THE EFFECT OF LUBRICATING OIL

On

THE PUNCTURE STRENGTH OF PAPER INSULATION

By

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I

INTRODUCTION

The properties of oil-impregnated paper insulation are well known and the importance of this material to the cable industry can hardly be over-emphasized. Its flexibility and high dielectric strength make it ideally suited for high-voltage cables and is also widely used in high-voltage capacitors. Since perfectly dry paper, due to the excellent insulating qualities of its fibrous structure, has a high insulation resistance, and consequently a low power loss, compared to the impregnating oil, the characteristics of the final product will naturally depend largely on those of the latter. The purity and degree of refinement are the controlling factors which determine the ultimate characteristics of the final product. What, then, is the position of lubricating oil? To what extent is its use as an impregnating oil limited? Under what conditions might its use prove deleterious? The literature abounds in material dealing with oil-impregnating paper, but in all cases a commercial insulating oil is used. Nowhere is lubricating oil mentioned except as an agent in collecting foreign particles, which results in a low resistance leakage path on the surface of insulation. The use of paper insulation in small electric motors is universal and wherever leaky bushings are encountered, the slot lining will generally be found to be saturated with oil. Beyond an accumulation of foreign material on the surface of the insulation, are there any other harmful effects on the insulation?

It was for the purpose of answering the above questions that this investigation was launched. The results were not the best that could be hoped for, and in view of the preliminary nature of the work, the data gathered had to be interpreted on an arbitrary basis. However, sufficient evidence was obtained to warrant definite conclusions and indicate a course of further investigation. Any further work on this subject would necessarily yield information on the characteristics of the impregnated material on a quantitative basis and these results might indicate a definite, though limited, use of lubricating oil as an insulating medium.

Indebtedness is hereby acknowledged as follows: G. E. Snyder of the Westinghouse Electric and Manufacturing Company for the helpful suggestions and information furnished, the General Electric Company for the paper insulation used in these tests, and the members of the faculty in the electrical engineering department of the Virginia Polytechnic Institute for invaluable aid and advice in the selection of the equipment used.

II

REVIEW OF LITERATURE

In recent years, as the scope and importance of dielectric research has increased, voluminous contribution to the literature has been made, evidencing a steady increase in our knowledge of dielectric phenomena. Strangely enough, though, a very large proportion of the literature is of little or no practical value. The reports of most investigators have generally been complete as regards description of procedure and results, but have been conspicuously lacking in the most important consideration: influencing external conditions. The factors which can affect the dielectric strength of insulation are manifold and it is imperative that the influence of these factors on experimental results be taken into account. Otherwise, the value of the results must remain dubious.

The A. S. T. M. Standards for 1936* and 1937** contain an excellent summary of, and descriptions of methods of controlling, these external influences. Recommendations made are the results of a thorough investigation of the problem by a special committee of experts and are considered authoritative. The Standards also make specific recommendations as to size and shape of electrodes, selection of test equipment, and methods of testing. These latter will be considered below.

Influencing factors having a direct bearing on the present work are (1) size and shape of electrodes, (2) duration of voltage, (3) temperature, and (4) moisture.

Electrodes

The problem of electrodes does not end with the mere choice of a particular size and shape. It is necessary to know the configuration of the field associated with the particular geometric arrangement to be used, for the field shape has a direct effect on the value of breakdown voltage. This influence must be taken into account, or otherwise the values obtained are meaningless.

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* A. S. T. M., Proceedings, Part I, Vol. 36, 1936, pp. 918-927
**A. S. T. M., Proceedings, Part I, Vol. 37, 1937, pp. 436-439

A detailed treatment of this problem is contained in R. W. Sorenson's translation from the German of A. Schwaiger's Theory of Dielectrics[1]. In this work, the author gives several methods of calculating fields. A chapter on conformal representation is also included, being written, of course, with a view to plotting electric fields. Edge effect in electrodes is dealt with at some length and procedure for correction is described. Schwaiger's method is based on the practice of curving the edges in order to produce a uniform field. However, there is yet another method which he does not mention, namely, the use of guard rings.

Guard ring arrangements used with parallel plate electrodes for determining dielectric constant is described in A. H. Scott's Determination of the Edge Correction in the Measurement of Dielectric Constant in Part II of the Technical Papers* included in the A. S. T. M. Standards for 1937. Although this paper deals only with the measurement of dielectric constant, the electrode arrangements are equally applicable to the measurement of dielectric strength. However, because of the difficulty in centering the guard ring with respect to the electrode, this method is not often used. Sometimes tinfoil is used (as described by A. H. Scott), but the chief objection to this is that the air films between the electrode and specimen is extremely difficult, if not altogether impossible, to remove.

The A. S. T. M. Standards for 1937** states the accepted fact that "dielectric strength decreases with increase in diameter of the electrode; this is particularly pronounced with thin sheets and negligible in thick

* A. S. T. M., Proceedings, Vol. 37, 1937, Technical Papers, Part II, pp. 655
** A. S. T. M., Standards for 1937, pp. 438

ones." Although specifications are given, they are necessarily arbitrary, since the size chosen is a matter of individual judgment.

Duration of Voltage

A. Schwaiger, in the Theory of Dielectrics[1], states that "if the breakdown voltage of a material is known and suddenly applied, a period of time will elapse before breakdown occurs (time lag)....... Studies of insulation materials have established the principle that the application of voltage must not be for too short a period if we wish to know the puncture strength for continuous stress"**. This statement, as the author shows, is a logical consequence of the thermal and thermoelectric theories of dielectric breakdown. The essential features of both of these theories (along with the electric theory) are considered at some length by Schwaiger.

J. B. Whitehead[2], in a work entitled Impregnated Paper Insulation, considers the subject as follows*: "Two broad types of dielectric failure or breakdown are recognized.... The first is the so-called pure electric breakdown, instantaneous in action, and commonly understood to be due to direct electric rupture of the ultimate dielectric structure, and so to a rise of potential gradient above a critical value. This type of failure rarely occurs in practice...... The second type of failure is characterized by conspicuous influence of the duration of time in which electric stress is applied. The indication is of a progressive deterioration

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** A. Schwaiger, Theory of Dielectrics, pp. 35
* J. B. Whitehead, Impregnated Paper Insulation, pp. 41

associated with the flow of current.....". After stating that this second type of breakdown is of a thermal nature, he goes on to say that "as based on the inherent properties of the material, it would occur only at abnormally high stresses continued over an interval of time or in high temperature surroundings.

The title mentioned in the last paragraph is a detailed description of the work done by the author on oil-impregnated insulation. It considers not only the impregnated material, but the component parts, that is, oil and paper. The properties of the materials, methods of impregnation, and test procedure are all comprehensively discussed.

Having taken cognizance of the principle quoted above, the A. S. T. M., in its Standards for 1936, lists three types of tests.* These are the "short time dielectric strength test", the "one-minute step-by-step test", and the "endurance dielectric strength test". The latter, being the most important from a practical standpoint, is described in greater detail than the other two. In this test, the time of voltage application is thirty minutes per step. It is used to determine the dielectric strength at high temperatures for long periods of time.

Temperature

It has long been known that temperature greatly influences the dielectric strength of insulation. Experiments indicate that a rise in temperature of 25° C. will increase the conductance of materials in some

* A. S. T. M., Proceedings, Part I, Vol. 36, 1936, pp. 918

cases a thousand fold. It is this effect on conductance which is of primary importance and it ties in closely with the thermal theory of breakdown. Although external temperature changes constitute an important consideration, it is much more readily controlled than that produced by the application of electric stress. The existence of a difference of potential causes a current flow through the finite resistance of the material, thus producing heat. The resistance is thus further reduced and the effect becomes cumulative. At the point where instability occurs the insulation breaks down. This is essentially the basis of the thermal theory.

A. Schwaiger, in his Theory of Dielectrics[1], as mentioned above, discusses this theory thoroughly. He states that the theory* "is due to A. Semm of Germany who conducted, in 1920, experiments on cable losses with respect to time. He found that if voltages above puncture strength were applied, losses increased continuously with time, resulting in breakdown. At lower voltages losses became constant and the cable operated continuously." Schwaiger further states that this idea was extended by K. W. Wagner, who "advanced the theory that puncture occurs when the thermoelectric equilibrium becomes unstable; this theory was based on new and fundamental measurements." Wagner showed that as long as heating is small the relation between voltage and current is linear. But as the voltage is increased and more current flows, resulting in a progressive decrease in resistance, the temperature rises until the current begins increasing faster than the voltage. Finally the current

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* A. Schwaiger, Theory of Dielectrics, pp. 29

increases without changing the voltage. This condition, which Wagner calls the "dynamic state", culminates in breakdown. Experimental determinations of characteristic curves have been made and Wagner's wood electrode method is described by Schwaiger.

A compromise between the elctric and thermal theories is found in W. Rogowski's Thermoelectric Theory which holds that the resistance of insulation depends on both gradient and temperature. J. B. Whitehead[2] subscribes to this view in considering oil-impregnated paper. In refuting the statement by M. Hochstadter and W. Vogel that the breakdown is of a pure electric nature, he cites* the fact that, in long time tests, there is a sudden rise in temperature and power factor during the several hours preceding breakdown. He agrees with them, though, that there is "no serious temperature change at high stress over long periods of time" up until the last few hours. Therefore, he "concludes that breakdown, when it comes, is never of pure electric or other sudden type, but has all the characteristics of the so-called thermoelectric failure."

Moisture

Dielectric strength is adversely affected by the presence of moisture inasmuch as it causes an increase of conduction, with a consequent increase in power factor. Whitehead[2] has determined the relationship between this component of power factor and moisture content in the case of chemical wood-pulp paper (kraft paper)**. The curves he

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* J. B. Whitehead, Impregnated Paper Insulation, pp. 175
**J. B. Whitehead, Impregnated Paper Insulation, pp. 31-34

obtains indicate an exponential relationship up to about 0.2 of one per cent moisture content. Up to this point the increase in this component of power factor is small. However, as the content increases still further, the power factor increases rapidly. This, as Whitehead indicates, fits in with the theory of ionic conduction which pictures conduction as a result of the creation, due to moisture, of ionic paths in the material and their extension as the moisture content is increased.

Oil

From that group of hydrocarbons whose component members consist of mixtures of vaguely determined substances is derived two industrially important substances, namely, lubricating oil and insulating oil, both derived from crude oil with a parrafin base.

One of the most comprehensive treatments of liquid dielectrics in general is found in Andreas Gemant's Liquid Dielectrics[3]. In this work the author does not confine himself to a description of electrical and chemical properties of liquids, but considers their mechanical and thermal properties as well. Oxidation of liquid insulators is discussed at some length. Gemant gives two important factors* which affect the oxidation process. The first is the effect of temperature, which is to increase the speed of oxidation. The second is the effect of foreign substances, metal in particular. These minute particles, acting as a catalytic agent, serve to promote the oxidation process. This latter effect, there-

* Andreas Gemant, Liquid Dielectrics, pp. 52-53

fore, makes it imperative that a liquid insulator be highly purified.

Gemant also describes the behavior of liquid dielectrics in high intensity fields. Under this heading he discusses the motion of the liquid in the direction of the field, chemical changes due to the presence of the field, ionization of gases present, and the effects of breakdown on the dielectric. The ionization of gases in such a field is the chief cause of breakdown. Consequently, a satisfactory liquid insulator must have a low gas content.

Properties of insulating oil are described in some detail by A. Schwaiger in the Theory of Dielectrics[1]. Here the effect of foreign particles is considered differently from Gemant. Schwaiger cites microscopic studies in which the phenomenon was observed directly. It was seen that particles, particularly water, with a dielectric constant higher than that of oil were drawn into the field, adhering to each other and bridging the gap between the electrodes, thus causing breakdown. However, since Schwaiger names water as the chief source of trouble in this respect, and Gemant mentions metal, it is probable that both affects occur together.

Schwaiger also pictures that "veiled gaseous discharge" theory of breakdown, which, he states, has been widely confirmed by experimenters, especially in Germany. This theory considers breakdown to be due to the motion of gaseous ions under the influence of an accelerating electric field.

Effects of temperature, pressure, frequency, and wave form are also discussed. Methods of purifying and removing foreign substances and gases from oil are described and their relative merits and uses are described.

III

THE INVESTIGATION

Before proceeding with a description of the investigation, it is well to point out here the fact that, because of the means used to carry out the investigation, the actual data obtained was of no scientific value. Whereas all dielectric research on a scientific basis has as its object the determination of properties of insulation as a material, the present work was planned to yield data which could be interpreted on a comparative basis only. As a consequence, no significance can be assigned the actual values of dielectric strength obtained here. Because solid insulation in general, and paper in particular, is not homogeneous, its behavior is highly anomalous, and it is extremely difficult to duplicate results, even under ideal conditions. It is for this reason primarily that the method used here was chosen.

Object

The results of J. B. Whitehead[2] and many others make it apparent that the presence of impurities in insulating oil seriously affects the life of oil-impregnated paper. However, there is nowhere any mention made of the immediate effect on the dielectric strength, nor is lubricating oil compared with insulating oil. It is the purpose of this investigation, therefore, to ascertain whether or not ordinary lubricating oil has any immediate deleterious effect on the puncture strength of paper insulation, and to determine the extent of that effect, if found, over a period of time.

Method of Procedure

It was pointed out in the opening paragraph that for the purposes of this investigation actual values of puncture voltage were unimportant, the only requirement being that the values obtained be reducible to a common basis. In this way, most of the difficulties arising from the influencing factors discussed in the "Review of Literature" were circumvented and the procedure greatly simplified.

The plan of procedure developed took the following form: (1) Selection and construction of electrodes, (2) design of suitable test circuit and selection of equipment, (3) treatment of specimens, and (4) method of testing.

Electrodes

Figure 1 illustrates the mechanical arrangement of the electrodes used. The electrodes (A) consisted of two circular brass discs with square edges, $1\frac{1}{2}$ inches in diameter and $\frac{1}{4}$ inch in thickness. Each disc was fastened to a brass rod (B) by means of a screw (E). This rod, in turn, fitted into another rod (C) which was fastened horizontally, with

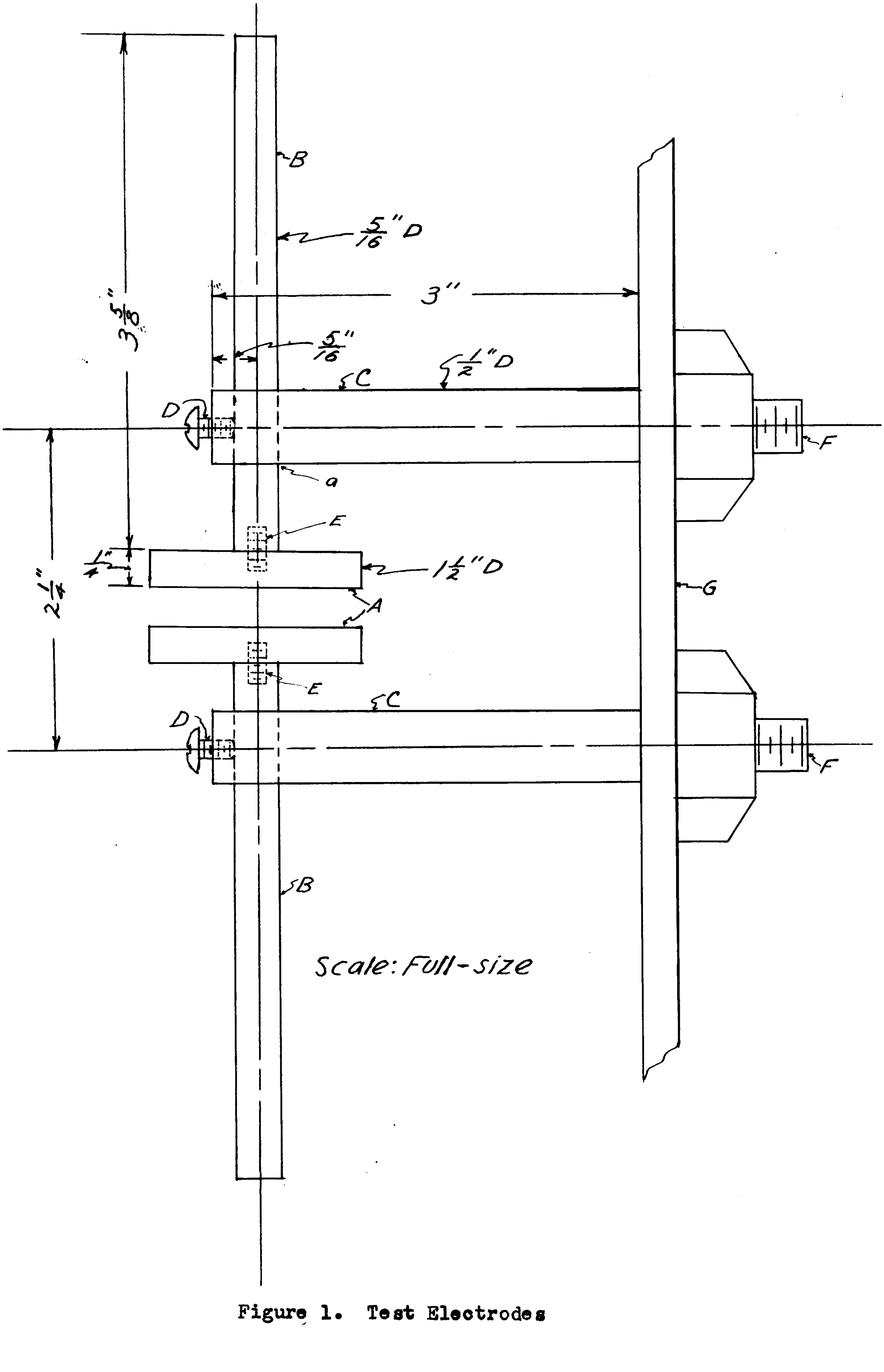

Figure 1. Test Electrodes

a nut, to a stationary piece of insulating board (G). The lower rod (B) was fixed in a permanent position by a set screw (D), while the upper rod (B) was adjustable along the vertical and could be held at any point by the upper set screw (D). The terminals for the applied voltage were at points (F-F).

Of course, the square edges of the electrodes precluded the possibility of the existence of a uniform field between them, which would be a prime requisite if the insulation were to be tested as a material; but, as previously pointed out, only comparative data were sought. Therefore, the only precaution necessary was to insure that the field was the same for every individual test; and since the lower electrode was fixed in position, it was important that the upper electrode be adjusted to assume, for each test, the same position, exactly, relative to the lower electrode. This was achieved by first centering the electrodes as accurately as possible and then carefully tightening the upper set screw (D), Figure 1. With the electrodes thus centered, two aligning marks were made, one on rod (B) and the other on rod (C), so that they met at a point in the corner at (A). In this way, even though the alignment of the electrodes was disturbed between tests, they could be easily realigned by reference to these marks, thus making it possible to bring the electrodes back together in the same relative positions for each test.

Test Circuit and Equipment

The test circuit employed may be resolved into three components:

(1) voltage control, (2) test transformer, and (3) protective devices.

A motor-generator set was used to supply the 60 cycle alternating voltage required, the generator having a capacity of seven kva. Voltage regulation was obtained by means of rheostatic control of the generator field and the use of a manually operated induction regulator. The latter furnished a regulation of approximately 20 per cent and functioned as the fine adjustment control. Since, with two rheostats in the generator field circuit, the voltage could not be brought down to a sufficiently low value, a multi-tapped autotransformer, furnishing a transformation of approximately 14 to 1, was employed. With this combination, the voltage could be reduced to a minimum value of 1.8 volts, as measured by a voltmeter. The same voltmeter was used throughout the investigation and it was assumed that its calibration remained constant.

Figure 2 is a diagram of the circuit used. The 60 cycle source was connected to the terminals (A-A). The induction regulator (B) contained two-phase windings, the primary being wound on the rotor and the secondary on the stator. However, only one phase was required and the other phase remained idle. The output of the induction regulator was connected across the high voltage terminals of the autotransformer (C), the low voltage taps being connected, through the switch (S), to the primary of the test transformer (D).

This latter transformer was a General Electric, oil-filled, instrument transformer with a constant transformation ratio of 1 to 400. The range of secondary voltage employed was from 1000 volts to 3600 volts,

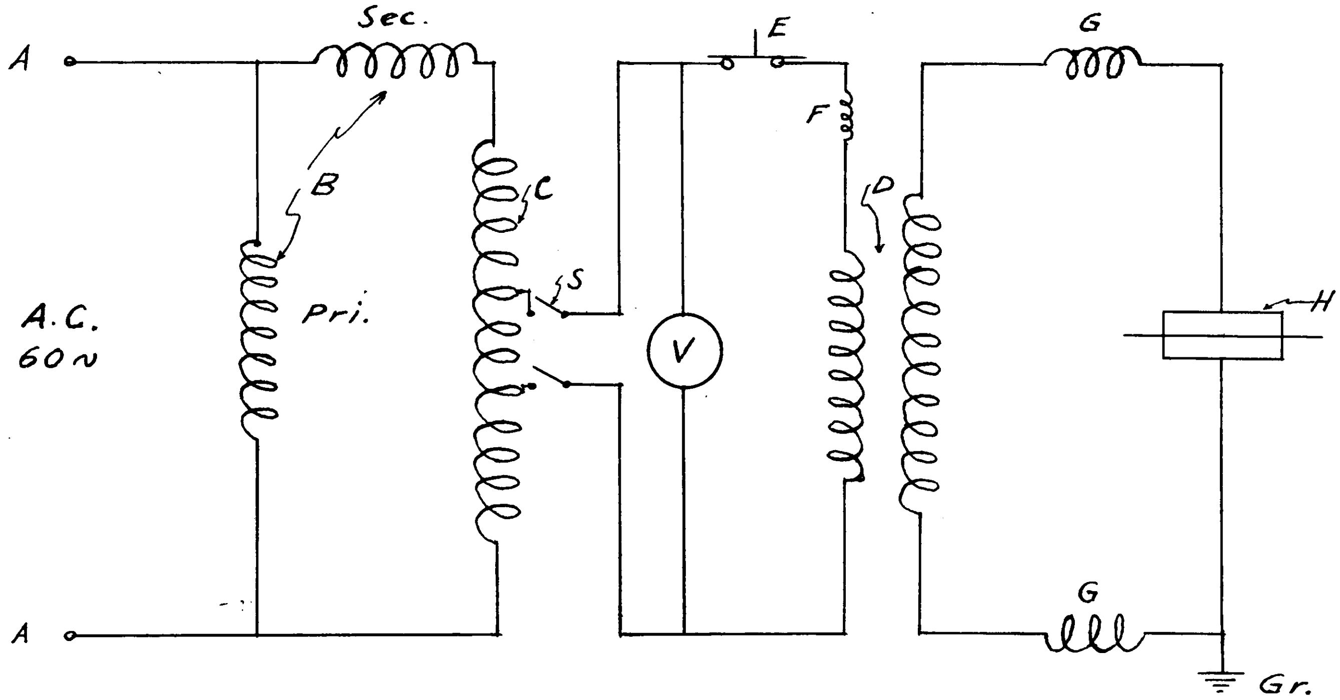

Figure 2. Test Circuit

or a primary voltage range of 2.5 - 9 volts. Over this range, at least, the transformation ratio was assumed to remain constant. The secondary voltage was applied, through inductance coils, to the electrodes (H).

Two types of circuit protection were required, the first being against sudden voltage surges caused by opening the circuit. An air core choke coil (G) was connected in each leg of the secondary. Also one of the electrodes was grounded, thus providing a leakage path for the charge induced in the transformer winding. In order to protect the circuit against excessive current when the specimen broke down, an overload relay was used in the primary circuit. The solenoid (F) and contacts (E), Figure 2, were connected in series with the primary winding.

Treatment of Specimens

Untreated kraft paper was chosen for test specimens. (This paper is manufactured from 100 percent wood pulp and is widely used as a cable insulation and for slot lining in fractional horsepower motors.) A 0.010 inch paper, designated by the General Electric Company as number 1294, was selected.

The first part of the investigation was concerned with determining immediate effects of lubricating oil on the paper. Accordingly, the specimens were immersed in oil for periods of time ranging from one hour to 40 hours. At the end of each immersion period they were removed from the oil and the excess oil removed by pressing between pieces of absorbent paper. The specimens were then ready for the dielectric strength test.

Upon completion of the first part of the test procedure, a sufficient number of specimens were immersed in oil for one hour and for 24 hours. They were then removed as in the first part, but instead of testing immediately, the two groups were enclosed in separate sheets of absorbent paper and shelved, to be tested at intervals of time up to about a month. The actual test periods were 168 hours, 552 hours, and 720 hours.

Method of Testing

As pointed out before, the inhomogeneity of paper made it extremely difficult to duplicate test results. At first, each test of a treated specimen was followed by another of an untreated specimen. In this way, it was hoped that results would be obtained which would be amenable to comparison. Although the values of breakdown voltage for the untreated specimens were fairly consistent, those for the impregnated specimens varied considerably. Thus it became necessary to exercise a great deal of caution and personal judgment in ascertaining correct values of breakdown voltage. This phase of the work will be discussed more thoroughly under "Discussion of Results". Broadly stated, then, the method of testing consisted of first determining that the dielectric strength of the untreated paper remained constant over a variety of conditions of external (room) temperature and humidity, and then testing the treated specimens in sufficient numbers to furnish a basis for estimating the most probable value of dielectric strength.

Each specimen was tested by increasing the applied voltage by steps of 200 volts each, beginning at 1000 volts. At each step the voltage was applied for a period of five minutes. This procedure was followed in every test.

Results

The results sought in this investigation were comparative values of puncture voltage for the untreated specimens and the oil-impregnated specimens. These are presented in Tables 1 and 2.

Referring to Table 1, the first column, beginning at the left, gives the immersion periods for the paper in hours, ranging from one hour to 40 hours. In the second and third columns are given the values of puncture voltage for the untreated specimens and the impregnated specimens respectively, corresponding to the different immersion periods. It will be noticed that a single value, namely, 2000 volts, is used for the untreated specimen. This value is a result of twenty separate tests made over a period of fifteen days under a variety of conditions of room temperature and humidity. Approximately 75 per cent of these tests yielded a value of 2000 volts; the rest of the specimens broke down at 1800 volts. These results indicated no appreciable influence of external conditions, and it was considered reasonable to assume a constant value of 2000 volts.

As previously mentioned, the values for the treated specimens varied considerably. The figures given in Table 1 were not all arrived at in the same identical manner. In some cases as many as four separate tests were made, and in others as few as two. Sometimes the values obtained were averaged, at other times one or two values were eliminated from consideration. In short, inhomogeneities of the material and time lag of breakdown were the prime considerations in judging values.

Table 2 gives the results of tests on specimens which had been

Table 1. Immersion Periods

Immersion Periods (Hours)	Puncture Voltage	
	Untreated Specimen	Impregnated Specimen
1	2000	2800
5	2000	3000
15	2000	3000
19	2000	3300
24	2000	3400
40	2000	3500

Table 2. Puncture Voltages for Different Shelving Periods

Shelving Period (Hours)	Puncture Voltage			
	One Hour		24 Hours	
	Untreated Specimen	Impregnated Specimen	Untreated Specimen	Impregnated Specimen
168	2000	2600	2000	3400
552	2000	2400	2000	2800
720	2000	2200	2000	2600

allowed to stand for relatively long periods of time after immersion in lubricating oil. Three periods of time (shelving periods) were used as indicated in the first column on the left. The second and third columns give the results of tests on specimens which had been immersed for one hour, while the last two columns show the results for 24-hour immersion specimens. The values of puncture voltage shown were arrived at in the same manner as stated above.

The values of Table 1 were used to plot the curve in Figure 3, using immersion periods as abscissae and puncture voltages as ordinates. Contrary to what was expected, the puncture strength showed a steady increase with the lengthening of the immersion period after one hour. For one-hour immersion the value jumped from 2000 volts to 2800 volts as shown by the dotted portion of the curve. At 40 hours the puncture voltage had nearly reached a constant value as indicated by the flattening of the curve in this region. Up to this point no deleterious effects of the oil were apparent.

No curve was plotted for the data in Table 2, since, due to an oversight in handling the specimens, the data were not deemed amenable to graphing. However, even so, some conclusions can be drawn from the data as presented. This will be discussed in the next section.

IV

DISCUSSION OF RESULTS

Contrary to anticipation, the effect of lubricating oil on paper insulation was to increase its puncture strength, as indicated by the

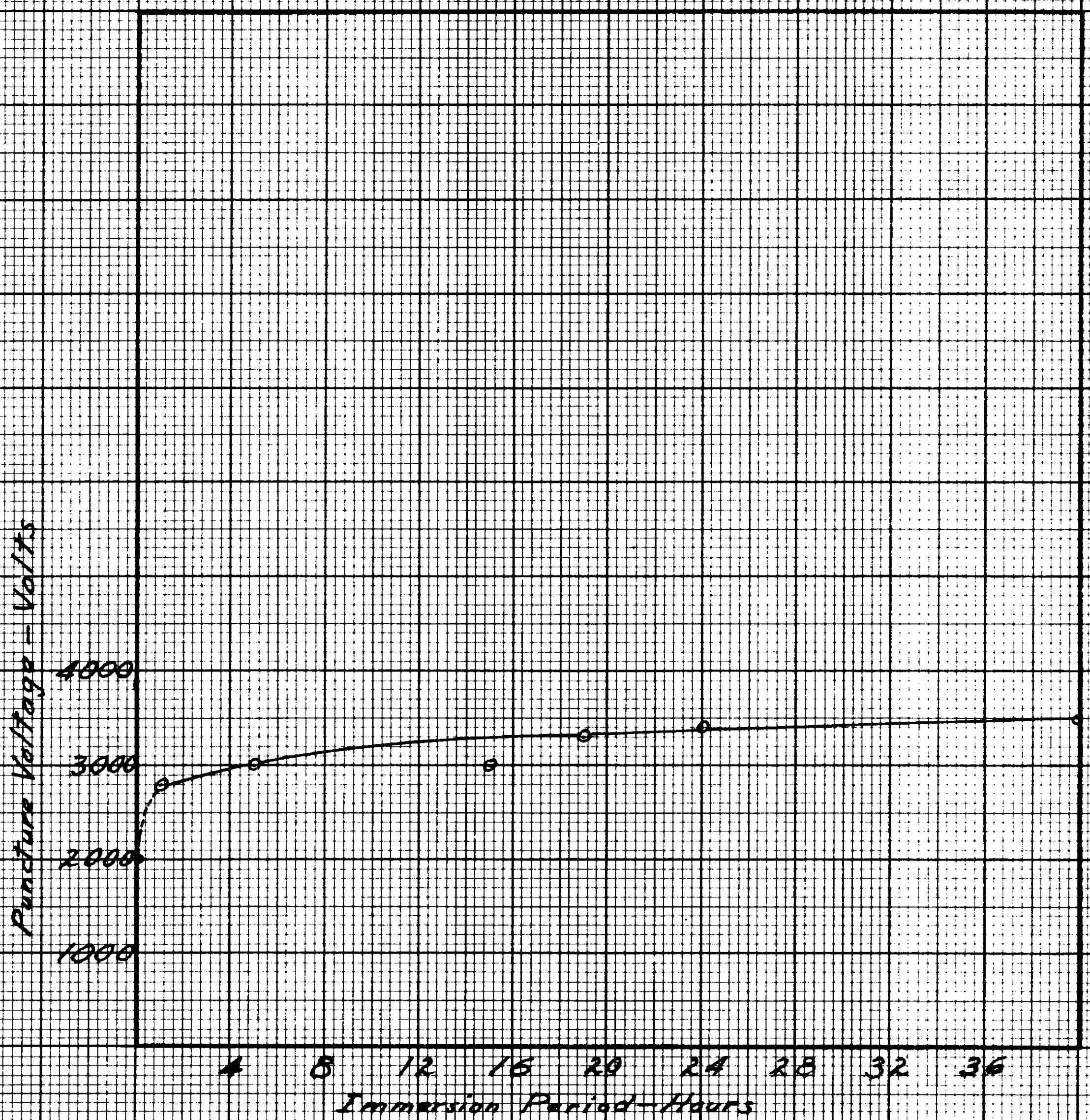

Figure 3. Variation of Puncture Voltage with Immersion Period

data in the previous section. These results can be explained, however, by first considering the differences between lubricating oil and insulating oil.

Both oils are derived from the petroleum crudes, but, in the process of distillation, insulating oil boils off at a lower temperature and therefore has a lower viscosity; the higher the temperature range of a given distillate the greater the viscosity will be. The dielectric constant also increases and since dielectric strength varies in an inverse manner to that of dielectric constant, the dielectric strength of insulating oil will be greater than that of lubricating oil.

But the chief difference is suggested by the following statement from J. B. Whitehead's[2] Impregnated Paper Insulation: "For use as insulation, a fairly wide temperature range of distillate is used, but a high degree of refinement is necessary. This is accomplished by successive distillation and filtration."* In other words, an insulating oil must be free, to a high degree, of foreign substances such as moisture and gas. Naturally, lubricating oil will not measure up to this requirement and a high ionic content exists which, under a high enough electric stress, would prove deleterious to both the oil and paper. According to the "veiled gaseous discharge" theory mentioned in the "Review of Literature" breakdown in liquids results from the motion of these ions under the influence of an accelerating electric field. If the field is great enough, the motion of these ions will generate heat to an extent great

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* J. B. Whitehead, Impregnated Paper Insulation, pp. 49

enough to seriously affect the oil and paper. However, if the voltage is relatively low, the effect will be negligible and have little influence on the puncture strength of the material. This is essentially the explanation of the results obtained here, as presented in Table 1. The voltages used were relatively low and any heat that was produced was conducted away by the electrodes fast enough to prevent cumulative heating. Consequently, the impregnated specimens showed an increase in dielectric strength because of impregnation. If the values of voltage used had been much greater, as would have been the case if a much thicker specimen had been used, the results would probably have been different.

The second part of the investigation, the results of which are given in Table 2, was devised for the purpose of obtaining evidence of chemical changes, particularly oxidation, in the impregnated specimens over a long period of time. From a glance at Table 2, one might easily conclude that such effects were present. However, as mentioned in "Results", due to an oversight in shelving the specimens the results cannot be interpreted so readily. The error committed was the enclosing of the specimens in absorbent paper. As a consequence, a great deal of the oil absorbed by them was lost to the latter. This was evidenced not only by the oily condition of the absorbent paper, but also by the greatly decreased degree of translucency of the specimens. Consequently, some of the contribution of the oil to the dielectric strength of the impregnated specimen was lost and the decrease indicated in Table 2 cannot be construed as being entirely due to oxidation, or any other chemical change. In view of the fact that the puncture strength in no case fell below, or, as in fact, not even as low, as that of the untreated specimen, it is reasonable to assume that oxidation, if present at all, was not great enough to seriously affect the specimen. Even though a great deal of oil was lost by the specimens, a sufficient quantity remained to wreak what damage it might have been capable of in the maximum shelving period of 720 hours. Although longer periods were not used, it is quite possible that if the shelving periods were increased indefinitely, deterioration would eventually become rather pronounced.

Referring to Table 1, it is seen that the puncture strengths for the one-hour and 24-hour immersion specimens were 2800 volts and 3400 volts, respectively. After being shelved for 720 hours, these values had dropped to 2200 and 2600 volts (see Table 2). These figures, therefore, represent drops in puncture strength of 78.6 per cent for the one-hour immersion specimen and 76.5 per cent for the 24-hour immersion specimen. This would seem to mean that the drop was independent of the immersion period. But it will be noticed in Table 2 that for the 24-hour immersion specimens the drop between 168 hours and 552 is disproportionate when considered on the basis of results for the one-hour immersion specimens. This irregularity is probably due to the error mentioned above. In view of these circumstances no definite statement can be made on the point. The best procedure would be to repeat these tests, correcting the error made in shelving the specimens.

As has already been stated, the anomalous behavior of the impregnated specimens made the determination of puncture voltage extremely difficult. In order to convey some idea as to the method of deducing these values, the following examples are given.

Consider the value, in Table 2, for the one-hour immersion specimen after 720 hours, namely, 2200 volts. This value was arrived at from three separate tests. The first specimen broke down at 2400 volts on the instant of closing the switch. The second specimen broke down at 2200 volts, 20 seconds after the switch was closed. The third also broke down at 2200 volts, but after 45 seconds. The first specimen measured 0.00906 inch at the point of puncture, whereas the latter two both measured 0.009 inch. Since puncture of the first specimen occurred instantaneously, it might well have taken place in a period of time comparable to those for the other two specimens at a somewhat lower voltage. Also the greater thickness might account, in part, for the higher value. In view of these observations the value of 2200 volts was chosen.

The above example was one of the simpler cases. Even greater disparities were encountered. For instance, consider the value of puncture voltage for the 24-hour immersion period after 720 hours (Table 2). Three tests were made, giving results as follows: (1) 2400 volts, puncture instantaneous, 0.009 inch thickness; (2) 2800 volts, puncture in one minute, 0.00906 inch thickness; (3) 2600 volts, puncture in five seconds, 0.00903 inch thickness. Now the first specimen might have broken down at a lower voltage, since puncture occurred at the instant the switch was closed. The second was of greater thickness than the other two and so its puncture voltage could be expected to be higher. The third specimen seemed to represent the average between the first two, as indeed did its value of puncture voltage. Therefore, in this case, a value of 2600 volts seemed to be a logical choice. Similar reasoning was used in each case.

V

CONCLUSIONS

Based on the foregoing discussion, the following conclusions can be stated:

1. Even after simplifying experimental procedure by seeking only comparative figures, valid results are difficult to obtain. The chief difficulties arise from the inhomogeneities of the material.

2. The effect of ionization on the dielectric strength of paper insulation is negligible at low voltages, at least for short periods of application of voltage.

3. The oxidation process in paper impregnated with lubricating oil is extremely slow and has no immediate effects on paper. The application of low voltages does little to accelerate oxidation.

4. The immediate effect of lubricating oil on paper insulation is to increase its dielectric strength. In this respect, the behavior is the same as if insulating oil were used.

5. Over a very long period of time and under a high stress lubricating oil will probably cause deterioration in paper insulation

much more rapidly than if insulating oil were used.

6. There is no obvious reason why lubricating oil should not be used as an impregnating oil for low voltage applications.

VI

FINAL SUMMARY

Due to the fact that only comparative results were sought, the investigation was greatly simplified. On a comparative basis, the effects of external influences were largely eliminated from positions of vital importance and the use of an elaborate test circuit was unnecessary.

The equipment consisted of a high-voltage test transformer which supplied the test voltage; an induction regulator, autotransformer and generator field rheostats for voltage control; overload relay and air-core inductances for circuit protection; motor-generator set for a source of 60 cycle alternating voltage. The electrodes were circular, square edge brass discs.

Specimens were immersed in lubricating oil for periods up to 40 hours and then tested for puncture strength. Following this, specimens were immersed for one hour and 24 hours and each of the two groups tested at intervals of time up to 720 hours. In each test the voltage was raised in steps of 200 volts, starting at 1000 volts. The puncture strength of the untreated paper was determined by testing a sufficient number of specimens over a period of days.

The results obtained indicated no immediate deleterious effects of lubricating oil on paper. On the contrary, there was an improvement in puncture strength, accounted for by the fact that the relatively low voltages used did not make ionization a serious factor. The results of the long-time tests were unsatisfactory, as explained previously. However, they did permit the conclusion that deterioration of paper impregnated with lubricating oil would become apparent much sooner than if insulating oil were used. Oxidation, although probably existing, was apparently too slow to affect the results.

VII

APPENDIX

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