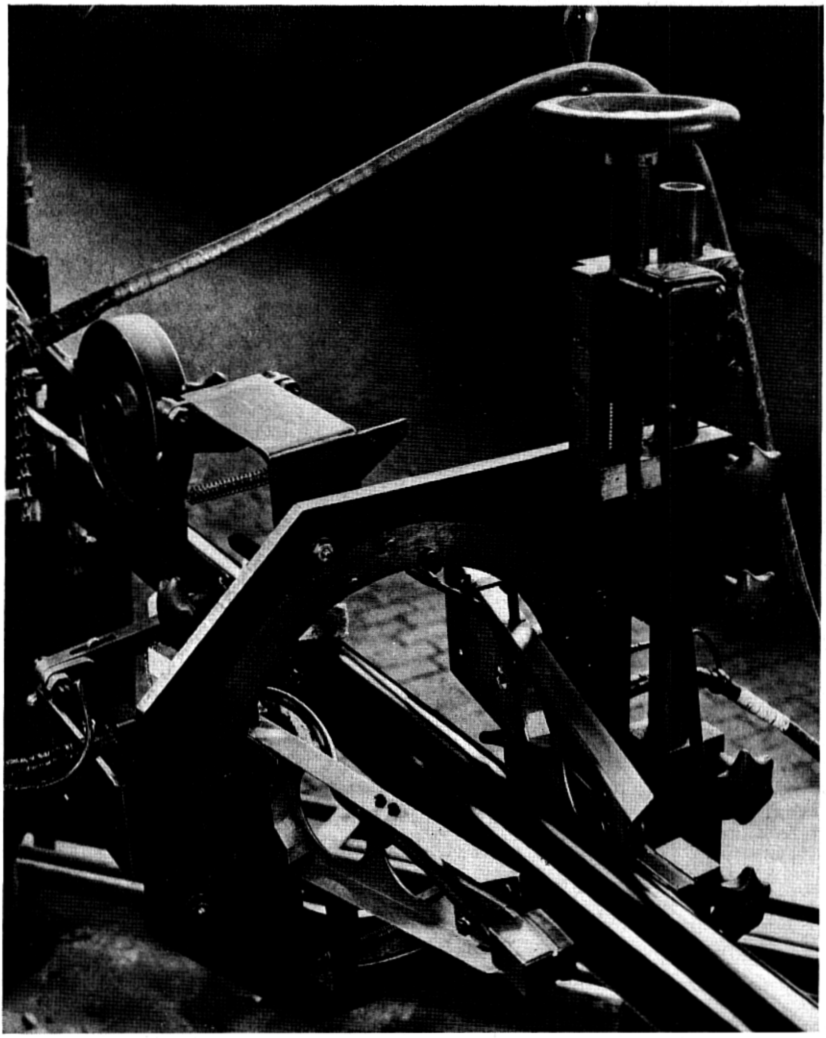
about 10 feet long) and are maintained mechanically in the testing position by the probe assembly (see Figs. 3 and 5(a)).

In the design of the probes and their assembly, various difficulties had to be overcome. The probes operate on cables subjected to some unavoidable swings and vibrations while moving with speeds up to 80 feet per minute. The capacitance from either of these probes to the metal cable core, in equivalent conditions, should match each other within approximately one-thousandth of a $\mu\mu$F. This capacitance should not be appreciably affected by limited displacements of the probes with respect to the cable plane of symmetry, such as may occur in actual operating conditions.

The first experiments with probes of a conventional design, having flat, or nearly flat, contact surfaces, were quite discouraging. The probe-to-core capacitances fluctuated to an intolerable degree as a result of even minute cable displacements.

Eventually, probes were developed which met all the requirements. Each of these probes is in the form of a cut-off segment of a toroid. The major axis of the cut-off elliptical plane is oriented in the direction essentially parallel to the cable axis, while the convex center part of the probe slides on the cable sheathing. This form of probe has the advantage, common with the spherical form, that the capacitance from the probe to the cable core varies but little as a result of displacements and changes of position caused by the cable motion. But the toroidal form has the following advantages over the spherical: first, for the same residual capacitance to the cylindrical cable core, the transverse dimensions of the former are smaller; and, second, the capacitance of the toroidal form with respect to a cylindrical cable core can be conveniently adjusted by the simple expedient of twisting the probe element in a plane parallel to the cable axis. (Adjustments with a precision exceeding one-thousandth of a $\mu\mu$F were actually performed).

The probe electrodes, surrounded (except for the contacting face) by the B-shielding, are mounted on mechanically balanced light aluminum arms [Figs. 5(a) and 5(b)]. There might be one, two, or four probes to an assembly, which can be turned over 360° around the cable axis. For eccentricity measurements two probes can be simultaneously used, having a spacing of 180° (for measurement of eccentricity across a diameter) or of 90° (for measurement of elipsoidal eccentricity). Also for eccentricity or direct thickness investigations and process settings one probe only may be used, with the other bridge measuring arm connected to an auxiliary standard.



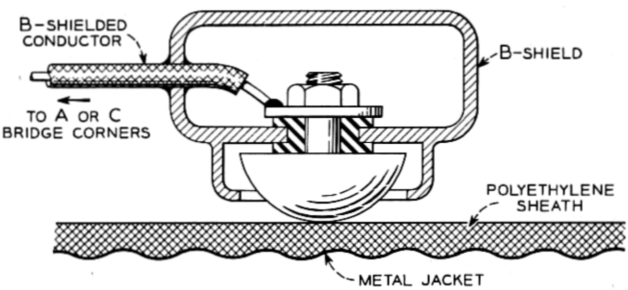


FIG. 5 — (a) Measuring probe assembly. (b) Probe element.

The average capacitance from the probe element to the grounded metal core varies from 1.1 to 1.3 $\mu\mu$F for cables measured.

3 EXPERIMENTAL RESULTS

3.1 *Circuit Performance Under Stationary Conditions*

Incremental capacitance sensitivity for grounded direct capacitance measurements, in normal operating conditions with the probes in contact with a cable sample: order of 0.001 $\mu\mu$F.

Circuit stability and repeatability for periods over one hour duration: $\pm$0.003 $\mu\mu$F.

Overall linearity of the unbalance indications, as read on the recorder scale within the range of plus or minus 0.25 $\mu\mu$F off center-balance position: $\pm$ (3 per cent + 0.003 $\mu\mu$F).

Mechanical Stability: Moving or twisting of the connecting leads has no effect on balance stability. Swinging of the cable under measurement, even beyond the limits encountered in actual working conditions, produces barely noticeable effects on the balance indication.

Capacitance measurements on flat polyethylene samples: One of the measuring bridge arms was connected to the auxiliary standard of 1.20 $\mu\mu$F. The other arm was terminated by the probe in contact with a flat polyethylene sample placed on a grounded metal-plate. Thickness of samples at the point of contact was measured with a micrometer to the nearest 0.0005 inch. Capacitance unbalance readings were taken directly on the recorder scale to the nearest 0.005 $\mu\mu$F. In order to avoid noticeable "air-gap" and "surface" effects, which occur when stacking several samples, in no case were more than two flat samples in a stack measured. Under these conditions, repeatability of readings was within one recorder division (0.005 $\mu\mu$F), equivalent approximately to one-thousandth of an inch. In a typical case shown on Fig. 6, of 38 measurements taken in the thickness range from 0.052 inch to 0.168 inch, only three measurements were off from the averaging curve by more than 0.002 inch. (Further investigation disclosed that these three points, marked "Δ" on Fig. 6, were all associated with a particular sample.)

Capacitance measurements on stationary cable samples. In order to establish statistical reliability of measurements on actual cables by the described capacitance method, a number of cable samples were tested, varying in core diameter, average polyethylene sheathing thickness and mechanical construction.

A typical graph resulting from plotting capacitance increments versus micrometer measurements of a cable sample is shown on Fig. 7. Out of

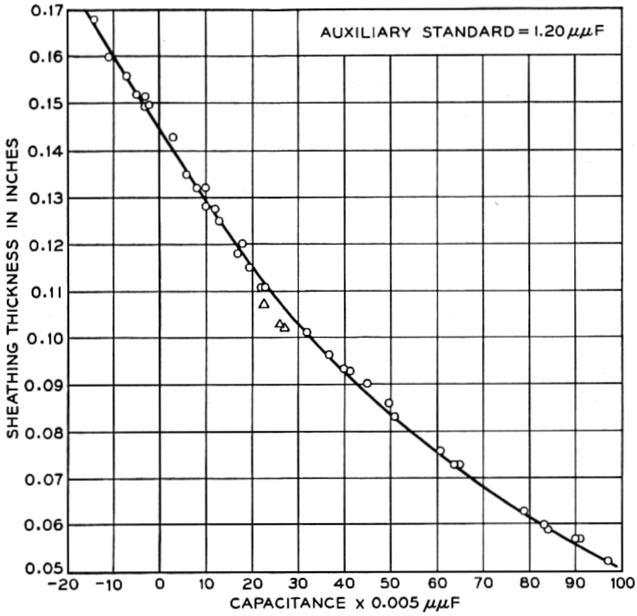


Fig. 6 — Capacitance versus thickness measurements of polyethylene plate samples.

25 measured points, 21 are contained within ±0.003 inch limit off an average curve. Three out of four remaining points (marked "Δ") were found to be from cable areas where application of the thermoplastic cement was excessive (explanation for an extraneous position of the fourth point had not been found by the time these measurements were concluded).

On the basis of over 800 measurements it has been estimated that at least 75 per cent of the plotted points are within the limits of ±0.003 inch deviation from an average capacitance versus thickness curve, for samples taken from the same cable. For samples taken from different cables these deviations ranged sometimes up to ±0.005 inch. A few points (less than 5 per cent) showed deviations larger than 0.01 inch. With some rare exceptions, these extreme deviations indicated larger than actual sheath thicknesses, and in most of the cases they were associated with areas where an excess of the flooding cement was present.

3.2 Incremental Capacitance Measurements on the Production Line

Experimental measurements on over 500 feet of cable length were performed on the production line with one of the bridge arms connected to the probe, and the other arm to an auxiliary standard of nominal value 1.20 $\mu\mu$F. The probe was placed on the surface of a cable moving with a speed of approximately 50 feet per minute. The line, along which the probe was sliding over the sheath, was marked for subsequent measuring purposes. At discrete intervals, the angular position of the probe with respect to the cable circumference was advanced by an angle of 90°. The unbalance signals were traced on the recorder chart with a standard sensitivity of 0.005 $\mu\mu$F per division. After completion of the cable run, the sheath was stripped and washed (to remove flooding compound) and micrometer measurements were taken along the probe route at points six inches apart. Subsequently these micrometer measurements were plotted in scales equivalent to the recorder chart.

A typical example of a measurement performed on a cable section approximately 250 feet long (a total of 500 measured points) is shown on Fig. 8. The upper curve represents a photograph of the recorder tracing. The lower curve was obtained by connecting point-to-point actual thickness readings and plotting them on the non-linear vertical scale following the capacitance versus thickness function (similar to that as shown on Fig. 6), to make both charts graphically equivalent.

From comparison of these graphs a few observations can be made. In fact, these curves represent fundamentally different methods of derivation. The recorder indications are continuous average readings based on an area having a definite width and a length of a few corrugation spaces

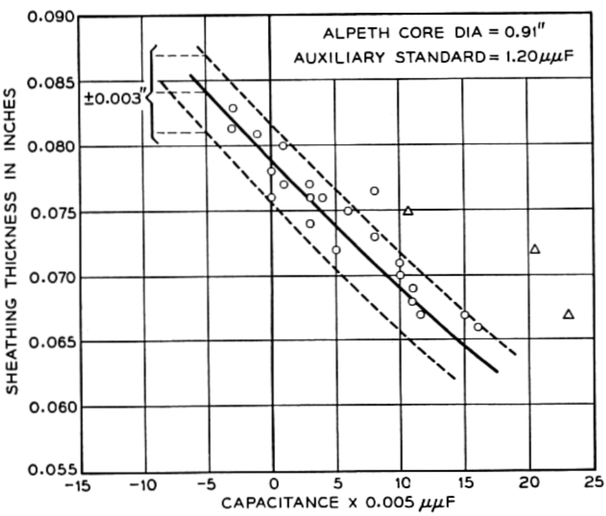


FIG. 7 — Capacitance versus thickness measurements of cable sheathing sample.

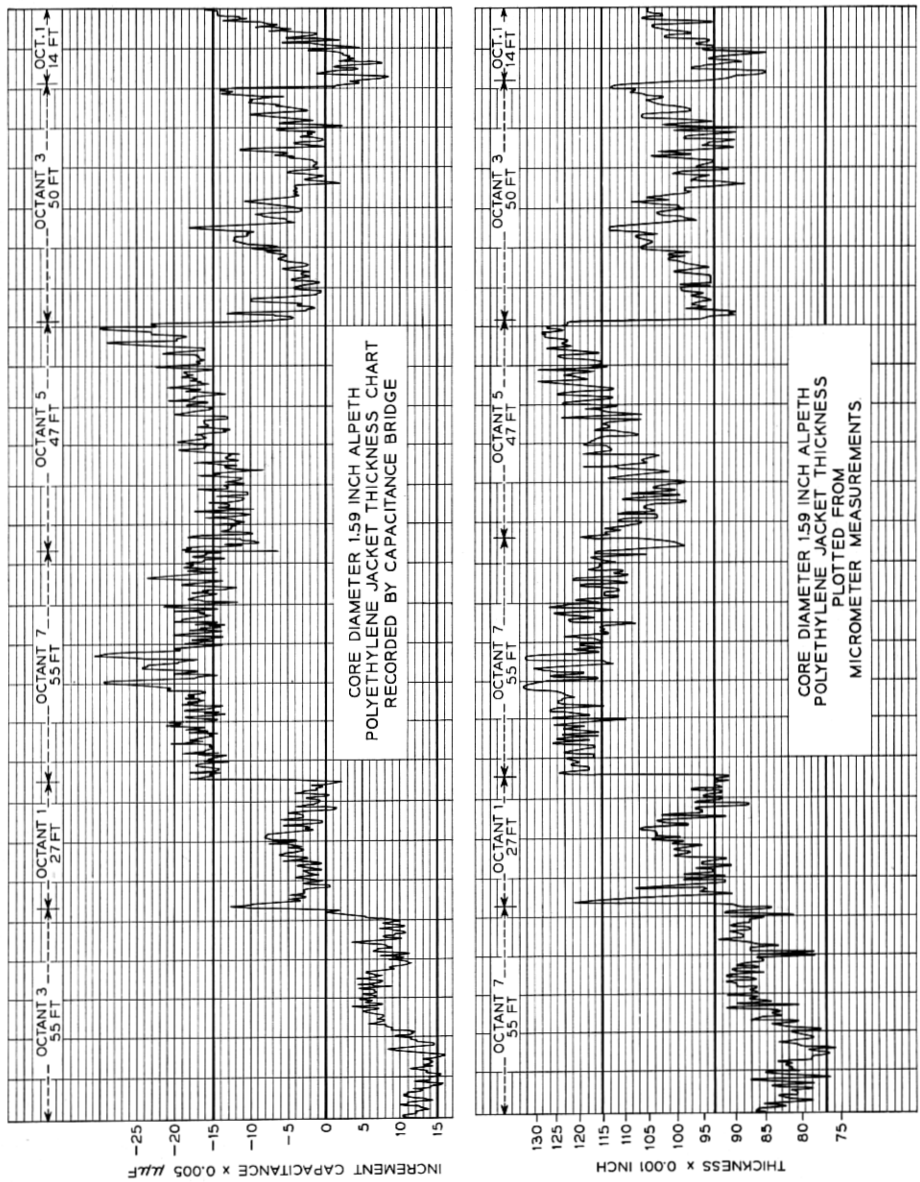


FIG. 8 — Comparison of a recorder graph taken on a production (upper curve) with the micrometer measure-

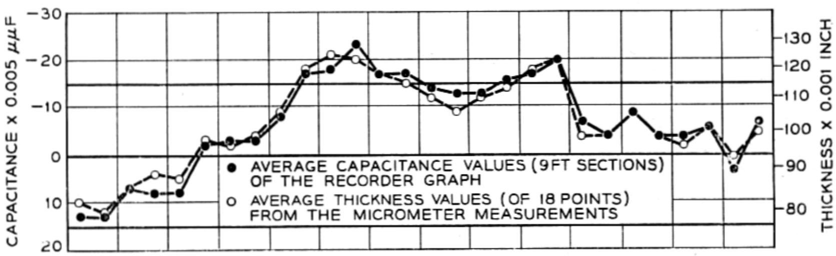


FIG. 9 — Comparison of average values from graphs of Fig. 8.

while the micrometer readings are point measurements taken at discrete distances at the bottom of the corrugation valleys in the polyethylene jacket. Despite this fact, the statistical character of both graphical results is closely similar (See Fig. 9). Assuming an average translation factor of 0.005 $\mu\mu$F per 0.001 inch, and discarding tracing errors, the agreement for incremental measurements between both methods can be estimated to be of the order of 0.003 inch. This accuracy is ample for any practical purpose of incremental thickness control of cable sheathing.

4 CONCLUSIONS

The method presented here for non-conductive sheath thickness measurements yields sufficient stability and translation reliability to be considered an improvement in the art. In particular, the incremental capacitance measurement accuracy of the order of 0.003 $\mu\mu$F (equivalent to less than 0.001 of an inch of incremental sheath thickness) is sufficiently high to disregard, in practical applications, the error of the test set itself. When measuring flat samples in stationary conditions accuracies of the order of 0.002″ for absolute thickness are obtainable.

Reliable differential measurements of cable sheathing on the production line can be realized on a statistical basis. Accuracies of the order of 0.003 of an inch for incremental sheath thickness (eccentricity) measurements were consistently attained in actual manufacturing conditions.

Extensive experience with the described measuring system indicates that it can also be applied for absolute sheath thickness measurements yielding desirable accuracies. This application, however, involves various manufacturing and process control problems extraneous to the measuring system per se. These aspects, therefore, are not discussed in the present paper.*

* Development of techniques for absolute sheath thickness measurements, using the described system, is being conducted by W. T. Eppler of Western Electric Co., Inc., Kearny, N. J.

5 ACKNOWLEDGMENTS

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