

Cable Corona Signals—Their Origin and Detection

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Abstract—To clarify some of the variables associated with the origin and detection of cable corona, two solid dielectric cables were constructed and tested. One, with various types of corona-producing elements introduced into it, was scanned at progressively increasing voltage. Some corona elements gave signals whose intensity increased with voltage. The intensity of others changed very little, presumably because the number of discharging sites within a single element increased with voltage. This report demonstrates that the magnitude of corona signals does not have a direct relationship to the corona current being discharged. The second cable (1000 feet) was made from a number of lengths of an RG8U coaxial cable (50 ohms) connected by matched *T* connectors at various positions along its length. One end was connected to a spectrum analyzer, the other left open. To simulate corona, frequencies from 0 to 3 MHz were injected in turn (at each connector) through a 10-pF capacitor. The magnitude of the detector response depended on frequency, the location of the *T* at which the corona-simulating spectrum was injected, and total cable length.

Presently available methods for the detection of corona elements are unsatisfactory because of 1) standing-wave phenomena, 2) lack of information feedback for correction action, 3) corona-free termination requirement, 4) self-extinction variables, 5) variations in rate and time of voltage exposure, 6) operator interpretation dependence, and 7) insufficient sensitivity (signal/noise ratio). These weaknesses can be overcome with a unique inch-by-inch scanning system which uses signals directly transmitted radially through the insulation wall to indicate the presence of corona and which is several decades more sensitive to corona signals than the most sensitive full-reel method.

INTRODUCTION

THE announcement of a 1966 meeting (sponsored by the New York Section of the IEEE) on the problem of corona in solid dielectric said, "The tremendous increase in the use of solid dielectric cable in recent years has not been without problems. Moisture, the chief culprit in paper insulated cable failures, has been replaced by ionization (corona) as the villain in solid dielectric cables. Effective prevention and detection of ionization and its source in cables, jackets, joints, and terminals is still the subject of much debate and experimentation."

Most previous work correlating corona intensity with signals appearing on a measuring device has been done with carefully made cavities in simple electric configurations.^[1] However, actual corona elements are vastly more complex both in configuration and chemistry as well as in signal path to a detection device. This paper aims to clarify the origin and detection of corona in cables. It will be evident from the studies made that voltages derived from corona disturbances are subject to many variables. Consequently, a signal transmitted to a cable end from an actual corona element cannot be directly related to charge and measured in picocoulombs. Sensitivity is better reported in microvolts per centimeter deflection over noise.

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ORIGIN OF CABLE CORONA SIGNALS

Consider what happens when insulation is stressed with ac voltage. During each half-cycle of stress, a charge is built up at discontinuities within the insulation wall. These discontinuities may be gas inclusions or the interface between dissimilar solid materials. When the stress becomes high enough, ionization occurs with an attendant abrupt release (or discharge) of all or most of the energy stored up to that time. During the succeeding half-cycle, after the voltage has decreased sufficiently to interrupt ionization, a charge is again established as voltage builds up to its new peak. This energy is also discharged when ionization recurs. As a result, all corona signals occur near the peaks of the applied sinusoidal voltage.^[2] These repetitive discharges of stored energy, representing stepped-changes in voltage, are the source of the signals, transmitted by one means or another, used to indicate the presence of corona. Typical voids generate currents far too small to be measured directly. If it were not for the ability of a tuned detector to be shock-excited into a wave-train, the existence of corona could be shown only when very intense.

Since these electrical discontinuities are of various shapes and have surfaces of varying electrical conductivity, the discharge behavior and the signals emanating from them also vary widely. For example, it is likely that an electrically "clean," spherical cell might discharge all or most of its energy at one time, upon reaching ionizing potential. A signal derived from such a cell should have a single spike per half-cycle, and increase proportionately in magnitude as stress is increased. On the other hand, an irregular void or gas cell with conducting particles on its walls might initially discharge one small site which, by radiation excitation and delayed conduction, would sequentially discharge other sites. This signal should have many small spikes, increasing in numbers but not in amplitude, as stress is increased. This effect was seen in transformer bushings by Oliver *et al.*^[3]

The preceding analysis was confirmed by data from the first test cable. This 15-kV rubber-insulated cable was specially manufactured to contain various corona-producing elements at different locations and depths of the insulation. These included gas cells of various shapes, foreign conducting particles, insulating particles of differing dielectric constant, and disruption of the semiconducting strand shielding. The cable was repeatedly scanned at voltages ranging from 5 to 15 kV. The charts derived from these scannings are reproduced in Fig. 1 where each band shows the amplitude obtained for each element at a given voltage. It will be noted that the defect marked *A* increased in amplitude as stressing voltage was increased, while that marked *B* had essentially the same amplitude at all voltages. This effect is assumed to be related to the number of pulses discharged per cycle. In *A* the number of pulses presumably did not change as voltage was increased. Defect *B* presumably discharged its increased energy by increasing the number of pulses. Since a low-amplitude signal might well represent considerable destructive corona energy, the need for adequate sensitivity in corona detection equipment is underscored. It is clear that the life of some insulations is directly proportional to the number of intense discharges.^[4] Whether the same relation holds for less intense discharges is yet to be determined. In the absence of such data,

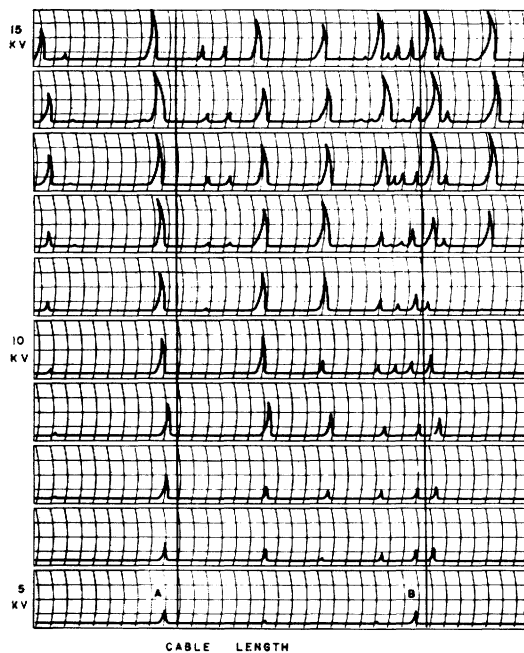


Fig. 1. Recorded corona scanning of cable defects in first test cable.

the wisest course is to reject even those low-intensity signals discernible with the scanning device described in the following.

As exposure to corona is prolonged, changes in the chemistry and conductivity of the surfaces may occur. The geometry, gas content, and gas pressure may undergo changes. In this case the nature of the discharges and the signals derived will also change.^[2] It is in fact possible for complete extinction of corona to take place. For example, self-extinction may occur by the formation of a conducting path around the gas cell with consequent removal of stress. This, from a breakdown standpoint, is not as innocuous as it appears. The current carried around the cell is not only a local heating element but a stress discontinuity which, combined with degraded dielectric and thinner section, can cause failure.

FULL-REEL DETECTION OF CORONA SIGNALS IN CABLES

There are two general types of methods for detecting signals generated by corona discharges:

1) *full-reel* methods by which the step-voltage generated by a corona discharge is first coupled to the power cable conductor and shield, then transmitted along the cable to a detector at one end

2) *scanning* methods in which the step-voltage generated by a corona discharge is directly radiated from the corona-producing element in the cable to a detector as each longitudinal increment of the cable is exposed sequentially to that detector.

In a typical *full-reel corona test*, one end of the cable being tested is attached to a voltage source. At this point, a high-pass filter, tuned circuit or bridge circuit^[5] is utilized to suppress the 60-Hz and associated harmonics of the energizing voltage, while permitting high frequencies indicating corona to pass to an oscilloscope or loudspeaker as an indicating device. In operation, the energizing voltage is raised to a point at which noise components are either seen or heard; this is the corona initiation voltage (CIV). The voltage is then lowered until the disturbances disappear; this is recorded as the corona extinction voltage (CEV). The cable is rejected if its CEV falls below a specified level.^[6]

Until recently there has been no industry-accepted sensitivity requirement for full-reel corona sets. IPCEA in September 1966 proposed that "The sensitivity of the corona-level test apparatus with the cable under test connected shall be so established as to detect a calibrating pulse of 40 picocoulombs or less under a signal-to-noise ratio of not less than two times. The calibrating pulse shall have a) a rise time to reach crest value in 0.5 microsecond or less and b) a minimum pulse duration of 50 microseconds when coupled with a calibrating condenser of 100 picofarads or less."

Kreuger^[7] feels that "a sensitivity of 2 to 10 picocoulombs can be reached at an actual test." By narrowing the band of a commercial broad-band equipment from its original 30-300 Hz to some undisclosed value, Eager and Bader^[8] were able to increase the sensitivity of their full-reel corona test tenfold to 4 pC on long lengths of cable and to 0.1 pC on short lengths. These authors express sensitivity in picocoulombs because it is considered that the greater the energy discharge, the more damage will occur to the insulation.

While the use and calibration of a full-reel test method appears simple and unambiguous, it is not. For example, the picocoulomb approach to calibration makes a number of assumptions which are not always valid. The detection devices used, like most amplifiers, are sensitive to voltage. Of course, a given voltage pulse ΔE applied across a capacitor C will produce a quantity of electricity which can be expressed in picocoulombs since $Q = C \cdot \Delta E$. However, it is shown later that this calibration approach cannot be assumed to give a valid estimate of the energy discharged in a cable void. First, some signals do not increase with voltage, though the available energy has obviously increased. Second, reflections can completely suppress signals. It is concluded that detector sensitivity should be reported as a voltage amplification factor.

Next to be considered are the problems introduced by using power cable as a coaxial transmission line to carry the high-frequency components of the corona signal to the detector. Usually the characteristic impedance of a power cable is of interest only when short lengths are tested for service in which a carrier circuit is superimposed on the power circuit. However, characteristic impedance is very important at detection frequencies, e.g., when the step-voltage generated as the result of a corona avalanche is coupled to the coaxial transmission line with an extremely high impedance and the resulting voltage signal travels in both directions from its origin. Some of the signal passes without reflection through the cable termination where the detector is located (near end) and shock-excites the detection circuit into ringing at its natural frequency. If the transmission line is not terminated resistively in its characteristic impedance, which may be as low as 25 ohms, some of the signal will also be reflected at subsequent intervals from both ends. The timing of these reflections from the far end and reflections from the near end will either prolong or stop the wave train being generated by the detector in its response to the initial step-voltage signal produced by the defect. Whether the ringing wave train is prolonged or stopped depends on both the longitudinal position of the corona-producing defect and the total length of the cable regardless of frequency used for detection.

It should be emphasized that observation of corona signals on an oscilloscope is limited by the *writing speed* of the cathode-ray tube. The phosphors on the tube require finite time to excite to usable brightness. To insure adequate visibility of the corona signal, it is therefore necessary that the shocked wave train contain a sufficient number of oscillations to excite the phosphors.^[3]

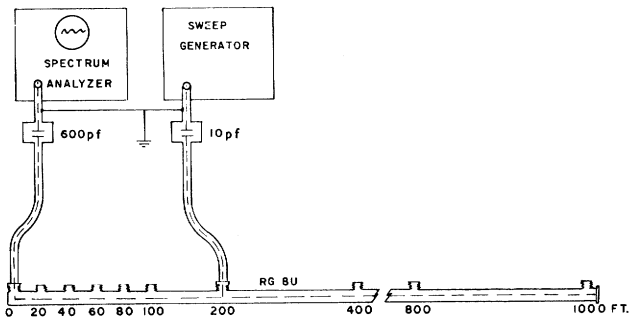


Fig. 2. Test setup for reflection studies.

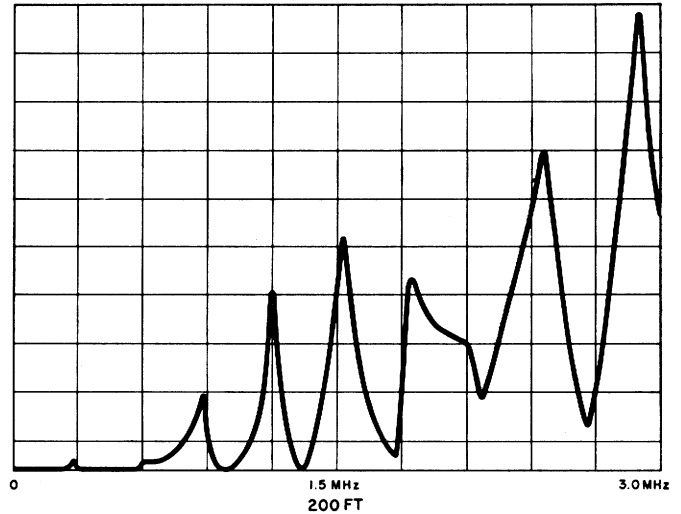


Fig. 5. Panoramic analysis of reflection effects on second test cable. Signals injected at distances from detector indicated.

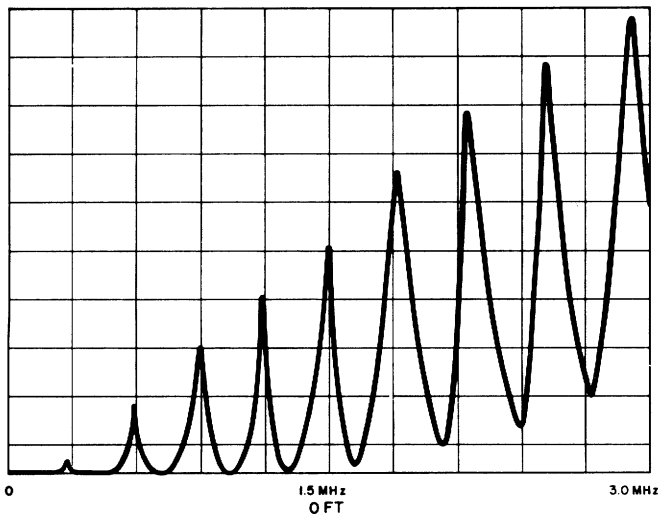


Fig. 3. Panoramic analysis of reflection effects on second test cable. Signals injected at distances from detector indicated.

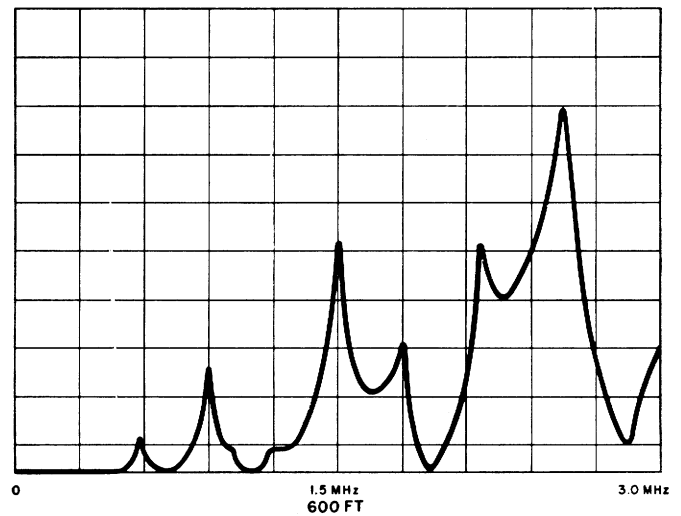


Fig. 6. Panoramic analysis of reflection effects on second test cable. Signals injected at distances from detector indicated.

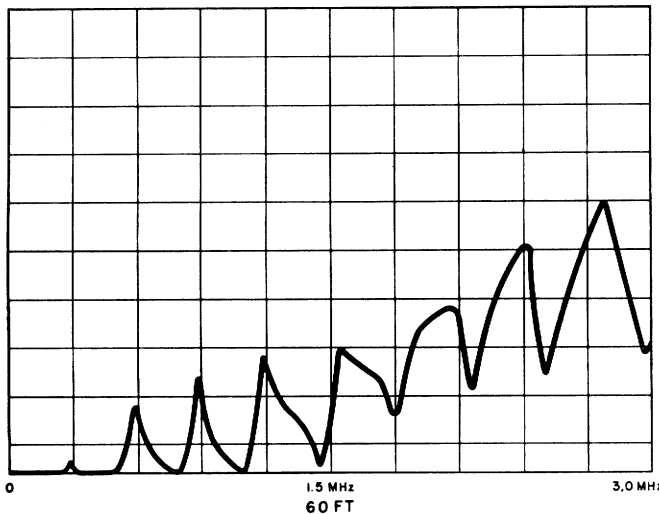


Fig. 4. Panoramic analysis of reflection effects on second test cable. Signals injected at distances from detector indicated.

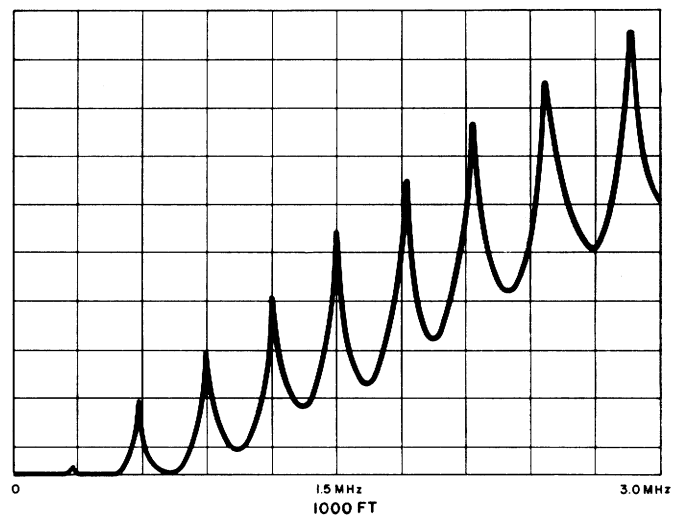


Fig. 7. Panoramic analysis of reflection effects on second test cable. Signals injected at distances from detector indicated.

A further complication is the fact that a portion of the wave-train produced by the shocked detector will enter the cable and in turn be subjected to the reflections described in the foregoing. Whether this effect prolongs or stops the ringing wave-train depends on cable length and interactions with the reflections from the defect-generated step-voltage. Since it is the wave-train which is used by the oscilloscope to make visible the existence of corona, it is readily seen that cancellation effects due to these standing waves will make the observation of corona a function of both defect position and cable length.

This analysis was confirmed by data from the second test cable. A 1000-foot length of RG8U coaxial cable was made by combining five 20-foot lengths, one 100-foot length, and four 200-foot lengths, with matched T fittings. At one end of this cable, a panoramic radio spectrum analyzer, model SPA-3, was connected through a 600-pF capacitor to simulate a typical coupling capacitor. A panoramic generator was attached in turn to each of the Ts along the prepared cable. The coupling capacitor was 10 pF, a value chosen to approach the high-impedance coupling to the cable conductor and sheath of a typical corona element in cable insulation. The generator was adjusted to sweep a band from 0 to 3 MHz in order to encompass all the frequencies normally used in corona detection equipment. The end of the line was left open to simulate this normal condition in full-reel testing. Fig. 2 illustrates the test setup.

Photographs of the display on the spectrum analyzer were made for each signal injection position which depict the signal strength available at all frequencies from 0 to 3 MHz (to simulate a corona signal) as a function of signal injection position and total cable length. Figs. 3-7 represent a number of these traces and illustrate the effects of reflections in this typical full-reel configuration. Although the curves show a considerable change of amplitude with detection frequency as a function of injection position, an entirely different set of curves would be derived if the total cable length were also changed. The voltage nodes in such curves would occur at different frequencies than in Figs. 3-7. The attenuation at the low-frequency end in Figs. 3-7 is a result of the 10-pF signal coupling capacitor mentioned previously. A typical defect would be coupled by a smaller capacitance than 10 pF, and result in even greater attenuation at low frequencies. It will be noted that reflection effects are severe even at zero distance. This would simulate a corona element at the end nearest the detector.

To minimize the problems posed by reflections in the full-reel corona methods, the following three approaches may be taken. The first two have serious drawbacks:

- 1) With *very wide band detection circuitry* the voltage nodes in an unterminated line are averaged out, but appreciably more energy is needed to excite these detectors, since highly damped circuits are required for broad bandwidths. Shocked wavetrains are not formed; therefore, it is not possible to form the envelopes needed to attain the low writing speeds for satisfactorily bright oscilloscope traces. Lastly, it is not possible to select a discrete frequency having minimum interaction with external radiation. The result is a poor signal/noise ratio. This has also been recognized by Eager and Bader.^[8]

- 2) A *low frequency* (e.g., 10 kHz) may be used for detection, as recommended by Eigen in 1954 and later by others including Eager and Bader. Longer lengths may thus be tested before the wavelength of the detection frequency becomes a problem. However, the corona element is normally coupled to the cable by an extremely small capacitance. The series impedance presented

to the signal thus increases as frequency decreases. Furthermore, the lower the frequency the more difficult it is to remove 60-Hz harmonics from the energizing source. Finally, the lower the frequency, the more the system may be influenced by ambient noise. The net result (as with wide band detectors) is a serious reduction in signal/noise ratio.

- 3) The *cable may be terminated* in its characteristic impedance. It is certainly not feasible to terminate a high-voltage cable in its characteristic impedance, say 25 ohms with a simple resistance because of the tremendous power involved (at 50 kV for example). However, a termination which is series-tuned to the detection frequency with a residual resistance amounting to its characteristic impedance is feasible. This would be a pure resistance at the detection frequency but would still present a high impedance at the 60-Hz energizing voltage.

The need for terminating a cable in a pure resistance equal to its resistive characteristic impedance is also recognized by Mason.^[1] However, the capacitor he introduces to reduce the power drain of a pure resistance does not adequately solve the power consumption problem. Further, it changes the phase angle of the termination.

Even though it is not standard practice in the industry to terminate a cable in its characteristic impedance for a full-reel corona test, the full-reel approach to corona detection should suffice whenever gross corona occurs in a cable, that is, whenever corona is distributed throughout the entire length. In fact, some who rely entirely on the full-reel approach to corona detection say corona always occurs along the entire length of cable rather than in a few discrete places. This is not surprising in view of the full-reel corona detection system's inability to locate individual corona-producing elements.

ADDITIONAL DEFICIENCIES OF FULL-REEL CORONA DETECTION METHODS

From the previous discussion of standing-wave formation, it is evident that the usual full-reel corona detection methods cannot be reliable for indicating the existence of corona-producing elements. In addition, even if the cable is properly terminated in its characteristic impedance, the full-reel methods are subject to the following inherent drawbacks.

Lack of information feedback for correction action: As the use of solid dielectric insulations is increased and wall thicknesses are reduced, it has become even more important to identify the nature and origin of corona-producing elements as well as to reject cable containing them. By studying individual defects, corrective measures can be taken to minimize their occurrence. It is also possible to subject various types of corona-producing elements in differing insulation materials to life-attrition tests to determine their deleterious nature. A diffuse finding from a full-reel test will permit none of these actions.

Corona-free termination requirement: To prevent terminal corona from masking or being confused with cable corona, it is necessary to prepare corona-free terminations for both ends of the cable for each sample tested. Preparing such terminations requires a high degree of skill, especially at higher voltages. In addition, the cost is quite high for such terminations at current production pay scales.

Self-extinction variables: The time required to raise voltage, study the scope pattern, eliminate uncertainties due to spurious discharges, and lower the voltage to determine extinction, is often sufficient to allow *self-extinction* of corona. In this event, the signal which indicated corona is easily mistaken for a spurious

discharge, and the cable is judged to be acceptable by the operator even though it contains an unknown but potentially dangerous defect or defects.

Variations in rate and time of voltage exposure: The rate at which voltage is both raised and reduced, as well as the time of voltage exposure, can affect the corona mechanism and consequently the signals derived. To make reproducible measurements and judgments, it is important these conditions are maintained constant and repeated consistently. The necessity for studying the oscilloscope traces for corona onset, and determination of extinction introduces variables into the preceding manually-performed procedures.

Operator interpretation of oscilloscope traces: The traces displayed on an oscilloscope are derived from many sources, including simultaneous corona elements which may interact in various ways, and are further confused by noise components. Since there are no guidelines for consistent, reproducible acceptance levels, operator interpretation of the significance of the display is required. This results in considerable variation of personal decisions.

Insufficient sensitivity (signal-to-noise ratio): Since the entire cable capacitance is shunted across the corona signal, which is coupled to the cable from its site by an extremely high impedance, the resulting very poor voltage division reduces the corona signal available for measurement. There are additional minor losses of signal due to attenuation per foot and the series impedance of the required power separation filter. Ever-present noise components limit the usable amplification and thus the effective sensitivity.

SCANNING METHODS

In 1937 Savage^[9] patented a means for testing electric insulation. Insulated cable was passed through a metallic tubular electrode connected to a high voltage transformer, much as in conventional spark-testing equipment. Spark failures and corona-producing elements were detected when high-frequency oscillations occurred in a tuned circuit. A marking device indicated the general position of the defects. However, this device was limited in voltage by its lack of stress relief at the ends of the tube and by the low CIV of the air in the tube. Further, the marking device was inaccurate.

Test-Train Method

In 1957 Gooding and Slade^[10] described a cable scanning method which became known as the *test-train*. This method with its unique stress-relief arrangement had been devised to overcome some of the deficiencies of full-reel testing. The cable insulation was stressed radially by passing the cable through an insulating tube of demineralized water.^{[11], [12]} At the center of this tube, an electrode attached to the stressing voltage source was introduced. The return lead went to metallic troughs at each end of the tube and to the cable conductor. Since the water in the tube had a much higher dielectric constant (80) and much lower resistance (10^7 ohm·cm) than the cable insulation (<7 and $>10^{12}$ ohm·cm, respectively), the stress developed on the cable was independent of its radial position at any point along the tube. This arrangement established a change in stress on the insulation which went from maximum at the center to zero at the ends. The change in stress was gentle enough longitudinally that external corona did not occur. A detector was coupled capacitatively to the energizing transformer to respond to corona elements. The three main advantages of this method over the full-reel approach are:

- 1) Standing-wave phenomenon was eliminated.
- 2) Recordings of defects permitted some feedback of information.

- 3) Corona-free terminations were not required.

The following deficiencies of full-reel testing, however, still remained:

- 1) Self-extinction variable, the extended time of exposure to corona-inducing voltage often caused corona signals to disappear while searching for the defect site.

- 2) Variations in rate and time of voltage exposure; to determine the exact location of a defect it was necessary to shift the cable back and forth for maximum signal, mark the cable outside the tube, move the cable out, and then measure back to mark the defect site. This introduced rate and time variability.

- 3) Operator interpretation, the decision to mark for rejections was still left to the operator who had to differentiate between spurious and valid indications.

Further, the signal-to-noise ratio was not appreciably improved over full-reel corona methods. It is true that the shunting capacitance had been greatly reduced; however, the cable and reels were exposed to external signals because it was uneconomical to provide an adequate shield. These external signals were re-radiated to the detection system along with corona signals, and therefore limited usable sensitivity.

Micro-Scanner System

In 1962 Eigen and Geary^{[13], [15]} disclosed the development of the Micro-Scanner system, Fig. 8, for scanning unshielded cable.¹ This system uses the same water-filled insulating tube as the test-train. The tube is energized with the required voltage as its center and grounded at each end, thus establishing a linear voltage gradient from maximum at the center to zero at both ends. However, instead of coupling the detector to the energizing transformer, special probes are placed at appropriate positions along this voltage gradient.^[14] They respond to the direct radiation of signals from corona-producing elements at the specific voltage of the gradient at which they are placed. Each probe is a pair of elements with identical geometrical shape, oriented in the same plane and connected in a differential manner to the detection circuitry. The identity in shape and orientation is necessary so that noise components regardless of polarization or amplitude will cancel. Corona avalanches passing sequentially to the probes (as the cable is moved) unbalance the pair, and thus produce an appropriate signal in the detector. Noise signals impinging on the cable external to the tube re-radiate cylindrically under the probe pairs with equal phase and amplitude. They are thus cancelled by the differential circuitry. Noise signals radiated directly to the closely spaced probes from a distance of more than three feet appear essentially as plane waves, and also cancel.

One function of the probes is to activate a multipen chart recorder which, by drawing the characteristic shapes of the corona signals at a number of voltage points, develops a contour for study by research personnel and classification of corona types by quality control personnel. A second function is the rejection of cable containing corona-producing elements at voltages below a specified acceptance value. Two of the probe-pairs are utilized for this purpose. The first is located on the exit half of the

¹ Extension of the sensitive Micro-Scanner approach to the outer screen-shield portion of a cable and the resulting complete elimination of the full-reel corona test will occur, hopefully, in the not-too-distant future.

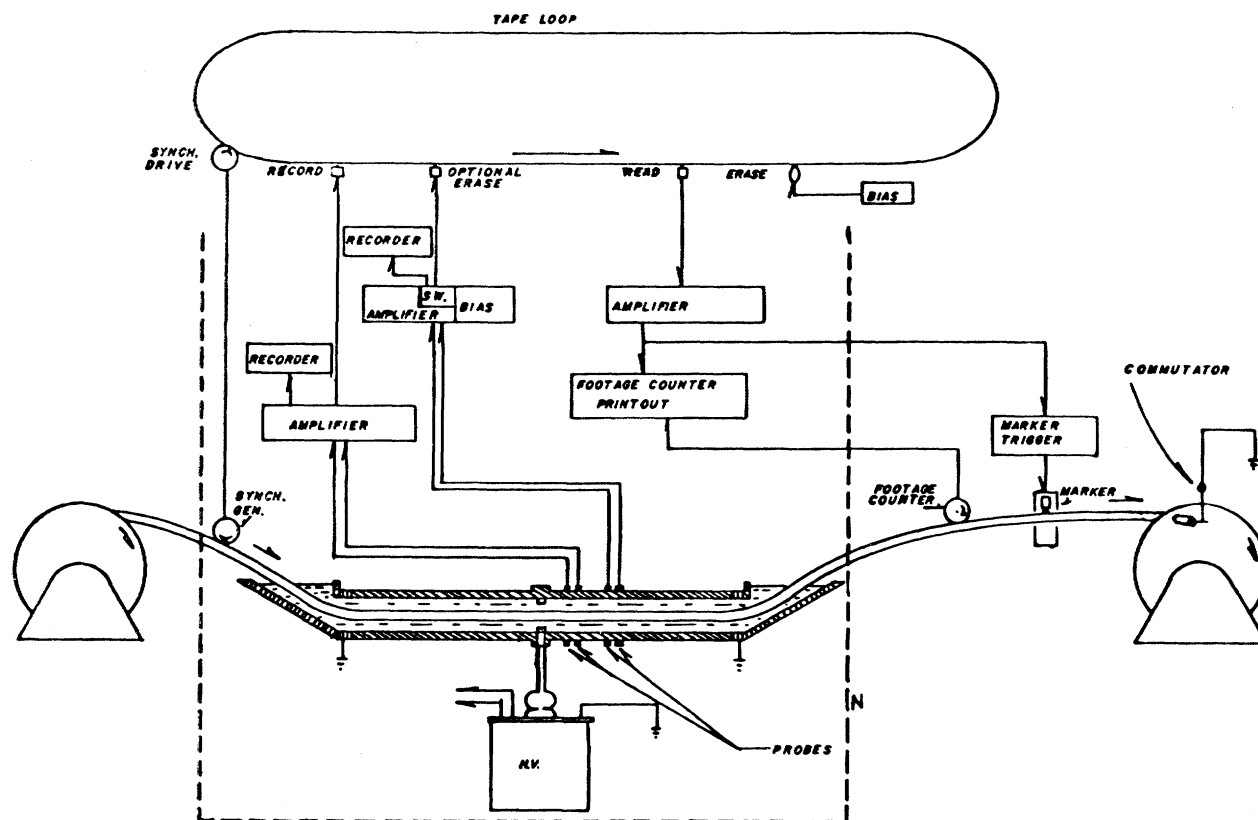


Fig. 8. Diagram of Micro-Scanner system.

tube, 15 percent down-voltage from the center. Signals from this probe are detected and applied to a magnetic recording head on a tape loop which runs synchronously with the cable. The second probe-pair is 40 percent down-voltage from the center at the specified corona acceptance level. Signals from this second probe, after detection, are coupled through appropriate circuitry to a second head on the tape loop. This head, spaced from the first recording head by a distance equivalent to that between the two probe-pairs, is in a *normally erase* mode. That is, it will erase everything that was recorded, *unless* a signal is derived from the second (specification level) probe. In this event, the erase function is deactivated, and the original finding allowed to pass. (This *time probability* logic greatly enhances the noise immunity of the system. The probability that noise bursts, which are violent enough to get through the differential circuitry, would occur in the exact time sequence of a corona element passing between the two sets of probes is small indeed.) At a point on the magnetic tape loop equivalent to the position of an automatic marking device, a third head reads the remaining information on the tape and operates a paint spray to mark the actual site of the defect. At the same time a footage printer is actuated to record its position.

The entire operation of the Micro-Scanner is completely automatic and independent of operator judgment. The cable is scanned at a speed of 220 F/min without stopping. Since the exposure to stressing voltage is only momentary, self-extinction cannot occur before the existence of corona is recorded. A fail-safe automatic calibrating device searches each circuit for proper operation and the entire Micro-Scanner line shuts down if there is any deviation from prescribed levels.

The sensitivity of the Micro-Scanner system is now considered. In the section on full-reel corona methods, sensitivity values were quoted ranging from 40 to 0.1 pC. When 0.01-mV (peak-to-peak) pulses were applied to the Micro-Scanner detector, all recording and marking functions were strongly activated. Since the pulse generator was coupled to the detector by a 2.4-pF capacitor, the Micro-Scanner sensitivity could be expressed as 2.4×10^{-8} pC, about eight decades greater than the full-reel corona test sensitivities. Of course, the picocoulombs approach is objectionable for full-reel corona calibration and it is preferable to use a voltage sensitivity value for standardization of all corona testing equipment. It should be emphasized that the detection rings in the Micro-Scanner are always coupled to a detector with this 0.01-mV sensitivity. Since any signal detected at this sensitivity by the system automatically results in cable marking and rejection, no noise components can be tolerated even at this great sensitivity.

In discussing full-reel corona detection methods, reference was made to those who claim corona always occurs along the entire length of cable rather than in a few discrete places. This misunderstanding does not exist for the user of a Micro-Scanner, which reveals the locations of individual defects. As a result of feedback from this system, the quality control group was able to eliminate gross-corona and minimize the occurrence of individual defects by improvements in manufacturing processes and techniques. It is now found that corona-producing elements in cables, when they occur, are relatively few in number and located at discrete sites rather than diffused throughout the cable. The continuing analysis of scanner-derived information is further reducing the frequency of such individual imperfections. Since in

practice, cables fail at one point at a time—the single weakest point where electrical stresses concentrate—it is essential to locate and eliminate these single corona-producing elements in order to avoid failures caused by corona.

CONCLUSION

While incorporating the known improvements of corona detection introduced by previous scanning methods, the newest cable scanning system, known as the Micro-Scanner, has the following additional inherent advantages. It has freedom from uncertainties due to standing-wave formation. The findings are automatic and not subject to operator interpretation. Uniform rate and time of stress application permit reproducible measurement. The time of exposure to stress has been minimized, thus reducing the risk of corona self-extinction and overlooking serious defects. Corona-producing elements are detected with extremely high and equal sensitivity throughout the length of any cable. Further, the information feedback inherent in the system permit the location and correction of defect-causing procedures in the cable manufacturing process. Clearly, the Micro-Scanner system, overcoming the weaknesses and shortcomings of other corona detection methods, can provide assurance that a cable is free of corona-producing elements at the conductor and in the wall of insulation, the most sensitive region of the cable.

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Discussion

G. S. Eager and G. Bader (General Cable Corporation, Bayonne, N. J.): We believe that the data given in Figs. 2–7 are not applicable to corona discharge. The reason is that the use of a sinusoidal sustained wave of 0 to 3 MHz to simulate corona discharge is not proper, and the spectrum analyzer detection circuit of Fig. 2 is different from the power separator filter used for corona measurements. A description of the wave disturbance one obtains due to a void discharge in a cable is given by Eager and Bader,^[8] as well as other places. If a pulse rather than a sweep generator is used, phenomena such as standing waves, as shown in Figs. 3–7, will not be obtained. Fig. 9 shows the correct way to obtain reflection data from the ends of the cable. When this is done, in place of Figs. 3–7, the data given in Fig. 10 is obtained. These clearly show that pulses give results drastically different from those of sustained waves. This is an accepted fact indicated by Kreuger,^[10] Mason,^[17] and others. It can be seen from Fig. 10 that the amplifier response follows a regular pattern and is substantially the same for pulses regardless of where they are inserted. The amplifier response is then not variable, as shown in Figs. 3–7. When the pulse is inserted near the end of the cable, the response is affected by a regular pattern, as explained by Eager and Bader.^[8]

We do not agree with the authors' statement that the picocoulomb approach to calibration cannot be used. In obtaining data for Fig. 10, we used three shapes of pulses as shown, all having the same charge in picocoulombs but of different voltage amplitudes. The response was a straight line as shown. This is obvious proof that the detector response is proportional not to the voltage, as the authors indicate, but to the charge.

The authors describe tests on a 15-kV rubber-insulated cable and demonstrate that the amplitude response of the Micro-Scanner due to discharges in voids differs with the magnitude of the applied 60-Hz voltage depending on the nature of the void. They conclude from these data that detector calibration cannot be based on picocoulombs pointing out that picocoulombs are not related to energy. Obviously, the Micro-Scanner response therefore cannot be calibrated in picocoulombs. Actually, no known detector can relate picocoulombs to the energy of the discharge. The voltage amplification factor cannot be related to energy, and for full-reel tests it cannot be related to picocoulombs either. However, as shown in Eager and Bader,^[8] picocoulombs can be related to the size of the discharging void and therefore it has a meaning. This fact is recognized by many people and explains why IPCEA, IEC, and many others recommend calibration based on picocoulombs.

The authors cannot interpret correctly the data in Fig. 1 because their scanner is sensitive to voltage. Actually, what Fig. 1 indicates is that at site A the discharging area becomes larger as voltage increases and at site B the discharging area does not increase with voltage. If the response of a detector is related to picocoulombs, then at site A more picocoulombs are measured at the higher voltages and at site B the same picocoulombs are measured at the higher voltages. Therefore, the Micro-Scanner should be redesigned to have a response related to picocoulombs. It will then be in step with most other detectors now in use.

The Micro-Scanner system falls short of what is desirable for corona measurements because it does not test the finished cable as shipped to the customer; it scans only the insulated core. A promise is made that the scanner may, at some future date, test the insulated core after the insulation shield is applied. Should the scanner be so used, it would still fall short of what is desirable because the cable could subsequently be damaged during the application of the semi-conducting shield, the application of the metallic shield and coverings, or at some other time prior to final test. A skip in the insulation shield or other subsequent damage to the internal insulation structure would not be detected by the scanner. However, a full-reel corona test on completed cable prior to shipment would detect such defects. In our experience, a great majority of voids in practical cases occur between the insulation and insulation shield which would not be detected by the present Micro-Scanner. At best, therefore, the scanner is only an aid to factory processing and tests on full reels of finished cable must be relied upon for final quality assurance. The authors indicate that the scanner helps quality control personnel to pinpoint the location of defects. This also is readily accomplished with

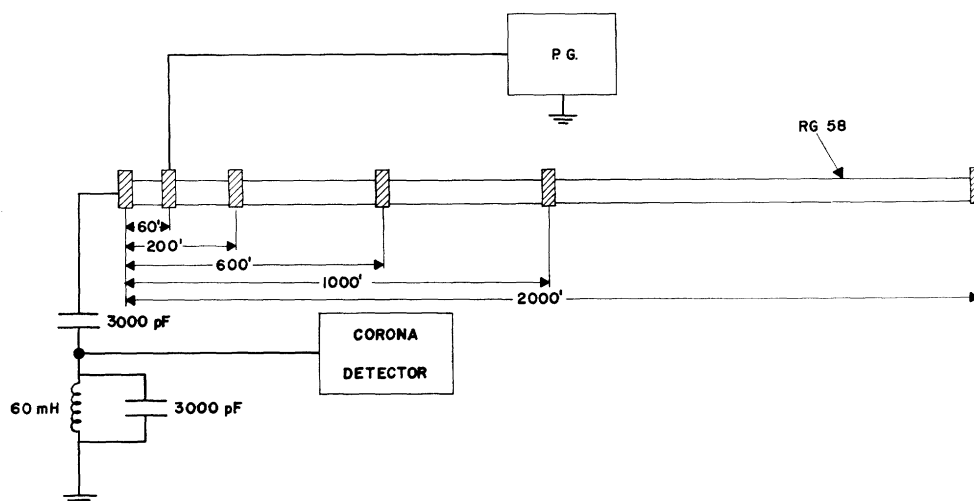


Fig. 9.

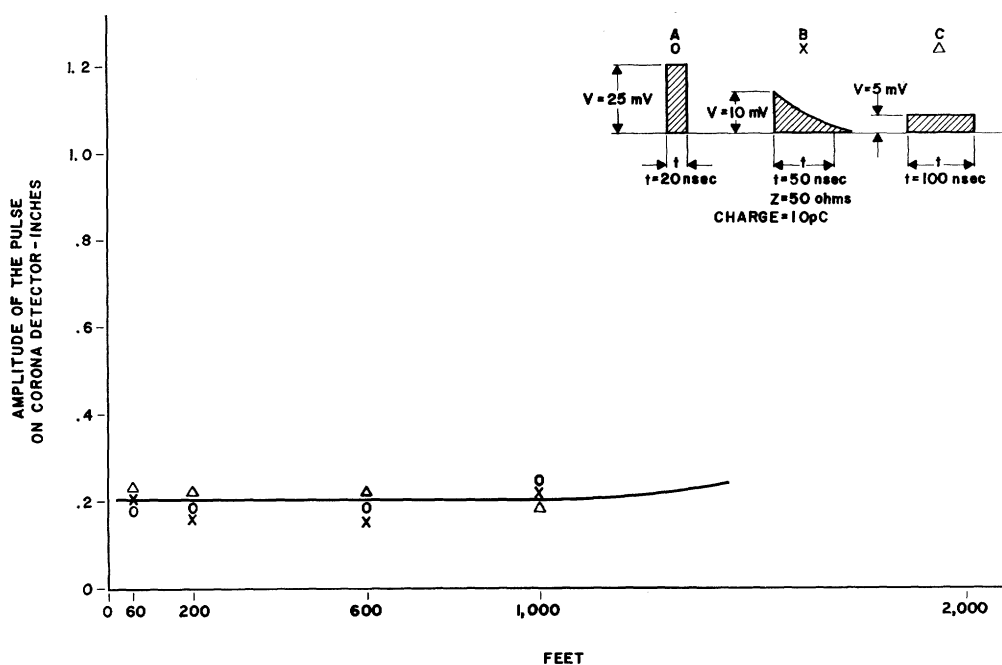


Fig. 10.

full-reel detection; we found the source of voids simply by cutting factory lengths to shipping lengths and by using well-known special laboratory techniques (as described, for example, by Kreuger^[16]) for pinpointing the voids on the shipping lengths that do not pass the required corona level. We also use a scanner of our own design capable of scanning shielded cores for this purpose which we plan to discuss in a paper before the IEEE.

No details are given concerning the Micro-Scanner circuitry, in either the present or preceding paper.^[16] Consequently it is extremely difficult to comment on many aspects of the paper concerning, for example, the type of probe-pairs, the amplifier input impedance, the calibration circuit, the type of transient voltage caused by corona which appears at the probe-pair, etc. However, from what can be deduced from the vague descriptions, the principle of operation of the Micro-Scanner system is not based on detecting direct radiation of signals from the voids as stated, but on detecting the charge which replaces that released in the void. In other words, the probes must detect the motion of the charge of electrons, rather than the electromagnetic field emanating from the corona discharge at the site. This is so because the energy of the electromagnetic field emanating

at the location of the probe is much smaller, and emitted at a much higher frequency than can possibly be detected. A corona discharge emits energy due to recombination of ions with electrons. This process is described by Planck's equation (see Maxfield and Benedict,^[18] page 246), which shows that the energy is emitted at frequencies of the order of 10^{15} Hz. This frequency is highly attenuated in polyethylene insulation and is several orders of magnitude higher than the highest frequency response of an amplifier. This indicates that the Micro-Scanner cannot be responding to radiation phenomena.

The sensitivity indicated in the paper of 2.4×10^{-8} pC means that the authors would be able to detect one sixth of the charge of one electron which must be incorrect by many orders of magnitude. As a matter of interest, the charge generated by the friction of waving a pencil in the air exceeds the charge indicated as detectable by the Micro-Scanner.

There is an ideal tool available to make tests on full-reel lengths of cable. We described this apparatus in our paper^[8] and, by the proper selection of components of the power separator-filter-type detector, a sensitivity of 4 pC may be obtained on full-reel lengths of completed cable. The corona measurement procedure used in our plants

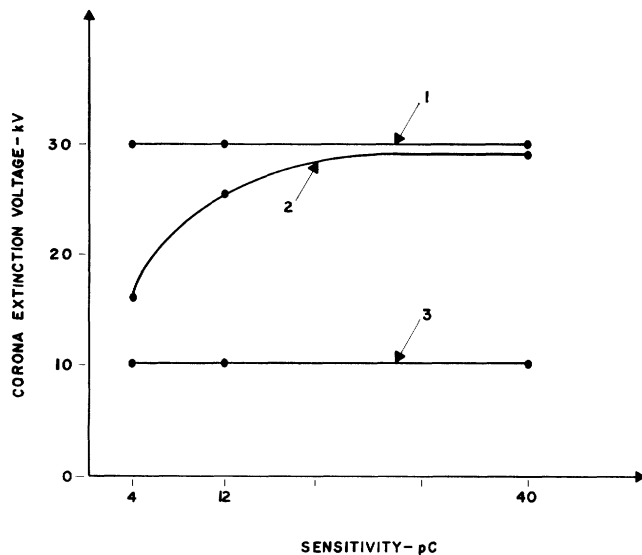


Fig. 11.

TABLE I

Corona Extinction Voltage, kV						
Cable No.	Cable Length, feet	Contin-uous Detector, 0.4 pC	Full-Reel Detector			Approximate Void Size and Location
			4 pC	12 pC	40 pC	
1	2500	9	9	12	15	13 mils at conduc-tor
2	2500	25	25	25	25	20 mils at insula-tion shield
3	2500	15	19	25	30	5 mils at conduc-tor
4	2500	13	16	21	26	8 mils at conduc-tor
5	2000	20	20	20	20	more than 30 mils at insulation shield
6	2800	30	30	30	30	no voids
7	2100	9	9	9	9	many voids ap-proximately 14 mils near the conductor

on full reels of completed cable consists of three measurements made at three different sensitivities: 4, 12, and 40 pC. Fig. 11 gives an example of corona characteristics measured on three 15-kV polyethylene-insulated URD cables with conductor size No. 2 AWG, extruded strand and insulation shields, and 220 mils of insulation. Cable No. 1 was corona-free up to 30 kV at all measured sensitivities. This cable is considered as extra-high quality from the corona standpoint. Cable No. 2 was corona-free up to 30 kV at 40-pC sensitivity and lower corona extinction voltages were measured at 12- and 4-pC sensitivities. This cable has a very limited number of voids of small size not visible to the eye and therefore, the corona voltage depends on the sensitivity of the corona detector. This may be considered high-quality cable. Cable No. 3 indicates very slight dependence of corona extinction voltage with sensitivity of the corona detector. This cable either has many voids or one large void. It is apparent that this method of corona measurement provides a procedure which not only qualifies completed cable on a *go/no-go* basis, but also provides a method to evaluate completed cable quality. Another important advantage is that during the corona test cables in the category of Cable Nos. 1 and 2 are subjected to much higher voltages

than the specified extinction voltage. This eliminates all problems with regard to self-extinction of corona discharges in voids since this effect appears often at voltages slightly above the corona inception voltage. It should be emphasized that to obtain cables falling in these it is usually necessary to employ extruded semiconducting shields.

We have established the correlation between full-reel testing and foot-by-foot scanning of the cable core employing a continuous corona detector developed primarily for laboratory studies for testing cables having a semiconducting insulation shield. Our detector for continuous corona measurements differs from others. It continuously measures and records the CEV within a voltage range approximately up to 3.5 times the operating voltage of the cable. To establish a correlation between results obtained by means of this detector and a power filter-type detector used for full-reel testing, several cables were tested on both systems and later examined to find the source of corona. Typical results are given in Table I.

Cables tested were Size 4 AWG 15-kV URD polyethylene-insulated with extruded shields. They had had concentric wires which were removed for corona detection measurements when using the continuous corona detector. Cables No. 1, 2, 3, and 4 were originally corona-free up to 30 kV and artificial voids were made, as indicated, near the far end of the cable. Cables No. 5, 6, and 7 were as received from the factory.

In general it may be concluded that when CEV is low, the full-reel test gives the same results as the foot-by-foot measurement. This is also true when the voids are at the insulation shield. If a single void is near the conductor and CIV is high, the full-reel measurement gives slightly higher values at the 4-pC sensitivity. It is also obvious that when more than one void exists, which is almost always the case in our experience, the full-reel and foot-by-foot tests give the same results.

It was stated that a full-reel detector does not have the ability to detect individual corona sites which appear at random. As just indicated, a large void is easily detected because the charge in picocoulombs is large; one small void is detected by a circuit similar to the one described in Eager and Bader^[16] because this circuit integrates a large number of discharges having low picocoulombs which appear because the voltage is raised above the ionization starting potential. As a matter of fact, the scanner may not even locate a small void because the stress is not raised high enough to discharge the void; the authors indicate that the Micro-Scanner is operated at 15 kV for a 15-kV cable, which is a low voltage for such a cable.

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D. A. Costello and R. Bartnikas (Northern Electric Company Ltd., Lachine, P.Q., Canada): In their comparison of scanning and full-reel corona testing methods, the authors raised a number of interesting points. Certainly, we subscribe to the view that one or other of the various scanning methods which have evolved from the Gooding train is indispensable for development purposes. However, we are not convinced that such a device is required, or even significantly superior, for routine test purposes. Nor do we feel that it yields information which cannot be misinterpreted.

For instance, the authors draw certain conclusions based on the corona intensity peaks obtained by means of a recorder, as illustrated in Fig. 1. As recorders are essentially integrating devices, proportional both to amplitude and the number of pulses, great care must be exercised in the interpretation of such results. The sequence of discharge events in physical voids may assume rather complex character as recognized by the authors. Considering a hypothetical cavity with equal breakdown and zero residual voltages in the two polarities and negligible discharge times, discharges will occur on the points on the applied voltage wave wherever the voltage across the void exceeds integer values of the breakdown voltage along the up-

ward and downward excursions of the voltage trace. This results in a step-like increase in the number of discharge pulses with applied voltage. Even in the most simple cavities, i.e., those containing metallic electrodes, variations occur in the breakdown voltages from polarity to polarity and within the same polarity accompanied by finite and variable residual voltages. In such circumstances, it is found that the number of discharges increases usually quasi-linearly with applied voltage. However, the magnitude of the discharge voltage, defined as the difference between the breakdown and residual voltages for a given discharge epoch, remains surprisingly constant, thus yielding a detected corona pulse of nearly constant amplitude. Evidently, this also implies a nearly constant energy loss per discharge. In voids having plane-parallel dielectric electrodes, similar behavior usually prevails at each discrete discharge site, although the overall discharge sequence appears to be considerably more complicated as a result of the occurrence of several discharge sites whose breakdown voltages differ by a finite value. Nevertheless, the corona pulses for the individual discharge sites do not increase with voltage to any significant extent as this would entail either a decrease of the residual voltage, an increase of the breakdown voltage, or both for each discharge site. This again implies an approximately constant release of energy per discharge per each discharge site.

With spherical cavities having dielectric boundaries, the breakdown voltages of the various discharge sites would be expected to differ appreciably as a direct outcome of a large variation of the air path within the cavity. Accordingly, the discharge rate and magnitude of the corona pulses emanating from such cavities increase with applied voltage. The former increases with voltage as a result of an increase in the number of discharge pulses for each site and because of the additional pulses arising as more and more discharge sites commence ionizing, while the increase in the latter is solely characteristic of the discharge sites with larger breakdown voltages which commence ionizing as the increasing voltage exceeds their breakdown strength. A similar effect could also be obtained with a number of voids which have varying breakdown voltages, but in which the number of discharge sites need not be more than one. Although upon ionization onset the vapor pressure, geometry, and surface conductivity of the void may undergo change, it is unlikely that this would give rise to a reproducible variation in the breakdown voltage of the void with changing applied voltage.

Accordingly, we suggest that the increase of the peak *A* in Fig. 1 with applied voltage is either a result of an increase in the number of discharges, or both an increase in the number of discharges and the onset of new discharges with larger magnitudes. It does not appear to us to be a result of an increase in the magnitude of a given pulse with voltages, as the authors have concluded. The peak *B* could easily have resulted from signal integration arising with an unresolved discharge pattern; a constant discharge count with varying voltage as implied by the authors would appear to be quite unlikely in view of the foregoing considerations. We believe that the authors could easily have resolved these uncertainties if use had been made of pulse-counting circuitry, preferably in conjunction with a peak voltage recording system rather than the integrating device they appear to have used.^[19]

On the basis of tests carried out using their Micro-Scanner system for unshielded cables, the authors expressed the view that voids exist in a few discrete places rather than along the entire length of a finished cable. We feel that both views represent oversimplifications of the actual situation. Extrusion techniques have now developed to the extent where voids at the conductor shield/insulation interface and in the insulation proper, if they do occur, exist at a few discrete places. However, in cables designed for operation at typical stresses as represented by the current IPCEA standards, it is usual for the semiconducting insulation shield to be applied in such a way that it fits the insulation tightly but is not homogeneously bonded to it. This facilitates removal of such a layer at terminations and splices, thereby avoiding the necessity for shaving off the semiconducting insulation shield. When distributed voids are spoken of, it is usually understood that these are located along the interface between the insulation and the semiconducting layer of material over the insulation. This is why in testing cables which exhibit ionization levels below, or uncomfortably close to the voltage at which they are intended to be operated, the apparent sensitivity of the detection equipment is relatively unimportant in the vast majority of instances, Fig. 12. This is also the basis of the not uncommon view that for routine go/no-go testing a 25- to 50-percent (rather than the usual 10-percent) safety margin may be relied upon to compensate for a sensi-

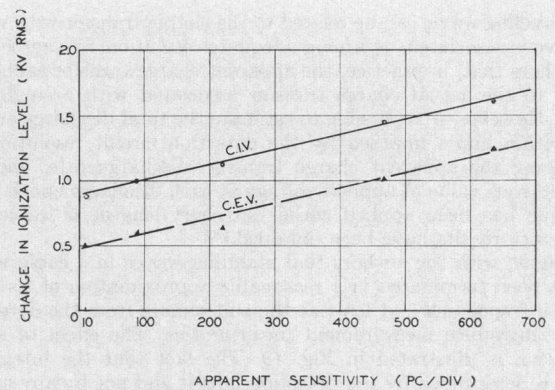


Fig. 12. Response characteristic typical of cable with distributed voids.

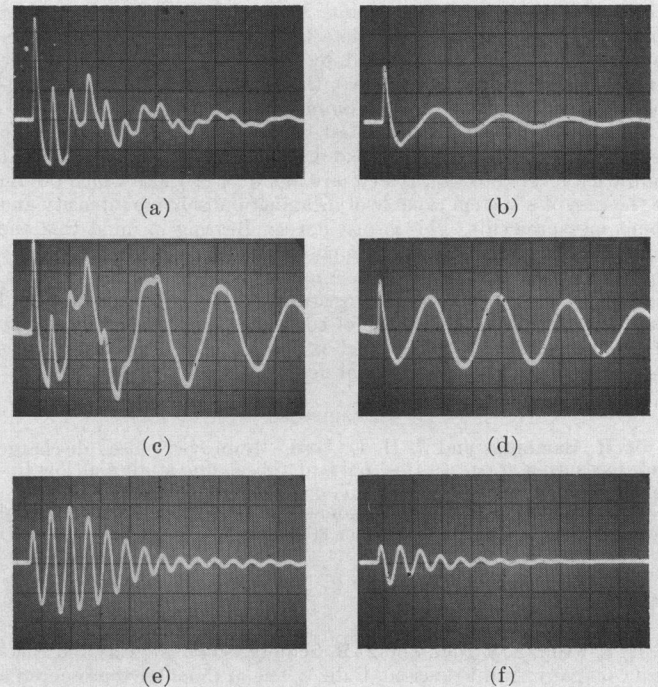


Fig. 13. Response waveform of LCR detection system obtained with tunable amplifier connected between detection impedance and display unit. Horizontal scale—10 μ s/division. (a) Far end of cable unterminated; with amplifier response flat to 600 kHz. (b) Same as in (a) but with far end of cable practically terminated with a resistor equal in value to characteristic impedance in series with a 0.05- μ F capacitor. (c) Far end of cable unterminated; amplifier tuned to natural frequency of oscillation of detection circuit. (d) Same as in (c) but with cable terminated at far end. (e) Far end of cable unterminated; amplifier tuned to peak at approximately 3.5 times the natural frequency oscillation of detection circuit. (f) Same as in (e) but with cable terminated at far end.

tivity deficiency in the detection apparatus used; patently, there is little intrinsic practical value in a true ionization level 50 percent above the operating voltage, as opposed to 10 percent above it. Finally, it is also the reason that simultaneous extrusion of the insulation and both the inner and outer layers of semiconducting material is necessary if design maximum stresses of the order of 100 kV/cm are to be contemplated, as in an economically feasible 115-kV solid dielectric cable.

We do not consider that the authors have demonstrated that it is more meaningful for detector sensitivity to be quoted in terms of a voltage amplification factor than in terms of apparent charge transfer. Eager and Bader^[8] have demonstrated that at least the oscillatory portion of an LCR detection circuit response, to an inci-

dent traveling wave, can be related to the charge transfer with which the wave is associated, assuming adequate resolution. We agree with the authors that, in practice, the apparent charge transfer cannot be related to the actual charge transfer associated with a single discharge. However, it is possible to estimate the total discharge energy level within limits imposed by the detection circuit resolution by considering the apparent charge transfer, discharge rate, and the instantaneous value of applied voltage at each discharge epoch. This technique has been applied earlier on short lengths of cable and satisfactory results have been obtained.^[20]

We agree with the authors that standing waves in a cable which has not been terminated in a reasonable approximation of its characteristic impedance—at least at the end remote from the detection circuit—introduce measurement uncertainties. The effect of signal integration is illustrated in Fig. 13. The fact that the integrated energy is determined by the detection circuit and not by any amplification/filtering system between the detection circuit proper and the display unit is obvious. Fig. 13 represents the response of an LCR system to a step function having a mains frequency repetition rate and injected at the *far-end* of a 1000-foot length of polyethylene-insulated cable. Had the authors injected a similar step function instead of sine-wave sweep at points along their test cable, and had they used two typical LCR detection circuits with natural frequencies of oscillation separated by about an order of magnitude (rather than a spectrum analyzer), they would have obtained standing-wave patterns less likely to be misinterpreted.

In any generalized review of test methods, there is a tendency to assume that the objectives of, and criteria which apply to, a routine ionization level detection system are identical to those which obtain in the case of a system capable of meaningful discharge intensity and count measurements. This is just not so. Bearing in mind that the minimum sensitivity standard proposed by the IPCEA referred to by the authors is not intended to be a measurement calibration system, we believe that the proposal constitutes a major step forward, and that detection systems capable of complying with the requirements of this proposal may be regarded as acceptable routine test devices for cables of current conventional design.

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J. H. Lawson, F. J. Dan, and F. B. Schullerts (Pacific Gas and Electric Company, San Francisco, Calif.): The authors have presented a most timely and interesting paper. It is hoped that their work on the subject will continue and that additional results will be released in the near future. A comparison of tests made by the scanning and full-reel methods on a number of prepared cable samples would be most valuable.

Oil-impregnated, paper-insulated cables are being replaced with cables using extruded solid dielectric insulations, such as polyethylene, in ever-increasing amounts for distribution power cable applications. For example, on the Pacific Gas and Electric Company system, cables with extruded insulation are used on nearly all new primary distribution circuits. Even in the transmission voltage class, solid dielectric cables are coming into limited semi-experimental use. From the utility viewpoint, therefore, these new cables must have at least the same insulation life as experienced with paper insulation. As the authors quoted, the "chief culprit" of extruded solid dielectric cables is corona. In order to maximize the probability of long life, corona detection techniques should be fully explored with the goal that cables be supplied to the user as defect-free as possible. The authors have contributed to this fund of knowledge.

The authors have stimulated some pertinent questions on the subject, viz.,

1) Both AEIC and IPCEA specifications make provisions for post-installation, high-voltage tests. This is to give assurance that the cable has been satisfactorily designed and manufactured to meet the rigorous treatment of the cable in the transporting, pulling, and

bending that occurs during installation and load cycling thereafter, under actual field conditions. If it were feasible, solid dielectric cables should also be subjected to a corona level test after installation for the same reasons. This would be desirable for corona sensitive polyethylene, especially because of the substantially reduced insulation thicknesses that have been suggested. It is evident that the factory corona level test should be as rigid as practical. To keep this test within reasonable limits, we ask what the authors' reaction might be to setting up simulated field installation conditions in the laboratory and making corona level measurements before and after the cable was subjected to the *field* abuse. For example, a cross-linked polyethylene cable with a known corona level of approximately 110-150 percent of the phase-to-ground rating could be *installed* and raised to the rated operating temperature of 90°C (and 130°C for emergency evaluation) and then tested for corona extinction.

2) Since maximum stress occurs at the conductor and is an inverse function of conductor diameter, would it be economical to vary the insulation wall specification values with conductor size for any given voltage the same as specified for paper-insulated cable?

3) The authors explain the so-called self-extinction that may occur when cables are subjected to prolonged corona which is more pronounced the higher the test voltage. The erroneously labeled self-extinction actually results in the formation of a conducting path around the gas cell. If the standard five-minute ac high-voltage test is made prior to the corona level test, the presence of certain voids may be masked out. This test voltage exceeds the corona level value by two or three times. On the other hand, if these tests are made in the reverse order, corona damage may have been initiated at the higher stress of the ac test. Which of these two options would result in the least possible ultimate damage or masking of true conditions of the cable?

4) Have the authors in their investigation determined the relationship of

- a) voltage stress with number of spikes on signal?
- b) voltage increase with number of pulses?

5) Will the authors kindly elaborate and clarify their statement under *Origin of Cable Corona Signals* that "It is clear that the life of some insulations is directly proportional to the number of intense discharges."

C. S. Schifreen and N. B. Timpe (Philadelphia Electric Company, Philadelphia, Pa.): This paper is a welcome presentation of the advances made in cable corona scanning by the sponsor company subsequent to its 1957 paper which described an earlier model.^[10]

Incorporation of the interference-free probe apparatus apparently has added a desirable feature in an effort to obtain more reliable discrimination of the corona signal as a result of its revised circuitry arrangement with the purpose of minimizing the effect of extraneous noise. It would have been helpful in demonstrating and evaluating this feature if the paper included a chart showing the magnitude and typical shapes of the sequential signals from a cable defect to each probe of a given pair as the "corona avalanches passing sequentially to the probes (as the cable is moved) unbalance the pair, and thus produce an appropriate signal in the detector." This feature, together with the basic concept of scanning the cable continuously while the high voltage is applied successively to only very short portions of the cable, would appear in principle to allow greater precision in defect detection than the alternate full-reel detection test techniques, particularly since the scanning method regards each cable portion as a lumped capacitance while the full-reel method regards the distributed capacitance of the entire reel of cable. While the authors devoted much of their text to emphasize the claim of superiority for their Micro-Scanner as a corona-detection device, it would have been more effective if they included actual evidence in the form of test data on the relative performance of the alternate methods used to test the same cable containing ionizable defects.

Another commendable new feature involves directing attention to any given void in a short portion of the cable as it moves past the two sets of probes. This should permit ascertaining whether ionization, once detected in this void by the first pair of probes, has ex-

tinguished itself as this void passes the second pair of probes at a suitably selected lower voltage (corresponding to a desired maximum allowable corona extinction level). In this connection, however, there are several questions which should be answered.

First, what precautions are taken to ensure maintaining the desired potential gradient from the midpoint of the scanning tube to the ground potential at its exit end? Progressive accumulation of contaminants at this end, resulting in part from the travel of the cable in this direction, could conceivably upset the gradient upon which the 15- and 40-percent potential differentials are based.

Second, we wonder whether the claim in the present paper of ability to detect defects such as "the interface between dissimilar solid materials" reflects laboratory findings attributable to the "sensitivity of the Micro-Scanner system," or if the same qualification is applicable here as was given to explain the detection of small metal particles in the Gooding-Slade test train^[10] (p. 1002), viz., "there always seemed to be a small air pocket associated with the metal fragment, and this led to its detection."

Third, it is not clear that the extreme sensitivity claimed for the Micro-Scanner (expressed as 2.4×10^{-8} pC) properly evaluates its merit in comparison with the "40-to-0.1 pC" sensitivity for the full-reel methods. It is not clearly defined whether the "0.1-mV (peak-to-peak) pulses were applied to the Micro-Scanner detector" while shunted by an appropriately proportioned cable capacitance.

Realization of the authors' hope for a "not-too-distant" future extension of the "sensitive Micro-Scanner approach to the outer screen-shield portion of a cable and the resulting complete elimination of the full-reel corona test" may be expected to offset the objection on the part of some cable manufacturers, presently proponents of the full-reel test method, that the Micro-Scanner is only a partial quality control technique. Acceptance of the electric scanning principle may follow, resulting in experience by more than one cable manufacturer with this technique, bringing about the desired broad industry evaluation of the meaningfulness of ionization and void size by having attention focused by test experts in the laboratories of other cable manufacturers toward a common system of quality control.

Unfortunately, for the present, with the conflicting claims of the two opposed systems of quality control, it seems that ionization sensitivity presents a third category of competition in addition to manufacture cost and effectiveness of engineering design. The future extension of solid insulation (extruded types) into the widening fields of 69-, 138-, and 230-kV cable systems requires better overall understanding of the ionization problems on the part of manufacturers and users. The concentration of our best efforts in one comprehensive and optimum sensitive technique should expedite such greater usage

retically at least, it is possible to diminish the influence of the outside pickup in the scanning method. However, we wonder how the authors got rid of the thermal noise and, above all, the amplifier noise. To the best of our knowledge, the quoted sensitivity of 2.4×10^{-8} pC (equivalent to 0.15 charge of an electron) sounds rather unrealistic as long as the whole testing stand is not placed in a Faraday cage and at close to absolute zero temperature.

2) The problem of reflections in the full-reel method of corona detection does not seem to be as detrimental as presented in the paper. Suitable choice of the detector circuit and termination can always eliminate the undesirable effects of the reflections. Concerning the reflections, we would like to ask the authors how they interpret Figs. 3-7, on which the units are missing on the vertical axes.

3) Without discrediting its advantages, the scanning method also has some deficiencies, for example, heating the water by higher voltages, longer testing time, inapplicability (at least for the moment) to screened cores, etc. We would appreciate the authors' comments on these points.

L. C. Ebel and A. E. Widmer (Anaconda Wire and Cable Company Hastings-on-Hudson, N.Y.): To substitute a scanning test of in-process material for a full-reel test of completed cable does not seem advisable. It is quite possible to have an irregularity on the outer surface of the insulation which during in-process scanning is completely filled with water, but when subsequently shielded is partially bridged and forms an ionizable void. A combination of scanning and full-reel testing is most desirable at the present time. Until a means of scanning of completed cable is perfected, we cannot abandon full-reel tests.

Although we agree that the rating of detectors by picocoulombs, without further specification, is inadequate, we feel that rating according to the authors' suggestions, by "microvolts per centimeter deflection over noise" or "voltage amplification factor" or "voltage sensitivity value," is equally inadequate. Ratings according to either method are uninformative except in the context of circuits used, signals applied, etc. Either the charge transfer method or voltage sensitivity method (or perhaps preferably a power sensitivity method) may be useful in monitoring *day-to-day performance* of a particular detector. However, a valid comparison among dissimilar detectors requires more information, and should not be made by specifying only one parameter, as is done when a detector is described as having a rated sensitivity of x picocoulombs or microvolts.

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J. B. Jordan and R. Saint-Arnaud (Laval University, Quebec, P.Q., Canada): The authors are to be commended for their contribution to the development of more sensitive methods of discharge detection in cables. However, several points in their paper are controversial and we would like to comment on some of them:

1) The authors claim that the sensitivity of the scanning method is several decades higher than the most sensitive full-reel method. Considering separately the input signal generated by the discharge and the performance of the detector, the signal transmitted directly through the insulation wall is not several decades higher than the one which propagates along the cable. In the case of a short cable the signal transmitted directly is only two times those traveling along the cable. This advantage may disappear, however, because a conventional discharge detector integrates the pulses reflected from the cable ends. If one compares the scanning method with a full-reel test of a long cable, then the signal radiated directly through the insulation may be ten times higher than the one received at the cable end, but not several decades higher. Thus, the exceptional sensitivity of the scanning method should originate from the properties of the detecting circuit itself. To assure a high sensitivity of a detection circuit one has to decrease the noise, since one is interested only in the amplification of the signal distinguishable from the noise background. According to the paper, the noise picked up by the cable externally to the tube is cancelled by the differential circuitry. Theo-

P. H. Ware (Simplex Wire and Cable Company, Cambridge, Mass.): With solid dielectrics being used for higher and higher transmission and distribution voltages, the study of corona detection assumes major importance. While the basic methods now used have been known for more than 25 years, it is only recently that exhaustive studies of the detection phenomena themselves have been made.

This paper, like that by Eager and Bader,^[8] attempts to understand what is actually happening within a cable containing a discharging void, and to relate the evidence as seen by an external circuit to the conditions in the cable itself. The authors present a strong case for the scanning method in corona detection, and there is no doubt that this is an excellent method where exact location of a discharging void is important, and where extreme sensitivity of detection in a long length of cable is desirable. From a production point of view, however, such sensitivity may not be necessary. Correlation of service records over many years with corona levels as established by existing detectors has shown that there is small probability of failure due to ionization or corona when cables meet industry corona standards even though scanning methods have not been used. As a research tool, it is unexcelled; as a production tool, it would be very useful but not necessarily indispensable.

In view of the fact that voltage ratings for extruded cables are increasing, we would like to ask what the authors estimate might be

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the voltage limitations, if any, for the scanning method. They state the scanning speed as a fixed rate of 220 feet per minute. We would like to know what difference in behavior results if the line is operated at speeds significantly higher or lower than this speed.

At the higher voltages where cables are used today, the integrity of the bond between the outer insulation shielding and the insulation itself is very important, as any separation at this point leads to ionization and ultimate damage to the insulation. Is it possible for the authors to locate with their device voids in a cable which is covered with a semiconducting insulation shield?

R. B. Blodgett and D. Eigen: Since Mr. Eager and Mr. Bader gave the longest and most elaborate discussion, we will answer their questions and comments first. These answers also apply to similar questions raised by the other discussers. They raise objections to our approach for reasons which are *scientifically* not clear to us. They first object to our use of a frequency analyzer to study reflections in a cable, stating we used a sinusoidal sustained wave 0 to 3 MHz and later concluding that "if a pulse rather than a sweep generator is used, phenomena such as standing waves... will not be obtained." However, we did not use a sinusoidal sustained wave. We used a particular kind of pulse generator, the Panoramic analyzer, which combines a generator with a detector. This analyzer generates pulses with a repetition rate of 60 Hz and a changing (nonconstant) rate of rise r . The rate at which the rate of rise changed was a constant: $d^2r/dt^2 = k$. This changing rate of rise is achieved by changing the inductance of a saturable reactor in an LCR circuit. The same approach is used to vary the constants in the analyzer's tuned detector circuit in step with the changes in the generating circuit.

The analyzer circuits include damping to prevent oscillation. In fact, the damping components include trimmers which we adjusted to attain the best resolution without ringing. With too much damping the circuit would lose sensitivity and selectivity like any broadband circuit with a low Q . With insufficient damping the circuit would become very sensitive and selective like the detector we discussed elsewhere, but in this use would give false responses. With ringing, any excitation at the frequency generated at one instant would carry over a false response to the different frequencies being detected at later instants. This phenomenon would make the Panoramic frequency analyzer useless for frequency analysis.

To recapitulate, both the signal components generated and the detector responses in the Panoramic analyzer are transient, not steady-state, in nature and should truly represent the transient phenomena of corona discharges. Reflections will depend on the wave velocity through the cable insulation, impedance discontinuities along the cable, and terminal mismatches of impedance. In fact, Millman and Taub in discussing pulse-type circuits state "Often it is desirable to terminate the cable at the sending-end as well to absorb reflections which would result if there should happen to be a slight mismatch at the receiving-end, or if there should happen to be any small discontinuities in the cable itself."^[21] A similar phenomenon is seen when radar pulses are carried on a transmission line. "In order to reduce the standing wave on the line to a minimum, a closer match of impedance is necessary than is usually possible with the impedance transformer."^[22] "In fact, pulse reflections can be used to locate very small impedance variations along a cable."^[23] Further evidence for the validity of our approach was given in the discussion by Mr. Costello and Mr. Barnikas who conclude "that standing waves in a cable which has not been terminated in a reasonable approximation of its characteristic impedance—at least at the end remote from the detection circuit—introduces measurement uncertainties."

Mr. Eager and Mr. Bader next object that the tuned detection circuit of our spectrum analyzer is different from the "power separator filter" they recommend for corona measurements. Calling a circuit a "power separator filter" does not change the fact that it actually is a tuned circuit, just like the detection circuit of our analyzer. Their "power separator filter" is tuned to 30 kHz while our spectrum analyzer automatically varies the tuning of its detection circuit from 0 to 3000 kHz.

As final "proof" that pulses give different results from those of sustained waves (even though we did not use sustained waves),

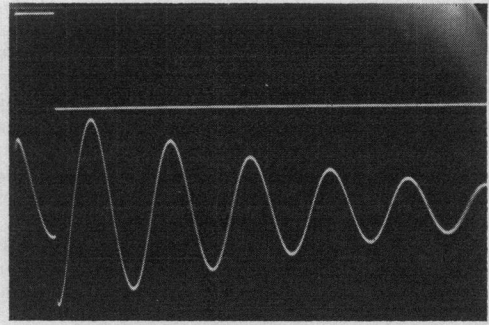


Fig. 14. Increase in amplitude of ringing due to in-phase pulse return.

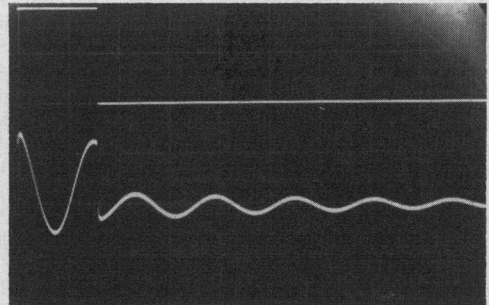


Fig. 15. Decrease in amplitude of ringing due to anti-phase pulse.

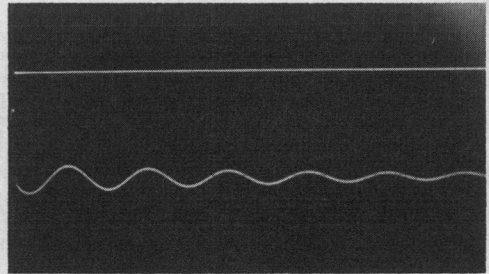


Fig. 16. Decrease in amplitude of ringing when pulse duration is short compared with ringing frequency.

they offer the data in Fig. 10. These data were obtained with a 30-kHz tuned filter, a *black-box* amplifier, and 2000 feet of cable, as shown in Fig. 9. It is interesting that Fig. 10 shows an upward extrapolation beyond the 1000-foot value even though there is no data point beyond 1000 feet. This is very close to the slight voltage reinforcement we obtained in a 1000-foot cable when the detector was tuned to 40 kHz (see Figs. 3–7). In any case, they confirm our statement that reflections in a 2000-foot length of cable would not be a problem with a detector tuned to a low frequency; the reflections which occur augment, but do not decrease, the signals. However, we believe the stronger useful signal obtained at frequencies higher than 40 kHz is more important in full-reel corona than avoiding the reflection problem.

They do not agree with our position that reflections pose problems in testing cable by full-reel corona methods. However, our position is supported by Mole and Kreuger^[25] who summarize their work as follows:

"Large errors may arise when discharges are measured in long lengths of completed cable, e.g., cables longer than 110 to 200 meters. These errors are caused by the traveling waves, originating from the discharge. One wave reaches the detector directly, the other is reflected at the far end of the cable and reaches the detector with some time-delay. The two traveling waves are superimposed in the detector and depending on the time-delay a too small or too large response may be obtained."

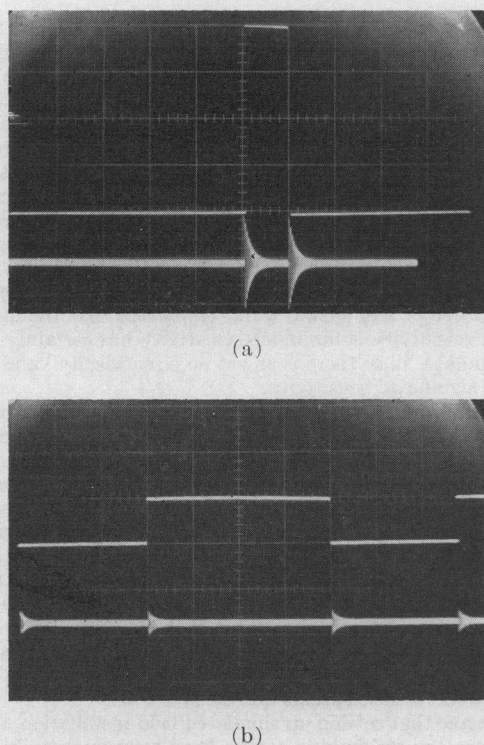


Fig. 17. Effect of equal area pulses when ringing frequency decays before pulse return.

They further agree that cable for a full-reel test should be terminated with a predominantly resistive impedance. In fact, they give a circuit equivalent to the series-tuned termination disclosed in our paper.

Mr. Eager and Mr. Bader go on to use the data in Fig. 10 as "obvious proof that the detector response is proportional not to the voltage, as the authors indicate, but to the charge." By detector they mean the combination of a "power separator filter" resonating at 30 kHz and a black-box amplifier. The amplifier, of course, like all amplifiers, responds to voltage, not charge, at its input terminals. The question then is, does their tuned power separator filter magically convert charge into voltage, as implied by Fig. 10. We say no since their conclusion is based on only three points on the curve relating voltage-response of their tuned circuit to the time interval between the initiation and return voltage spike. Why is the timing of the return spike relative to the initiation spike important? Because the reverse spike will either reduce, maintain, or reinforce the effect of the initiating spike depending upon their time-relation relative to the frequency of the tuned circuit.

For example, three square pulses with the same amplitude, but different durations, are considered. If the duration (16 500 ns) is equivalent to a half-cycle, the return spike will reinforce the initiating spike, doubling the amplitude of the *shocked* wave in the absence of any resistive components. This situation is shown in Fig. 14. The opposite effect is seen in Fig. 15, when the return pulse occurred a full cycle (33 000 ns) after the initiating spike. Since the response to the initiating spike had decayed slightly, because we intentionally damped the circuit, the return spike produces a small signal of reverse phase. In the third pulse (1370-ns duration) the return spike occurred 1/24 cycle or 15° after the initiating spike. This pulse can barely be seen in Fig. 16 even though its height is the same as in the two previous figures. This pulse produced a signal with an amplitude close to that in Fig. 15, when the pulse duration was 33 000 ns. Mr. Eager and Mr. Bader used pulses lasting from 20 to 100 ns; these correspond to 0.22 and 1.8 degrees rotation of the shocked tuned frequency. For such intervals, the interaction between the initiating spike and the almost antiphase return spike reduced the effective signal to a very low level; with the same conditions used for Figs. 14–16, no response was seen photographically. The calculated response for the 25-mV, 20-ns pulse is an effective signal of $0.2 \mu\text{V}$ while the 5-mV, 100-ns pulse would produce an effective signal of $1.0 \mu\text{V}$; these values are about 0.001 percent of the value for a 90° pulse.

These calculated values do not confirm Mr. Eager and Mr. Bader's equal sensitivity results. The disagreement might be due to deviation of their pulses from the rectangular waves used in our experiment and calculations.

In any case, it should be clear that applying pulses directly to the cable, as shown in Fig. 9, is not very meaningful with respect to cable corona. In cable, an actual corona element is coupled to the conductor-shield transmission line through an extremely small capacitance of the void-free insulation and shunted by the resistance in the components of the detector circuit. The effect is to differentiate the discharge. A positive-going spike is seen at initiation, but the rebuilding of charge is too slow to excite the tuned circuit; there is no return spike.

Their nanosecond pulses (*A* and *C* in Fig. 10) produce both a positive- and negative-going spike which will interact as demonstrated in the foregoing. What is needed is a sawtoothed pulse giving only one spike or a rectangular wave lasting long enough for the ringing produced in the tuned circuit by the positive-going spike to die out before the negative-going spike is produced. When this is the case, response is proportional to pulse amplitude or voltage, as shown in Fig. 17(a) and (b). Incidentally, the calibrator for corona detecting equipment recently adopted by the AEIC produces sawtoothed pulses at a rate slow enough to avoid the nonlinear response discussed previously. Mr. Eager and Mr. Bader give various reasons for defending the picocoulomb concept, but their main technical point is that a picocoulomb value can be related to the size of the discharging void even if it is not related to discharge energy. Unfortunately, too many assumptions are involved in assuming that a signal seen by a given detector can be related to a void size. Not the least of these is the assumption that every void discharges in one burst of energy rather than in several successive bursts. If we were dealing with a capacitor, there would be little doubt about the energy being discharged in one event. However, a gas cell in cable insulation has insulating, not metallic, surface. A discharge from one site does not necessarily discharge all other sites on which charge has been developed. Additionally, even during ionization the ohmic resistance of the discharge is certainly not zero. It is thus true that only a small portion of the total charge developed in a void is normally discharged during each cycle of the energizing voltage.

Furthermore, all amplifiers, even their black box, are voltage-sensitive. And a tuned circuit, even one made less sensitive by damping and named a power-filter circuit, is responsive to voltage, not charge, as shown in the foregoing. It should be emphasized that all detectors utilize power-filter circuits and differ only in frequency and bandwidth or *Q*. Specifying a threshold voltage, which a detector amplifier circuit can see over noise through a given impedance, is a straightforward approach which does not hide our ignorance of the void parameters by unspecified assumptions which may be quite erroneous.

Mr. Eager and Mr. Bader consider our scanner "at best only an aid to factory processing and tests on full reels of finished cable must be relied upon for final quality assurance." We are, however, confident that the Micro-Scanner allows us to eliminate flaws which would not have been detected by the full-reel corona test. A paper with our data is in preparation. In any case, we are happy to learn that Mr. Eager and Mr. Bader are in the process of developing their own system for scanning "shielded cores," by which they mean cables with a semiconducting material over the insulation but no metallic shielding. We will be interested to see how their system differs from our approach. Those familiar with Kreuger's scanning system will note the many similarities between it and our scanner which is presently capable of scanning screened cable cores. Some system like ours seems advisable when their present system is unable to show any difference in corona level when picocoulomb sensitivity is varied one hundred fold from 0.4 to 40 pC in testing cables obtained from the factory (see Cables No. 1–7 in Table I). Cable No. 7 had many voids near the conductor. Other cables containing voids are stated to be acceptable by present standards. Does anyone doubt that the probability of premature failure of these cables is greater than if they did not contain the voids?

Mr. Eager and Mr. Bader dispute our statement that the Micro-Scanner detects direct radiation of signals from voids and state "the probes must detect the motion of the charge of electrons rather than the electromagnetic field emanating from the corona discharge." The disturbance to the field caused by the corona discharge pulse or pulses, of course, generates an electromagnetic component. This

travels by well-known optical principles and is, in fact, picked up by our probes. It is a common error to suppose that the extremely minute currents involved in a corona discharge can actually be measured in the presence of the very large currents flowing in the cable itself. The corona energy itself, that is, the small packets of energy due to the recombination of ions with electrons, are, as we have often said, far too small to measure in the present state of the art.

We have strongly maintained in the past and reiterated in this paper that neither we, nor anyone else, can actually measure the discharge of a gas cell in a cable length in terms of picocoulombs. It is therefore surprising that the statement describing the fact that we inserted a pulse of 0.01 mV through a capacitor of 2.4 pF, which by conventional calculation would imply a charge of 2.4×10^{-8} pC, was interpreted to mean that we had in fact calibrated our detector in terms of charge. To be more explicit, the interpretation of voltage-derived signals in terms of charge, does, in fact, require the waving of a pencil or some other magic wand.

A major difference in approach to cable quality exists between Mr. Eager and Mr. Bader and us. We prefer to test with great sensitivity at a slight overvoltage. As shown by their discussion of full-reel corona results on four reels of completed cable, they prefer to test with low sensitivity at a high overvoltage. The 15-kV Cable No. 2 was corona-free up to 30 kV at 40-pC sensitivity, but not at 12- and 4-pC sensitivity. They report that this cable has a very limited number of voids not visible to the eye (presumably *naked*) and is considered a *high-quality* cable.

We do not agree that it is a high-quality cable, because *no one* up to the present time has been able to prove a direct relationship between the size of a signal derived by any means from a corona element and the time required for breakdown of the insulation due to that corona element. Any approach which does not keep this in mind is not only arbitrary but dangerous. Self-extinction of corona signals is caused primarily by the formation of degradation products on the walls of the gas cell. Testing the cable at much higher voltages than the specified extinction voltage does not prevent the formation of these products, as they maintain. The formation is, in fact, hastened by such practice and certainly does not "avoid all problems for self-extinction of corona discharges in voids."

Nor can we accept their statement that "a large void is easily detected because the charge in picocoulombs is large." While it is entirely likely that a large void will have a large charge, it is with discharge that we are concerned. Depending on the configuration, pressure, conductivity of surfaces, and specific stress applied, a large void may not even discharge at all. It is therefore difficult to understand the statement that a large void is easily detected. Their reasoning that a small void can easily be detected because these "contain a large number of discharges" is equally confusing to us.

Mr. Costello and Mr. Bartnikas as well as some other discussers infer that we developed certain conclusions based on corona intensity peaks as integrated by a recording device. We should have more clearly stated our position that no direct relationship has yet been established between the appearance of a signal and the destructive action of a corona element. This is the very reason we object to the use of charge in describing the sensitivity of a particular corona detection system. The careless use of the term *charge* can and, in fact, has given rise to the dangerous practice of separating benign corona elements from malignant corona elements as a function of x number of picocoulombs. We prefer to use voltage sensitivity over noise because this term simply describes the amplification and noise-immunity of a corona system without the assumptions needed for picocoulombs. If a relatively firm correlation can be established between the signals derived and the destructiveness wrought from corona elements, a more exact criterion should be established to describe a corona measurement system. We are working towards this objective.

It may be of some interest to note that the actual rejection of corona elements with the Micro-Scanner is based on binary bits of information recorded on the control magnetic tape and confirmed by signal processing. These bits contain only the information that a signal occurred and that in fact it was a signal derived from corona at our sensitivity. We do not assume, as inferred by Mr. Costello and Mr. Bartnikas, that all such signals come from a few discrete places in a cable rather than along the entire length of a finished cable. This is not necessarily so. We now find most of our corona elements in a few discrete places, though several years ago corona elements were widely distributed in production cables, even though they passed all industry-accepted tests.

We are glad that Mr. Costello and Mr. Bartnikas agree that raising the test voltage level cannot compensate for low sensitivity in corona detection equipment. Their comment about charge transfer, assuming adequate resolution, seems to overlook the fact that the corona pulse in a cable is coupled to the conductor-shield transmission line by a high and unknown impedance. Since the corona pulse itself is shunted by an unknown low and varying resistance, the very small capacitance in series with this pulse to the transmission line constitutes a highly differentiating circuit. The resultant signal even at the outset has little information of pulse duration and consequently apparent charge.

We agree that the minimum sensitivity standard proposed by IPCEA is a major step forward, but emphasize that the question of how much sensitivity is too much sensitivity has certainly not been resolved to date, since there is as yet no scientifically valid term for describing significant sensitivity.

Mr. Lawson, Mr. Dan, and Mr. Schullerts hope that our work in this area will continue. Our research on means for detecting corona and evaluating the significance of signals derived from this detection in relation to insulation failure is not only continuing but accelerating. However, no satisfactory correlation has been established as yet between the signals derived from corona in a cable and time to destruction. It would be sheer folly in the present state of the art to assume a tidy relationship and govern quality levels on this basis. Until such a relationship is firmly established, it is our practice to reject any cable which exhibits corona elements—no matter what the appearance of indicating signals—at the highest sensitivity that can be obtained.

Our answers to their specific questions follow:

1) We agree that setting up simulated field installation conditions in the laboratory for making corona level measurements before and after the cable was subjected to a simulated installation is worth further study.

2) We do not think it would be economical to vary the insulation wall with conductor size for a given voltage.

3) To avoid the masking effects of self-extinction phenomena, the Micro-Scanner is used prior to any voltage exposure.

4) We know of no simple relationship between voltage stress and the number of spikes on the signal. Neither is there a simple relation between voltage and the number of pulses. The geometry of the gas cell, the nature and pressure of gas, chemistry of the insulation changes, and electrical conductivity of the walls of the gas cells will all affect these relationships.

5) A number of workers, e.g., Starr and Agrios^[4] and Izuchi *et al.*,^[24] have found some correlation between the number of actual corona discharges and the life of insulation. It is presumed in their work that the number of discharges per cycle in a given voltage is a constant with frequency. Increasing the frequency of voltage application but not the voltage can be a useful method of accelerating failures due to corona without changing the mechanism as with voltage.

6) We agree that until the questions concerning corona level testing and the effects of corona on insulation have been fully explored, it would be wise to retain conservative insulation stress levels as well as test of corona detection methods and rejection of all detectable corona elements.

Mr. Schifreen and Mr. Timpe welcome our presentation, but suggested we add a chart giving the magnitude and typical shapes of the corona signals. We want to emphasize that we cannot yet relate the size or shape of a particular signal to the size or deleterious nature of a defect. A record is kept, however, of characteristic signals as related to actual defects found and removed from cable. Accumulation of these data has permitted identification of many types of defects from their characteristic signals alone. This program is continuing and is proving very valuable in quality control. To be certain that the potential gradient is maintained as a linear function from the midpoint of the scanning tube to the ground potential at both ends, two measures are taken. First, a system is utilized which automatically mixes water of high resistance with that of low resistance to maintain a resistivity in the tube low enough to maintain a resistive rather than capacitive gradient. Second, this water is pumped through the tube at a very high rate in the direction of cable travel to be certain of linear resistivity. There are gas molecules distributed throughout all material. When the stress is high enough, as can happen between two dissimilar materials, this gas will ionize. The sensitivity of the Micro-Scanner permits finding more of these than has ever been possible. In the Micro-Scanner configuration, the shunt value of cable capacitance does not affect the signal derivation.

This may readily be seen by the fact that a pair of probes separated by one foot from another pair of probes will not see a signal directly under the first pair. It will, however, see it when it has moved to a position directly underneath it. If the cable were acting as a lump shunt capacitance, this, of course, would not be true. We are not suggesting at this time that the scanning method be substituted for other test techniques. We agree wholeheartedly that a better understanding of ionization problems and utilization of the most sensitive techniques for detection of ionization is required.

Mr. Jordan and Mr. Saint-Arnaud asked how we interpreted Figs. 3-7 on which we did not indicate units on the vertical axis. No units were shown because the responses are all relative though linear. Control of resistivity of the water and dissipation of heat from the system maintains the temperature at ambient levels. The length of time that each increment of cable is exposed to voltage was selected so that there is sufficient time for ionization but not enough for self-extinction to take place. Increasing the effective exposure time can be accomplished quite easily by either slowing down the line speed or increasing the frequency of the supply voltage—if future work indicated this is necessary. The Micro-Scanner was not designed to be used with copper-shielded cables, but to examine cable cores (screened or unscreened) better than any other method. It is possible to test semiconducting screened cores in the Micro-Scanner at the present time depending on the type of material used. If the semiconducting material is such that scintillating particles from the surface generate noise signals, this would not be practical, either in our or any other system.

Mr. Ebel and Mr. Widmer point out that the Micro-Scanner should not be considered a substitute for a test on completed cable. We agree and regret that our paper was written in a manner to imply we thought otherwise. Our company uses the Micro-Scanner as an extra tool to detect incipient failure mechanisms which would go unnoticed with present standard test procedures. When a scanning method is perfected for use on completed cable, this position will be reviewed. We agree that rating detectors by either picocoulombs or voltage is not an adequate description of a corona detecting system. However, deviations in the standard performance of a particular sys-

tem can make use of either term. Our primary objection to the use of picocoulombs is that it assumes a significance not established. The comfort of this assumption could well mitigate against a search for a truly valid measure of performance.

Mr. Ware feels that our paper presents an excellent method for locating the exact position of a discharging void with extreme sensitivity in a long length of cable. He doubts that this is needed for production cable. Since no valid criterion for evaluating significant sensitivity has yet been established, it is not possible to state how much sensitivity may be necessary from a production point of view. Since failure data, often even within the organization concerned, have always been difficult to obtain and substantiate, it is premature to produce statistics on failure probability to date. Additionally, when a failure is analyzed, the destruction is usually so gross the cause can only be surmised. It is thus idle to speculate on the number of failures caused by corona. Mr. Ware also wonders about any voltage limitation of the Micro-Scanner. There are no theoretical limits to the voltages that may be applied to the Micro-Scanner with appropriate design. Further, it is entirely possible to locate corona defects in cables which are covered with a semiconducting insulation screen. When tapes are used as the screen, the noise from conducting particles in the tape may limit sensitivity. A line speed of 220 feet per minute was selected to insure sufficient voltage exposure to each increment of cable at the 60-Hz power frequency and also to avoid the possibility of self-extinction because of prolonged exposure.

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Calculation of Traveling Waves on Single-Conductor Cable Circuit with Cross-Bonding

TOSHIO IMAI AND YOSHIHARU WATANABE

Abstract—It is well known that when traveling waves invade a single-conductor cable whose sheath is cross-bonded, a rather high voltage is induced on the sheath circuit. Of the several experimental and theoretical examinations of this subject, most theories to date are constructed upon an idea of surge impedance. In the case of a cable circuit consisting of a conductor and sheath, this approach is imperfect since surge impedance cannot be easily defined. Using Hayaishi's method, it is shown that the problem of propagation, reflection, and refraction can be uniformly calculated without employing a concept of surge impedance, and that multiple velocity waves exist on both conductor and sheath.

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INTRODUCTION

IT IS widely accepted practice for a single-conductor cable circuit that the sheath be cross-bonded to prevent sheath-circulating current. It is known that abnormal voltage appears at the cross-bonding point when a surge comes into such a circuit.^{[1]-[6]} This subject has been discussed in a CIGRE report.^[7]

Attempts to analyze this phenomenon theoretically have also been made, and the principal ones are summarized as follows. First, Halperin and Miller^[1] furnished the calculating equations for reflection and refraction voltage at the cross-bonding point using surge impedance. But the process of reduction of equations is not indicated. Also, it is not clear how surge impedance can be obtained.

Next, Haga and Kusano^[2] and Ishihara^[4] provided calculating equations for reflection and refraction voltage at the cross-bonding point by similarly employing a concept of surge impedance. But no explanation is given regarding a method to obtain surge