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INVESTIGATION OF CABLE IONIZATION CHARACTERISTICS WITH DISCHARGE DETECTION BRIDGE

A REPORT OF AN INVESTIGATION

CONDUCTED BY

THE ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS

IN COOPERATION WITH

THE UTILITIES RESEARCH COMMISSION

BY

HUGH A. BROWN
J. TYKOCINSKI TYKOCINER

AND

ELLERY BURTON PAINE

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University of Illinois,
Urbana, Illinois
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BY
HUGH A. BROWN
ASSISTANT PROFESSOR OF ELECTRICAL ENGINEERING

J. TYKOCINSKI TYKOCINER
RESEARCH PROFESSOR OF ELECTRICAL ENGINEERING

AND

ELLERY BURTON PAINE
PROFESSOR OF ELECTRICAL ENGINEERING,
HEAD OF DEPARTMENT,
ELECTRICAL ENGINEERING
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INVESTIGATION OF CABLE IONIZATION CHARACTERISTICS WITH DISCHARGE DETECTION BRIDGE

I. INTRODUCTION

1. Introductory Statement.—A study of methods of testing the insulation of high tension cables has been made by the Engineering Experiment Station of the University of Illinois under a cooperative agreement with the Utilities Research Commission. A general survey of this investigation has been published in Engineering Experiment Station Bulletin No. 259.

The present bulletin is based on the results obtained in tests with the discharge detection bridge, a device which has been developed during this cooperative investigation.

2. Acknowledgments.—This study has been supported by funds contributed by the Utilities Research Commission, Inc., W. L. Abbott, President. An Advisory Committee was appointed as follows:

D. W. Roper, Chairman, Commonwealth Edison Co.
O. J. Bliss, Commonwealth Edison Co.
Herman Halperin, Commonwealth Edison Co.
G. W. Hamilton, Middle West Utilities Co.
W. H. Knutz, Midland United Company

This committee has held meetings quarterly at Urbana or at Chicago to consider progress reports and to advise regarding the program to be followed.

The experimental work forming the basis of this bulletin was done chiefly at the University of Illinois and at the high voltage laboratory of the Commonwealth Edison Company, Chicago. The discharge detection bridge was taken to the factories of four cable manufacturing companies during the summer 1931 and the results of a few tests on full length cables at these factories are included in this bulletin.

The tests in Chicago were greatly accelerated by the cooperation of the members of the Street Department and of the Testing Department of the Commonwealth Edison Company of Chicago. Acknowledgment is made of aid rendered by executives and engineers of various cable manufacturing companies who have made helpful suggestions and have furnished test samples. Special acknowledgment is made of the services of M. C. Holmes and L. P. Morris, Special Research As-
assistants for this investigation, and of W. J. Warren, graduate student in Electrical Engineering.

The investigation has been carried on as a part of the work of the Engineering Experiment Station of the University of Illinois under the general administrative direction of Dean M. S. Ketchum, Director of the Engineering Experiment Station.

II. DISCHARGE DETECTION BRIDGE

3. General Purpose of Bridge.—The problem of detecting the presence of ionization discharges within the gaseous spaces or voids between the layers of insulation of paper-insulated cables involves the separation of the minute discharge-disturbance currents from the comparatively large amplitude of the 60-cycle charging current of the cable under test. Not only is it quite difficult to separate these two current components, but the problem is also complicated by the existence of the harmonic residue of the charging current, the components of which often extend nearly into the group-frequency spectrum of the ionization currents themselves. The ionization discharge currents and the voltage disturbances due to them are complex in character, and it is assumed that they are high-frequency oscillations, whose periods are fixed by the electrical constants of the cable testing circuit, and have a group-frequency spectrum of between some 4000 and 8000 or 10 000 cycles per second. Investigation has indicated that this is probably the case, and that the discharge effects suffer high damping of a random character.

In Bulletin No. 259, just referred to, the principle of the discharge detection bridge has been described and analyzed in a qualitative manner: the fundamental bridge circuit is reproduced in Fig. 1a. The proper shielding of the bridge is an important item, and it is necessary to have a properly-designed output transformer connected between the bridge diagonals $DD'$ and the filter amplifier system. Transformers built for use with testing bridges are suitable. In such a transformer the winding of the primary must have equal shunt admittance between both terminals and the electrostatic shield placed between the primary and secondary, and it is desirable to have a high primary impedance, and a secondary impedance matched to whatever filter amplifier input impedance or connecting line impedance is desired. The fixed condensers in series with the primary windings are of the order of 0.005 microfarads, and serve merely to isolate the transformer from the high potential testing circuit. These condensers also aid in reducing the 60-cycle unbalanced-component effect on the
filter amplifier system. The condenser $C_a$ may be added when it is desired to measure power factor, thus providing a Schering bridge, but for ionization discharge measurements it is preferably omitted, for reasons discussed in the bulletin referred to. The air condenser $C_s$ does not need to be one having zero phase angle, but it must be free from corona or ionization discharge effects of any kind, and the
standard air condenser for power factor measurements meets these requirements. This bridge is easily assembled, requires a minimum amount of shielding, and is convenient for testing samples of cable not over 50 feet in length, when supplied with corona-free high-potential leads, as shown. It is desirable that the supply circuit and high-voltage testing transformer be free from all corona or leakage-discharge disturbances; but if there are some such effects they can be eliminated from the bridge testing circuit by making $C_s$ of about the same capacitance as that of the cable under test. It is then readily appreciated that corona discharges beyond the high-voltage point of the bridge are so balanced that they produce no resultant potential difference at $DD'$. Often a high-grade ionization-free piece of cable or an oil-immersed mica condenser may be used for $C_s$ in order to balance the circuit against the supply line disturbances. Referring to the ratio arms $R_1$ and $R_2$, it will be found that when they have unequal values, as is the case when the capacitance of $C_s$ is smaller than that of the cable, the greater the value of $R_1$ that can be used the greater will be the sensitivity of detection of the discharges. This is complicated by the fact that sensitivity of detection also increases with the value of $R_2$, so that increased sensitivity is usually realized by having the capacitance of $C_s$ considerably smaller than that of the cable. The combined phenomena of charging current disturbances and accompanying voltage disturbances in the bridge circuit are probably responsible for this effect, and are explained in the previous bulletin.

4. Type Suitable for Short Cables and Small Insulation Samples.—
The bridge described (shown in Fig. 1a) is suitable for testing insulation when the capacitance between conductor and sheath, or between test electrodes, is near but does not exceed 0.002 mfd. In samples of even smaller electrostatic capacitance, the resistance of the ratio arms $R_1R_2$ (Fig. 1a) must be increased for effectiveness and the capacitance of the air condenser $C_s$ decreased. When the capacitance is greater, the sensitivity of ionization discharge detection decreases, and other means are preferable. These will be described subsequently.

5. Compensated Bridge Used with Imperfect Supply Circuits.—
When the high-voltage transformer contains discharge disturbances of one kind or another in its secondary, or even in its primary supply circuits and associated apparatus, the detection of low-intensity ionization discharges within a cable under test becomes a more difficult problem. It is usually found that a low-capacitance standard ionization-free condenser is the only type available, and its use results
INVESTIGATION OF CABLE IONIZATION CHARACTERISTICS

in a potential drop across the output diagonals of the bridge due to these supply circuit discharges. In carrying out the present investigation it was necessary to use available testing transformers in the various laboratories and factories. Some of these transformers produced ionization disturbances above certain voltages, and special means were developed to make cable ionization discharge current detection possible under these conditions. No exact method of surmounting this difficulty was found, but a fairly satisfactory means of ionization discharge detection measurement was worked out with the aid of the compensated type of bridge shown in Fig. 1b. \( R_1' C_1 \) and \( R_2' C_2 \) constitute the compensating feature. Their purpose is to shift the phase of the resulting potentials across the bridge output diagonals so that at the points to which the primary of the bridge output transformer is connected there may exist potentials (due to supply circuit disturbances) which are in the same phase, this resulting in no effect upon the output transformer secondary terminals. The circuit constants of this compensating element form rather high values of shunt impedances, compared with \( R_1 \) and \( R_2 \), so that they do not materially affect the 60-cycle charging current amplitude balance. Another interesting result of such a bridge circuit is that, when it is balanced to eliminate supply circuit discharges, it also eliminates the effects usually due to the higher harmonics of the cable charging current. It must be remembered that the use of this compensating feature decreases the sensitivity of the bridge to discharge detection by from 25 to 40 per cent, hence \( R_1 \) and \( R_2 \) should be made as large as practicable, the shielding of the bridge elements should be carefully carried out, and a carefully-designed output transformer and filter-amplifier system must be provided. The output transformer must have the same balanced characteristic as that shown in Fig. 1a. With this bridge circuit ionization discharge characteristics were obtained on quite a number of cable samples at potentials of 90 and 114 kv.

6. Resonance Bridge for Long Cables and Wires.—The resistance ratio arms of the basic bridge circuit may be replaced by suitable variable inductances, increasing the effectiveness of the bridge for discharge detection. This introduces new characteristics and difficulties which require special attention. The introduction of a variable inductance produces a partial resonance effect, and it is then found that an optimum value of the inductance in series with the cable sheath is noticed in making adjustments; for this optimum value of inductance the discharge detection is most sensitive. Figure 1c shows
a special design of this type of bridge which incorporates a continuously-variable inductance in the cable side, and a fixed inductance and variable resistance in the air condenser side. It was found to be highly satisfactory when the high-voltage leads, testing transformer, and supply circuits were absolutely free from discharge disturbances. The presence of such disturbances rendered the bridge useless, and no satisfactory phase shifting or compensating arrangement could be worked out to balance out the undesirable effects. A slight discharge disturbance in any of the supply circuits seems to throw the entire testing circuit into vigorous oscillation, resulting in false high level readings. It was also found that discharges in an imperfect cable terminal or pothead produced a similar erroneous high-intensity indication when an attempt was made to isolate and ground such a pothead. The connection of a defective pothead to ground is indicated by dotted leads in Fig. 1c. Slight disturbances due to sparking of the supply alternator exciter commutator, or to the imperfect contact between slip rings and brushes of the supply generator rotating field, could be materially reduced and practically eliminated with the aid of high-capacitance condensers connected across the slip rings with the aid of a separate pair of laminated copper brushes; shunting capacitance across the high-voltage testing transformer primary is also quite effective. Here again grounding one terminal of the primary winding directly or through a condenser greatly increased the response of the bridge to the disturbing supply circuit discharges. When the bridge was connected to a thoroughly effective filter to suppress the effects of the charging current harmonics, it was usually found possible to dispense with the air condenser $C$, and ground the point $G'$, Fig. 1c. A filter was finally designed which made this practicable. The importance of these particulars in the successful use of this discharge detection equipment cannot be stressed too highly.

For testing cables whose length materially exceeds 50 feet the basic bridge detection apparatus failed to function in a sensitive manner, due, in all probability, to the effect of the large cable capacitance in absorbing the intensity of the disturbances resulting from ionization discharge. Special investigation indicated that the apparent intensity of a localized discharge as detected was reduced as much as 70 per cent when the cable was increased from 50 to 500 feet in length, taking the capacitance of the 50-ft. length of cable as 0.005 mfd. Investigation showed that the resonance-type bridge just described is well adapted to the solution of this difficulty. Quantitative data on artificial built-up cable sections indicated that the partial
resonance effect obtained in this bridge gave an indicated intensity which compensated for the usual absorbing effect in a 400- or 500-ft. cable. In the circuit comprising the cable under test, the variable inductance in series with its sheath, and probably the self-capacitance of the transformer secondary winding associated with its high inductance, would produce a partially resonant circuit within the expected spectrum of discharge frequencies, when between 20 and 100 millihenries were provided in the testing bridge variable-inductance element. An ionization discharge in a gaseous void excited the entire circuit into oscillation, resulting in the well-known resonance step-up effect across the inductance and the output transformer primary. The impedance of the primary of this transformer must be at least 20 times as high as that of the bridge inductance.

In using this discharge-detecting equipment it is very important to use cable potheads of a high grade which are practically free from ionization discharges. Careful shielding is also important, particularly with respect to the variable-inductance element in series with the cable sheath, as this element has a great tendency to pick up stray magnetic fields. In order to eliminate the effect of these stray magnetic fields an astatic design of the tapped inductance is highly desirable.

7. Filter-Amplifier and Associated Apparatus.—The success with which the discharge-detection equipment will function depends very largely upon the ability to obtain very high gain amplification, and upon the ability to completely suppress or eliminate the unbalanced residue of charging current and its associated harmonics. Standard design, low-pass filter sections, having a cut-off frequency of 2000 or 3000 cycles, were used, but without much success, due to the fact that they contained proportionally high resistance within their inductance elements. Development work on this problem eventually demonstrated that a coupled filter system was the only satisfactory arrangement. In order to compensate for losses in the filter it was found desirable to provide a certain amount of selective amplification between the filter and the bridge to raise the energy level of detected discharging intensity. Figures 2a and 2c show the filter-amplifier system in full detail with dimensions of all circuit constants indicated thereon. The preliminary amplifier of Fig. 2a is directly excited from the bridge output transformer, or through the medium of a standard line-to-grid transformer, the input transformer and two amplifier stages being completely self-contained in heavy gauge metal containers. The coupling inductances and capacitances of the amplifier provide con-
(a) Preliminary Amplifier with Tuned Coupled Filter

(b) Frequency Response Curve

(c) Main Amplifier and Output Indicating Equipment

Fig. 2. Pre-Amplifier Filter and Main Amplifier System
siderable filtering action. Following this the tuned coupled filter system effectively eliminates all 60-cycle and harmonic effects. Proper adjustments of the circuit constants of this filter and the coefficients of coupling result in the frequency response characteristic shown in Fig. 2b. The coils of the coupled filter are constructed in circular form and arranged astatically, as shown in the detail above the filter diagram. This has been found very necessary to eliminate the effect of even the weakest stray magnetic field. The main amplifier and output indicating equipment is detailed in Fig. 2c, the power tube of the last stage feeding into a rectifier tube circuit. The compensator circuit provides a voltage just sufficient to oppose the flow of current in the filter circuit due to the migration of electrons from the rectifier filament to the rectifier anode with no impressed e.m.f. in the circuit. Thus the output-indicating d.c. microammeter or milliammeter will show zero deflection with proper adjustment of the compensator circuit potentiometer. While 0.25 megohm coupling resistances are recommended for UX 240 amplifier tubes, it was found that, at the fairly high discharge group frequency, the plate-to-filament capacitances offered too much shunt admittance to such plate-circuit coupling resistances, hence the 0.1 megohm coupling resistances are better. The complete assembly of Fig. 2 and Fig. 1c was arranged in portable wooden boxes to facilitate transportation and save time in setting up the apparatus.

A convenient single vacuum tube 5000-cycle oscillator with a rectifier-type ac. output voltmeter and calibrating voltage divider was designed and constructed to go with the equipment. With the aid of this device any known value of 5000-cycle voltage could be impressed upon the filter amplifier system for calibrating and checking purposes.

8. Determination of Ionization Discharge Intensity.—In the investigation referred to at the beginning of Section 2 of this paper, a study was made of discharge phenomena and the bridge circuits, and the possibility of determining the quantitative discharge current intensity values. This investigation showed that disturbances in the cable charging current and in the impressed voltage produced potential effects at the bridge output diagonal, and that these effects seemed to be more or less in quadrature-phase relation to each other. Hence it was difficult to correctly determine an integrated discharge current intensity, expressing a result in actual current units. However, it was found that a fairly close comparative discharge current intensity could be estimated by adjusting the calibrating oscillator output voltage to
give the same deflection of the output meter as was experienced from the discharge bridge itself. This relates to only that part of the total frequency range of discharge currents utilized by the filter. This equal comparison voltage, divided by the resistance $R_i$ of Fig. 1a then gave comparative discharge current intensities when using the type of bridge shown. When using the compensated bridge a preliminary test was generally made to determine the reduction factor of the compensating circuit to be applied. For the resonance type of bridge comparative values were obtained by dividing the equal comparison voltage by the impedance at 5000 cycles of the variable inductance in series with a cable sheath. The resonance step-up effect, as previously stated, approximately compensated for the apparent reductions in discharge intensity experienced in long cables.

III. Behavior of Discharges with Varying Voltage

9. Effect of Removal of Impregnating Agent.—The behavior of the ionization discharge with varying voltage on the cable is intimately associated with the completeness of impregnation of the paper and the gaseous voids or spaces between the paper layers, as well as with the time of application of the alternating testing voltage. General discussions of ionization discharge characteristics will be given in due course, and their significance may be clarified by giving the results of a condition imposed upon a cable which will directly produce the characteristic to be investigated. Figure 3a shows the effect of removing cable compound. A short section of a 22 kv. cable was tested for ionization discharges, yielding the curve marked 1. After this one pothead was removed and about 2 feet of the sheath of the 20-ft. sample was heated with a gasolene torch until about one-half pint of impregnating compound was drained from the end of the cable. The pothead was then replaced, and the test repeated, yielding curve 2. When voltage is applied to a cable it is found that the discharge current passes through a maximum and subsequently settles down to a final value for most cables; this effect will be discussed in detail later. Therefore the curves of the type shown in Fig. 3a are obtained by applying the highest testing voltage, and after the discharge current has become constant in value the voltage is lowered in steps and readings of discharge current intensity obtained. Detail A shows typical behavior of many cables. The full-line curve to the left is for decreasing voltage, and if the voltage is again immediately raised the right-hand proportion of the hysteresis-loop type of curve is obtained. On
the other hand, it is not always possible to repeat this type of cycle; changing the rate at which the voltage is increased after it has been first decreased to zero, as explained, may result in the rising-voltage curve indicated by the broken line. Therefore consistent results are practically unobtainable when using increasing test voltages, unless the final test voltage is kept well below the critical point at which discharge currents begin to be cumulative with time. Returning to the test of Fig. 3a, it will be noted that curve 2 has a shape considerably different from that of curve 1; the partial saturation characteristic shown in the region of the index number 2 is probably due to a persistence of ionization discharge in the gaseous voids due to an altered voltage gradient through these voids after discharge has occurred for some time. This effect seems to be limited to a critical range of applied voltage. After obtaining curve 2, an accelerated deterioration test was carried out by maintaining 40 kv. on the cable for about 10 hours. After this curve 3 was obtained. The cable insulation has suffered considerably in quality because the subsequent application of the test voltage results in a materially increased volume of ionization discharges, as indicated by the relative ordinates of curves 2 and 3. Perhaps these three curves are most generally typical of all the cables studied in this investigation. Sometimes a cable will yield a curve of the shape of curve 1 if the test voltage is not carried above the normal operating voltage of the cable, but if the test voltage is increased 50 per cent beyond normal, the discharge current curve will often show the saturation effect, as in curve 2. Usually a cable having the characteristic of curve 1 shows practically no hysteresis-loop effect if the voltage is raised immediately after having been lowered.

10. Ionization Discharge and Power Factor Comparison.—Interest will center upon the coordination between voltage discharge curves and the typical power factor-voltage or ionization curve, commonly used in cable testing and investigation work. A study was made of the ionization characteristics of three well-known makes of cable, data being obtained upon 66-kv. 20-ft. samples, some of these being used cables and some new. Figures 3b and 3c show the results of these tests. These curves constitute a portion of the actual tests made, and in every case definite detection of discharge current and quantitative indications thereof were obtained at voltages well below the point at which the power factor was observed to increase materially with increasing voltage. The curves are significant in several respects in that they show behavior typical of quite a number of cables observed under
INVESTIGATION OF CABLE IONIZATION CHARACTERISTICS

varying conditions of accelerated and normal deterioration. Sample No. 19 was cut from a standard length of 750,000-cir. mils 75-kv. cable before the latter was put into service; sample No. 20 was cut out of the cable after 17 months' service at 66 kv. Figure 3b shows comparative discharge and power factor behavior. After 17 months' use the power factor increased, and the ionization discharge current began at a lower voltage and became cumulative with time as voltage is increased. Of course, oil infiltration from joints may improve impregnation in some cases; such an effect will be discussed later. Figure 3c shows a case where a cable improved with use, due to redistribution of saturant, infiltration of oils, etc. It is to be noted that the power factor decreased with use, and the discharges started at a higher voltage. They became cumulative at 35 kv. for the new sample, but did not reach the cumulative point until above 65 kv. for the used sample. Attention is again called to the fact that the ionization discharge curves show increased curvature upward at voltages well below the point where the power factor increased. In the case of Sample 21 in Fig. 3c the power factor did not increase over the range of voltages used, while there was a noticeable increase in discharge currents. This result was later confirmed in factory tests. It is generally understood that this material increase in power factor is due to ionization within the gaseous voids. If this is the case, the ionization within these gaseous voids must attain a certain level of volume or intensity before any appreciable effect upon power factor is indicated; the power factor is, of course, dependent most largely upon dielectric absorption, and some other phenomena which no doubt mask the comparatively small effect of ionization discharges of intensity. Contemporary investigations upon samples of paper and upon special ionization devices indicate that ionization discharges of intensities equal to those observed in the new samples are sufficient to produce damaging effects upon the paper and the compound or oil saturant in the paper. Figure 4a shows voltage-discharge curves and power-factor curves obtained from a group of 66-kv. cables upon which accelerated aging tests were being made. It is interesting to note that in these cables ionization discharge currents could be detected before the power factor showed any marked increase, and measurable discharges were detected for those cables which showed no change in power factor for increasing voltage. It is also remarkable that cable No. 3h failed first, followed by No. 6h. The test was discontinued before the other cables failed. Figure 4b shows how the ionization discharges increased from day to day during the aging tests. With semi-log coordinates the voltage discharge curves
Fig. 4. Discharge-Voltage Curves Obtained During Accelerated Aging Tests
of many other cables became nearly straight lines. The results indicated give some support to a belief that the increase in power factor with rising voltage is due more to the change of potential gradient in the paper when the adjacent layers of gas are ionized rather than to the actual ionization losses in the gaseous voids themselves. In a few actual cases a decrease of power factor has occurred in the region of the voltage at which detectable and measurable discharges begin. At this point some mention should be made of the so-called "negative ionization characteristic" of 132 kv. oil-filled cable at the elevated temperature. The power factor under such conditions may decrease with increasing voltage. A special test on an oil-filled cable indicated that it was entirely free of detectable ionization discharges. The decrease of power factor with increasing voltage on such cable seems to be due to effects other than gaseous ionization changes. Air was introduced into this cable, and without exception the ionization discharge intensity increased with applied voltage when the cable was at the elevated operating temperature. The result of this test is shown in curve A of Fig. 13. These characteristics indicate that the starting voltage for detectable ionization discharge currents, together with the comparative values of ionization discharge currents at the same voltages, furnish good criteria of the comparative degree of completeness of impregnation of the cable insulation by its oil or compound saturant. Further discussion of this test will be given later.

11. Ionization Discharge Behavior in Wire Insulation.—Members of the Cable Research Subcommittee suggested that the ionization-discharge detection method of testing insulation may prove of value in determining the merits of rubber or weather-proof wire insulation. It is reasonable to suppose that even rubber insulation may contain a certain degree of porous structure, and within the pores ionization discharge would be objectionable because of its deteriorating effect upon rubber. Also, if the insulation were porous to a considerable extent the change in potential gradients due to ionizing porous spaces would effect the puncture voltage of the insulation. Accordingly, samples of ordinary insulated wire for house wiring work were submitted, two samples being of high quality, and two supposedly of poor grade and of considerably lower price. These insulated wires were made into miniature cables, the sheath being provided by immersing the wires in containers of salt water or mercury, and terminals or potheads by using small aluminum funnels and sealing wax at the two ends of the wire sample. The end of the wire was drawn into the
spout of the funnel and held in place in the middle of the hole in the spout with beeswax, while molten sealing wax was poured into the funnel, leaving the end of the wire protruding from the wide mouth end of the funnel-like terminal. Beeswax was used at the spout end to taper off the angle between the spout and the surface of the wire. This arrangement was then immersed in the salt-water bath, with the wire sample and the spout ends of the funnels well under the level of the salt water. In this manner dangerous voltage stresses at the surface of the salt water bath were eliminated. The voltage between the conductor and salt water was then raised and lowered while discharge current readings were taken. Figure 5a and 5b show the results of this test, these results being typical of tests made subsequently. It should be noted that the samples corresponding to the full-line curves are from the poorer grade of wire. These curves for the poorer grade of wire have a greater slope, and show considerably greater discharge intensity than those for the higher-grade samples. After these curves had been obtained the voltage was carefully raised until puncture followed, and in every case the wire sample giving the curve with the steeper slope failed first, that is, at a lower voltage. In these particular tests it is certain that there are no discharges between the surface of the insulation and the salt water bath, a mercury bath giving exactly similar results. The ionization discharges occurring in

**Fig. 5. Discharge Characteristic Curves for Rubber-Insulated Wires**
the minute pores of the insulation give a more hissing-like sound in a telephone receiver than those occurring in larger spaces such as in air bubbles, or in cable insulation in which small holes as large as or larger than a pin head have been burned. For such larger spaces the ionization discharges produced a ragged tearing characteristic sound, very much like the intense static disturbances known in radio reception. It is interesting to note that tests made on flat samples of porcelain immersed in an oil bath and held between special discharge-free electrodes yielded similar curves, due to the different porous conditions of the porcelain samples. The ionization discharge obtained in the porcelain pores was of the same character as that for the wire insulation. In neither of these two cases was the typical rising and falling variation of discharge current with time indicated as with the cables, as will be discussed later.

IV. TIME VARIATION OF DISCHARGE IN CABLES

12. General Characteristics, Comparison to Power Factor Behavior.—The ionization discharge behaves in a peculiar and interesting manner during the first 20 to 30 minutes of voltage stress upon the cable insulation. Figure 6 shows time discharge behavior that is quite typical. Some cables give the characteristic shown by curve A. For such cables there is little or no increase in the discharges during the first minute of voltage application, in some cables the slight preliminary increase is so sudden that readings with which to plot the rise in discharge current cannot be manually obtained with sufficient rapidity. For such cables the discharge current very often remains sensibly constant after the first minute, in some cases it continues to rise very slowly for some 10 or 15 minutes, and in other cases it may be found to decrease slightly for 30 minutes, reaching a final constant value. The tests of Fig. 6 were conducted on 75-kv. 750,000-cir. mils cables, which normally carried about 38 kv. between the conductor and the sheath (see Fig. 3c). Curve B of Fig. 6 shows a radically different type of discharge behavior during the first half hour. For this cable the discharge current increased during the first half-minute of voltage application, passed through a maximum value, and then decreased along a more or less exponential curve, approaching a sensibly constant value within some 30 to 50 minutes; in many cables it becomes constant in less than 20 minutes. If, after some 30 minutes or so, the testing voltage is removed and then reapplied after different intervals of rest, a recovery characteristic is noted, this being illus-
trated by the additional curves indicated between the periods of "voltage off." It will be noted that the longer the rest period the greater the maximum value reached by the discharge current when voltage is reapplied, and the longer rest periods give a subsequent discharge characteristic of more gradual decrease. It has been found in most cables that the rest period necessary to obtain a repetition of the original discharge curve shown is usually more than 6 hours. This characteristic is one that occupied considerable study, and a short discussion of the effect of the products of ionization, increase of pressure within the gaseous voids, and other factors will be given subsequently.

Figure 7 shows curves for a series of special tests in which the variation of ionization discharge current and of power factor with time of voltage application for several cables was compared. It will be noted that, with one exception, for all of the cables the power factor increased at a gradually decreasing rate during the first hour of applied voltage stress. The ionization discharge current passed through a maximum and reached a sensibly constant lower value within the first 30 minutes. This apparently indicates that the gradual increase of power factor is due principally to increase of temperature, or other changing conditions, within the solid dielectric, the ionization discharge phenomena within the gaseous voids not producing an appreciable effect upon the power factor, or upon the variation of the latter. The increase of power factor may possibly be influenced by the end
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Fig. 7. DISCHARGE-TIME AND POWER FACTOR-TIME CURVES

product or result of the particular ionization discharge phenomena over a certain time within these cables. Cable No. 21 of the figure gave an entirely different type of behavior. In this case the power factor remained sensibly constant at a fairly low value, and the ionization discharge current did not pass through a noticeable increasing period. This latter discharge characteristic approaches somewhat that of cable A of Fig. 6. For the high-grade cables of constant power factor the discharge current was nearly always found to remain either
FIG. 8. CURVES SHOWING IONIZATION DISCHARGES IN FILMS AND BUBBLES
constant or to decrease or increase slightly from the initial value obtained as soon as voltage was applied. It is interesting to note that the cable samples whose behavior is shown in Fig. 7 were obtained from the same standard reel lengths of cable, as explained in the discussion of Fig. 3. In Fig. 7 the test on the used sample is shown adjacent (horizontally) to the test on the unused sample. Quite a number of accelerated life tests were made upon various cables, and in not a few cases it was found that the apparent impregnation would improve after a preliminary series of load cycles. This is the case with the cable samples Nos. 21 and 22, Nos. 22 being the unused sample and No. 21 a sample taken from the same cable after it had been in use. Comparing the used with the unused sample a considerable decrease in power factor and power factor variation is noticed, together with a decrease in the maximum ionization current, and a change in the manner of its variation.

13. *Similarity Tests of Discharge Behavior in Special Devices.*—As previously mentioned, studies of the manner of variation of ionization discharges in such devices as sealed corona tubes, gas films, bubbles enclosed between metal electrodes and thin glass plates, and gaseous films between small pieces of cable insulating paper were made. Figure 8 shows a group of typical characteristics. It should be noted that in the case of corona tubes containing various gases at or near atmospheric pressure, and of such gases in air bubbles, the ionization discharge current usually decreases during the first 10 to 20 minutes of voltage application, this decrease beginning immediately upon the application of the voltage. When pressure is externally applied to a gas film or bubble the ionization discharge decreases very much in intensity, as shown by curve C of Fig. 8, and a fairly intense ionization discharge may be completely eliminated by the application of a pressure of some 10 to 15 pounds per square inch. For the case of corona tubes containing oxygen or moist air a material decrease in pressure takes place due to the oxygen being converted into ozone, and the subsequent reaction of the ozone and other chemical substances within the tube. In most cases this was not accompanied by a material change in the ionization discharge current. Curves A, B, D, E and F show how discharge and pressure varies during the application of voltage sufficient to cause a fairly intense ionization discharge in corona tubes and bubbles. From these results it may be concluded that some of the characteristics of discharge in a cable may be partially explained, while no explanation is evident for some of the others, such as the rise in ionization discharge current with time during the first minute of
voltage stress. It is believed that where the ionization discharges are free to move or migrate from one locality to another between the layers of paper a discharge current unvarying with time will result, and where the ionization discharges are locally fixed the discharge current will fall off with time to a final steady value, as it does in the cases of closed corona tubes and enclosed gaseous bubbles, within which ionization discharges take place at or near atmospheric pressure.

V. DISCHARGES IN CABLES DURING HEATING AND COOLING CYCLES

14. Typical Behavior During Heating and Cooling.—A number of samples of cable were submitted to a series of accelerated aging tests in which the cable was at first heated by an oil bath or by circulating a current through the conductor while abnormally high voltage was
applied between the cable and the sheath. After the cable insulation and conductor reached the elevated temperature the heating process was discontinued and the cable allowed to cool down to room temperature, voltage being applied throughout this cycle. The heating and cooling cycle occupied 24 hours. A considerable number of power factor and discharge measurements were made upon these cables during the heating and cooling period. The tests were conducted in the high-voltage laboratory of the Commonwealth Edison Company under the direction of the engineers of that organization. The power factor behavior was studied by them, while the behavior of the ionization discharges was noted by the writers of this paper and their assistants.

Figure 9 shows a graph of the 24-hour ionization discharge behavior for five cables of the group tests. The lower curve shows the temperature variation of the conductor throughout each 24-hour day. It has been generally believed that the gaseous voids between the layers of paper and between the edges of adjacent layers increase in number and size during the time in which a cable is cooling and the body of the insulation is contracting or shrinking. Examination of the discharge behavior during the cooling interval shows this to be the case in practically all cables tested. There were a few cables in which no appreciable discharges appeared at any time. Referring to the figure, the cooling interval commenced at 2 P.M. and at about 3 P.M. the discharge current underwent a rather rapid rise from that time on until about midnight of the same day. The cooling interval was not complete until about 6 o’clock the following morning. It will be noted that in some cables the discharge current was maximum at a critical stage during the cooling, while in others it was at its greatest value for the cable at room temperature. When the cable was heating the discharges decreased rather rapidly to zero value at the elevated temperature. This zero value occurred in all except a few badly deteriorated samples.

15. Contrasting Power Factor Behavior.—During the temperature variation cycles the maximum power factor was practically always obtained at the highest temperature, decreasing somewhat with temperature, as indicated by the dotted curves in Fig. 9. Here the power factor is undoubtedly chiefly dependent upon the increased absorption in the dielectric at the elevated temperatures, and comparatively independent of the ionization discharge variation. It is interesting to note that in some cases such as cable No. 1h, shown in this figure, the ionization discharge intensity would increase very greatly with successive
cycles when the cable was practically at room temperature, and then later decrease, due to the fact that there was an improved impregnation at some local point from the movement of oil or compound. At the same time local hot spots which existed during the days of maximum discharge current would disappear. The power factor would generally not show any material decrease after a certain amount of accelerated aging had been accomplished. During a rest period power factors would usually decrease. Here again it seems that the power factor is most largely influenced by conditions within the solid and fluid dielectric independent of the direct phenomena of ionization discharges. Apparently, however, the power factor changes are often due to the end result of increased ionization discharges. If, during the progress of these temperature or load cycles any interruption to the test caused the high voltage to be removed from the cable for as little as 5 minutes, the rest period, this resulted in a time discharge behavior for the first 5 to 20 minutes of reapplication of voltage such as is indicated in Fig. 6. These interruptions also caused the power factor to regain a lower value and go through a characteristic subsequent increase when voltage was reapplied.

16. Ionization Discharge Characteristics Obtained in Factory Tests.—Observations of ionization discharge currents during several repeated series of accelerated life cable tests, and of the behavior of new and used cable samples apparently indicate that cables frequently experienced a permanent change in the apparent distribution of the impregnating saturant as the result of a certain lapse of time, and often as a result of the application of voltage, or an operation temperature cycle. Some samples of new cable showed certain discharge characteristics in a few preliminary tests, but after such cables were several months old, or had been put into service, these preliminary characteristics could not be found.

The Committee then suggested that some data on ionization discharge be obtained on cables at the factories, and that these cables be observed during their actual use, and records kept of their performance. In this way some coördination between the discharge characteristic of the new cable and its future service record might be obtained. Accordingly, the testing equipment used in this investigation was put into use in four different factories, and observations of discharge characteristics were obtained on certain cables designated by the Committee. It may be of interest to mention that factory tests should be undertaken only after a study of the conditions and fa-
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cilities for such tests. Supply voltages and testing transformers adequate for making power factor measurements are not always adequate for ionization discharge current detection measurement. In several cases changes, adjustments, and repairs had to be made in order to eliminate the harmful effects of poor wave form, supply circuit corona, incomplete electrical contacts, etc., in order that some one form of the several discharge bridge devices described would give correct indications. The factory engineers and officials were very much interested in the ability of the ionization discharge detection equipment to detect these faulty conditions in their testing facilities, and several expressed a desire to possess such equipment for this purpose, as well as for the purpose of studying discharges in cable and other insulation.

The new cables so tested exhibited most of the voltage, time, and temperature cycle characteristics already noted. It was found that practically all of the cables showed appreciable ionization discharges shortly after leaving the lead press and test floor. In some cases noticeable discharges could be detected with the listening stick telephone,* and with the aid of the resonance-type discharge detection apparatus quite a considerable volume of ionization discharge could be obtained. However, the power factor, as measured with the factory bridges, remained below $\frac{3}{10}$ or $\frac{1}{10}$ of one per cent, indicating what is now commonly recognized as a perfect cable. The power factors in most of those cases remained unchanged with varying voltage. This is generally believed to indicate zero ionization. It is believed that the evidence presented in this bulletin indicates that there may be a definite and directly measurable degree of actual ionization discharge in the minute gaseous voids, but that its effect upon the power factor or so-called ionization characteristic is nil. Figure 10 shows a typical group of voltage discharge curves obtained in the factories. In many cases the test could not be carried to as high a voltage as was desirable due to the occurrence of disturbances in testing transformers and supply motor-generators at the higher voltages. In most cases the ionization discharge currents are very small compared to those obtained in the average cable sample manufactured during the years 1928 and earlier. To what degree the comparatively more intense ionization discharges of the older makes of cables had an influence upon power factor has not fully been determined. All of these tests were made with the resonance-type discharge detection bridge upon the standard reel length of cable, some 400 to 550 feet.

The discharge-time curves and the so-called cooling curves for some of the cables tested in the factories are shown in Figs. 11 and 12. The cables were heated in ovens, or water tanks, or by circulating currents, and discharge current observations were made during the cooling interval. A quite appreciable increase in discharge current was observed at a critical stage during the cooling in almost every cable tested in the factory. In some cases the heating and cooling was ac-
companied by an increase in normal room temperature values of discharge current such as shown in curves C, Fig. 12. Some cables tested elsewhere than in the factories were either aged by use, or possibly by shelf life, and an increase of discharge current upon cooling could not be obtained. The initial excess of oil pressure near the cable sheath, and the gradual redistribution of saturant with time and voltage stress, apparently offer a probable explanation of this change in characteristic. It is well established that no solid-type cable is free from discharging gaseous voids when the cable is being cooled and the various phenomena of shrinking or contracting are present. Just what harm the ionization discharges in the gaseous voids may do during this interval, or during repeated intervals of this kind, is problematical. However it is known that ionization discharges between two adjacent layers of paper char the insulation in those particular localities when the discharges have a sufficient intensity and duration. There is potential danger to any cable in which detectable ionization discharges are present. As pointed out before, the ionization discharges may migrate from one point to another without serious effects, but in other cases, where they are limited to a particular locality due to wrinkles or other unusual causes, they probably have a deteriorating action on insulation.

VI. AIR INFILTRATION INTO OIL-FILLED CABLE

17. Normal Discharge-Free Conditions.—The investigation of samples of 132-kva. oil-filled cable revealed that normally there were no detectable discharges present. Investigation has indicated that this may be due to two primary causes. The first of these is the maintaining of oil in the cable under pressure, so that when the cable contracts at cooling additional oil is forced into the voids which open up. There is in all likelihood another factor of probably less importance than the first. It was previously pointed out that increasing the pressure upon a discharging bubble or film of gas caused the ionization discharge to cease therein. Therefore, minute particles, or bubbles, of air or gas may exist within the cable oil under pressure, or may even be absorbed by the oil itself in a molecular solution.

18. Air Admission Tests.—The result of an interesting test upon the effect of air admitted beneath the sheath of an oil-filled cable is shown in Fig. 13. This test has been briefly mentioned already in this bulletin. It requires only a very brief description. Air was forced into an oil-filled cable through a small pipe connection leaded into a hole
FIG. 12. DISCHARGE-TIME-OF-COOLING CURVES OBTAINED IN FACTORY TESTS
in the cable sheath, the pressure being applied by means of an ordinary hand tire pump. A few seconds after the application of pressure ionization discharge currents were indicated as shown in the curve, these increasing rather rapidly with time. The connection between the sheath fitting and the pump was then closed, and the ionization discharge passed through the typical maximum value and decreased in the usual manner for localized discharges. The pipe connected to the sheath fitting was then opened, and the oil under pressure in the cable soon began to ooze out carrying a few air bubbles with it. This continued for a few minutes, then the ionization discharges decreased to a very low value, and seemed to remain practically constant. Continued oozing of the oil apparently did not eliminate this low residue of discharge. Therefore the connection to the fitting in the sheath was shut off by means of a stop-cock, and the cable was allowed to rest with the oil pressure applied for some 8 hours. During this interval the low residual volume of admitted air was evidently absorbed by the oil under pressure, as there were no more detectable ionization discharges. This test was repeated with consistent results on several occasions. Apparently, if some air or gas does get into the insulation of the oil-filled type of cable the end effect of the oil under pressure is to completely eliminate ionization discharge. It should be mentioned that a cooling test upon the oil-filled cable following the test just described yielded no evidence of the opening of voids during the cooling interval.
VII. CORONA DISCHARGE AT SURFACE OF WIRE INSULATION

19. Detection of Invisible Corona.—The studies of cable ionization discharges were extended to those cables having no metallic sheath, and brief tests upon the behavior of the discharges in the porous structure of the insulation has been given. Some years ago it was pointed out that an insulated wire in contact with a metallic or other conducting surface,* usually flat, will show a faintly visible corona within the narrow crevice formed by the metallic surface and the curved surface of the wire insulation near the line of contact. This corona has been shown to be very injurious to the insulation, owing to the high chemical activity of the ozone resulting from such corona discharge. A suggestion was received that it would be worth while to measure these ionization discharges with the aid of the discharge detection equipment to determine if there might be actual ionization phenomenon below the point of visibility, at which it was previously believed deteriorating effects began. An investigation of this was undertaken, and it was very soon discovered that comparatively intense ionization discharges occur at voltages materially lower than those for visible corona. Comparative measurements were made upon samples of wire, and in every case it was found that there was a starting voltage for ionization discharge materially below the visibility point. For the different samples this difference was influenced by the conductor diameter, the insulation thickness, and the presence or absence of a braid covering. In some cases the voltage for measurable invisible corona was below the operating voltage of the wire and insulation. In Fig. 14 is shown in a very brief manner the arrangement for making the surface corona test. The sample of insulated wire lies upon a flat metal bed plate, and the conductor is connected to the high-voltage transformer secondary, while the bed plate is connected to the discharge detection equipment previously described.

20. Change of Invisible Corona Intensity with Time and Voltage.—The invisible corona discharge was observed to remain unchanged appreciably over a few minutes time, as it does in the case of some covered cable. In the case of some of the porous-insulated wires there was some change with time, especially after a certain amount of action of the corona upon the insulation. In some cases the ionization discharge intensity would increase slowly to a sensibly constant value. As the voltage is raised the potential gradient in the insulation and

*Davis and Crowdes; Corona Prevention and Ozone Elimination; Pamphlet, Simplex Wire and Cable Co.
in the narrow crevice-like air space between the cylindrical surface of the insulation and the bed plate increases until the ionizing gradient for air is reached within this space. As soon as ionization discharges take place in the air space the resulting disturbances are detected and their intensity recorded, the intensity increasing as the voltage is further increased. At some value of the potential impressed upon the sample, and of the ionization discharge intensity, visible corona appears in the narrow crevice. This point of visibility corresponds in all cases to a considerably higher voltage than the lowest voltage at which the ionization discharges are detected electrically and give readings upon the amplifier output meter. In Fig. 14 are shown typical test curves for four different types of insulated wire; the proportions of the conductor and insulation for each sample are shown, together with the accompanying curve of ionization discharge plotted against the applied voltage. The point where visible corona takes place is indicated by $S$ on the curve. As the voltage is raised this point of visibility is found, and it should be noted that visible corona occurs for a value of discharge current which is comparatively very intense, considering
the estimated value and the values which are obtained for the usual fair-grade paper-insulated lead-covered cables. The fact that visible corona occurs at a voltage very considerably above that required for detectable ionization discharges is strongly brought out by these plotted data. This same characteristic is shown in all cables tested.

21. Physical Effects of Invisible Corona on Insulation.—The problem of what physical effect the invisible corona may have on the insulation was considered to be one of paramount importance. Accordingly, this problem was assigned to Mr. William J. Warren, a Graduate Student of Electrical Engineering, for his thesis study. He found that the invisible corona did have an effect which was at least mildly injurious. In order to clarify the aspect of this problem it is desirable to outline briefly the procedure and the logical conclusion of this investigation. It may be first pointed out that the physical effects are not so directly evident as they are in the case of visible corona; in the latter case cracking and rotting of the rubber insulation, known as corona cutting, will result after an exposure of some hundred hours in the case of ordinary rubber insulation.

Several samples of wire, some insulated with moulded rubber, and some of the combinations of rubber and braided covering, were placed in temperature-controlled containers so that the temperature of the insulation could be raised and lowered periodically from day to day, giving a more or less regular load cycle, while voltage sufficient to produce considerable invisible corona discharge was continuously applied between the conductor and the metal contact plate. This voltage was maintained at a value about midway between that required to give electrically-detected discharges and that required to give visible corona in the crevice between the cylindrical insulation surface and the contact plate. In addition to this a few samples were wrapped with perforated copper tape and a like voltage maintained between this tape and the conductor. These latter samples were thus prepared so that power factor measurements could be made at intervals as the temperature cycles progressed. From time to time during the 77 to 80 days duration of the test measurements were made of invisible corona, the starting voltage of invisible and visible corona, and the power factor of some of the samples, and examinations were made of the physical appearance of the insulation in contact with the test plate. Figure 15 summarizes typical data and results obtained. Curves A of the figure, and also curves B, show the shift of the curves from the start to the finish of the test. It should be noted that after 70
days the voltage for electrically-detectable discharges decreased from voltage $E_o$ to $E_o'$, and that for the same voltage the intensity of the invisible corona discharge and of the visible corona component increased. The point $S$ on the curves represents the starting point of visible corona at the beginning of the test, and $S'$ the corresponding point at the end of the 70 days. In all cases the voltage for visibility was materially lowered. The points $C$ and $C'$, representing the points
at which visible corona disappears on lowering the voltage for the start and finish of the test, respectively, is also shown. The decrease with time of invisible corona voltage, i.e., voltage for the start of invisible corona, is plotted for 4 cables on curve sheet $C$ of the figure. The important fact brought out by these results is the change in the condition of the insulation at or near the surface of contact. After some 30 days exposure to invisible corona discharges, ionization discharges occur in the material of the insulation itself near the surface of contact. This is the only explanation possible of the fact that the detected ionization discharges begin at a lower voltage after the test has continued for some time. The voltage gradient required for corona in the crevice between the insulation and the plate remains the same as long as the insulation does not change in its diameter or curvature near the line of contact. The point of visibility, $S'$, at the end of the test is lower in value than the point $S$. Ionization discharges may begin in the insulation near the surface of contact after corona or aging has increased the porosity of the material. The potential gradient through that ionizing region of the insulation material or the porous structure may decrease. The corresponding voltage gradient in the air space or crevice between insulation and plate would increase, so that ionizing potential gradients of some 33 to 43 kilovolts per centimeter result in the crevice, with a lower potential applied between conductor and plates. It will be noted that $C$ and $C'$, the voltages at which visible corona disappears, are always lower than the points $S$ and $S'$, respectively. This can be explained by recalling the fact that when ionization in the crevice begins the conductivity and dielectric constant increase very much, lowering the voltage gradient in the crevice greatly, but the ionization discharges, once started, persist until a considerably lower voltage gradient is reached. This latter effect also has a material influence upon the ionization discharges in any porous spaces that may exist in the insulation material, because it results in an increased voltage gradient in these porous spaces. Some attempt was made to obtain power factor measurement of the samples tested in contact with the test plate, but changes in the insulation in this small restricted area did not appear to have an appreciable effect upon the power factor of the sample. No method was worked out whereby the insulating material in direct contact with the flat test plate could be accurately measured for power factor. The power factor curves, $D$ of Fig. 15, were obtained for those samples which were wound with the perforated metal tape for the power factor test. These samples were previously exposed to voltage on the flat test plate. The increase in power factor as the test
progressed is in all probability due to the effects of the ionization discharges in the region of contact between insulation and test plate, or it may also be due partially to the aging of the rubber. The fact remains, however, that the power factor of the insulation material increased when the voltage was held at a value about midway between that for detectable invisible corona discharges and that for the visible type, and in the case of some samples this voltage was not greater than the normal rated operating voltage of the insulated wire.

It seems probable that the continued existence of invisible corona discharges of considerable electrical intensity produce a microscopic corona cutting phenomenon. Previous investigation* brought out the fact that visible corona between an insulated wire and contact plate causes corona cutting of such a magnitude that it can be easily observed with the eye, but, since no such effect was observed at voltage gradients below the point of visibility, it was assumed that there was no corona cutting of the insulation. The investigation just outlined indicates that the electrically detected discharges or invisible corona possibly have a deteriorating physical effect upon the rubber insulation material. As previously mentioned, it is believed that the deterioration experienced in these tests consisted in the creation of very minute pores by virtue of the corona cutting phenomenon that is responsible for the earlier ionization discharge voltage after the progress of the test over some 35 to 70 days. The effect of natural aging of the rubber may be an important factor and is being investigated. A test over a period of six months has just recently been completed, but the data could not be included in this paper. The test showed visible pitting of the insulation surface. The test voltage was adjusted to a value midway between the visible corona value and the value where non-visible discharges could be detected electrically. Several of the test samples are being continued on the regular temperature cycle tests in an attempt to attain if possible the visually detectable cutting of the insulation. The temperature-controlled chamber was sufficiently tight in its construction to contain all products of the invisible ionization discharge, and after an hour or so of such discharges the characteristic odor of the corona discharge is easily detected, this being sufficient proof that there is a certain amount of what is generally called ozone liberated, and after a certain time it will undoubtedly have a destructive effect similar to that more quickly obtained by maintaining visible corona. This phenomenon and its effects could only be prevented by designing the conductor and insulation so that

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*Loc. cit., footnote p. 35.
the potential gradient in the air space or crevice between the insulation and a contact plate, such as might be present in a metal conductor junction box, would be below the theoretical or actual value for ionization, this value having been given as some 33 kv. to 43 kv. per centimeter. Many samples of insulated wire were received for this investigation, and the rating values indicated that some of the wires would normally operate above this critical voltage while others would operate below. The foregoing analysis was devoted principally to the rubber-covered wires. The investigation also included a few samples of wires insulated with rubber and braid-covered insulation. The complex nature of the ionization discharges and probable potential gradients in the meshes of the covering braid complicated the results so that interpretation was difficult; however, it should be stated that there was a similar shift of the invisible corona discharge curves, indicating increased ionization discharges either in the braid or in the rubber in contact with the braid covering.

VIII. SUMMARY AND CONCLUSION

22. Summary of Ionization Discharge Characteristics.—Many peculiar and interesting characteristics of the detectable and measurable ionization discharge currents in paper-insulated cables were discovered although several of them are difficult to interpret, due to many factors. Among the more important of these factors is the fact that the insulation is a complex dielectric including solid, liquid, and gaseous materials, and in this complex insulation crystal and amorphous structures may change from time to time with changes in potential gradients, temperatures, chemical products of corona discharge, etc. Ionization discharge starts at a certain voltage impressed upon the cable, and increases with the voltage, at first rapidly, then at a decreasing rate. In practically all cables the ionization discharge intensity, as directly measured with a bridge, will occur at voltages below those at which any change in power factor is noticeable. In many cases power factor remained constant, or decreased slightly with increasing voltage, but the ionization discharge intensity, although of low value, increased in proportion to the applied voltage raised to a power greater than unity.

Comparative studies and results outlined in this investigation indicate that the falling off characteristic of the ionization discharge with time is due to ionization discharges which are fixed locally in certain gaseous voids in the cable insulation. The cumulative rise of dis-
charge current for the first minute is a phenomenon that has had no parallel which would suggest an explanation. When the ionization discharges do not fall off during the first 30 minutes it is believed that the discharges in the gaseous voids or spaces migrate or shift in their locality. Oil is drawn into electric fields, but special experiments showed that ionization discharges disrupt and scatter oil films in the vicinity of the discharges. Distribution of cable oil or compound is thus affected. This conclusion was arrived at by studies of thin transparent films of mixtures of saturant and air in which electric fields and ionization discharges were active. The increase in power factor did not follow the increase and decrease in ionization discharge immediately. The change in power factor may be due to an end result of previous time-ionization phenomena.

Practically all solid cables showed a certain amount of ionization discharge upon cooling from an elevated temperature down to some critical temperature above the normal ambient value. When a cable is in the process of deterioration, or when a local hot spot is present, the ionization discharge intensity at this particular interval of the cooling may reach intense values.

The impregnation of the paper and interlayer spaces often improves with use, due to redistribution of the saturant, infiltration of oil from joints, terminal potheads, etc.

Oil-filled cables were found to contain no ionization discharges either at operating temperatures or ambient temperatures.

New cables which have recently been manufactured, and have not been in use, nor out of the lead presses in the factory for more than one or two weeks often give ionization discharges which are greater in intensity than those occurring with these same cables, or like cables, when they have been allowed to stand or have been put into actual use. They show formation of voids upon cooling. These characteristic ionization discharges in new cables may in some cases result in slight damage to certain parts of the surface of the insulated paper before they shift or disappear, due to better distribution of the saturant. Although the power factor remained constant for varying voltage, the ionization discharge intensity increased with voltage.

Insulated wires may show considerable ionization discharge within the porous structure of the insulating material, particularly in the case of weather-proof wires, and also in the case of rubber-covered wire, to a certain extent, when the rubber has aged considerably. The existence of the ionization discharges in these pores evidently increases
Ionization discharges of considerable proportions will exist between the surface of wire insulation and a flat metal contact plate at potential gradients considerably below the value necessary for visible corona discharge, and investigation indicates that this invisible corona has a small but definite deteriorating effect upon the rubber insulation at the line of contact. The physical effect may be that of corona cutting on a small scale.

23. Conclusions.—The discharge detection bridge and its associated filtering and amplifying equipment offer a practical and convenient means of determining the degree of ionization discharge volume or intensity existing in the gaseous voids, pores, or other abnormal ionizable structure of insulation when stressed by the application of testing alternating voltage.

The behavior of the ionization discharges in the voids or porous structure of insulation is generally different from that of the power factor as voltage, time, and temperature vary. The characteristics of ionization discharges in paper-insulated cables, wire insulation, and in wire insulation in contact with conducting surfaces, as detected and measured in intensity by the means used in this investigation, are important, and should be known in the design of all cable insulation.

Failure to eliminate electrically detectable ionization discharges may in many cases result in imperfectly insulated cable devices of various kinds.
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