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THE CHARACTERISTICS OF INSULATION RESISTANCE.

BY S. EVERSHED, MEMBER.

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SYNOPSIS.

1. INTRODUCTORY.

During recent years a great deal of valuable research work has been done to increase our knowledge of the properties of insulating materials, yet notwithstanding the progress so made the natural laws governing insulation resistance are but little understood. So little, that if at the outset of this paper a plausible statement were made to the effect that the insulation resistance of an electrical system depended mainly upon the dielectric properties of the insulating materials, it might easily pass unchallenged. Possibly some objectors might be found among those who have to maintain the insulation of electrical plant; for no one who has had much experience of the behaviour of insulation in practice, could fail to be struck by the disparity between insulating materials under test in the laboratory and the same materials under the ordinary conditions of use.

It is, of course, easy to guess that the disparity is generally due to the presence of moisture, and in fact the only insulating materials whose behaviour in use corresponds with their predetermined dielectric properties are those which are non-absorbent. Of the remainder, and they form the majority of the materials in common use, we can only predict that the insulation resistance of any electrical system in which they are used will be governed almost entirely by the moisture they absorb. Everyone knows that insulation resistance decreases on a damp day and recovers during dry weather. It is perhaps not so generally known that in most cases insulation resistance decreases, in a perfectly definite way and almost instantaneously, as the electric pressure upon it is increased, and slowly recovers if the pressure is restored to the initial value or cut off altogether.* The connection between these two facts is by no means obvious, yet they are so closely related that if we succeed in explaining one of them we shall certainly understand the other. It is often useful to attempt to explain familiar things; facts which, like the effect of a damp day on insulation, are so natural as to require no explanation—until we begin to think about them.

The effect of moisture, the effect of voltage, the effect of polarity, these and other phenomena commonly met with in insulation have been forced upon the author's attention for many years past, and the pressing need to find answers to the questions that so frequently arise in connection with insulating materials induced him to undertake an experimental research with a view to the better understanding of their behaviour in everyday use. This work has been in progress for three years, most of the time being spent in finding a firm basis for future work. But certain experiments have already thrown some light on matters which have hitherto been obscure, and the object of this paper is to render the knowledge so gained available for all those who are interested in the insulation of electrical plant. The specialist will find herein much with which he is well acquainted; but insulation largely concerns those who have no special knowledge about it, and on that account many things have been introduced into this paper in order to give a general view of the subject.

What is the margin between the working voltage and breakdown? That is the fundamental question at the root of every inquiry into the properties of insulation. If a definite answer is ever forthcoming, it will not have been found in "blind" tests of breakdown voltage. To conduct tests without any means for ascertaining what is going on in the insulator as the breakdown voltage is approached, without either observing the current or, better still, the resistance, is to shut our eyes and deliberately avoid looking for the cause of failure.† The author has therefore sought, by investigating the nature of leakage conduction, to establish some definite relation between applied potential difference and insulation resistance. If the curve expressing this relation be traced from a few volts up to

* Since the first half of this paper was written, Mr. P. R. Friedlaender has drawn attention to the relation between voltage and insulation resistance, and has given a typical example in the form of a curve. (Communicated remarks in the discussion on Mr. Rayner's paper on "High-voltage Tests and Energy Losses in Insulating Materials." *Journal I.E.E.*, vol. 49, p. 79, 1912.)

† The flash test as applied to some costly piece of electrical apparatus must have been inspired originally by something akin to the heroism of the savage.

the breakdown point, it will be found to consist in general of two parts of opposite curvature more or less like the voltage-resistance curve shown in Fig. 1. The two parts of the curve will be joined together by an approximately straight line, the length of which varies greatly according to the nature and condition of the insulation. This connecting link is sometimes so short that the two parts of the curve appear to meet at a point of inflexion and they then form a sort of ogee curve.

The research had not proceeded very far before it was realized that the shape of the first part of this characteristic curve is determined by the extent to which leakage is due to moisture, and further that leakage through the substance

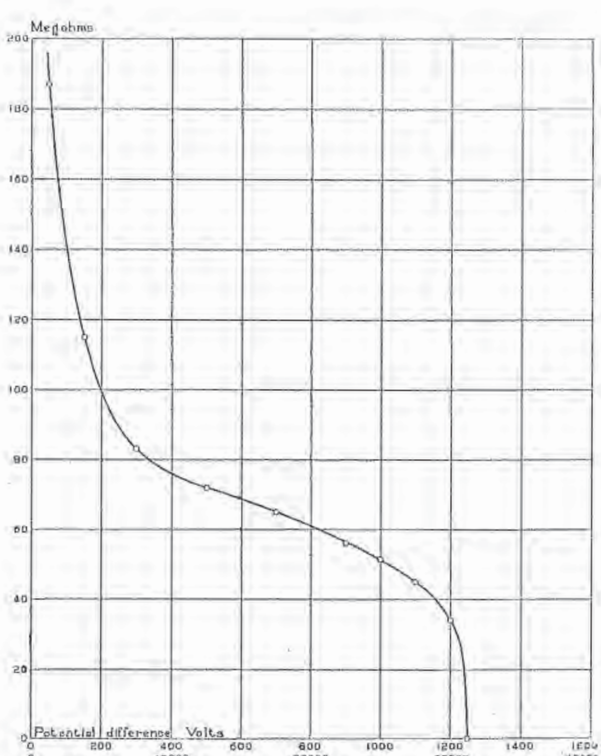

FIG. 1.—Complete characteristic curve for Cotton containing a normal amount of moisture absorbed from the air.

of the insulator—dielectric leakage—was negligibly small compared with that caused by the merest trace of moisture. This leads to the point of view that for most practical purposes an insulator may be regarded as having no inherent conductivity, the conducting power which it appears to possess being usually caused by leakage over damp surfaces. If the insulator is porous then the leakage surfaces are not only those outside the insulating body but those surfaces which bound the maze of capillary channels inside the porous material. If this idea be provisionally accepted at the outset the facts brought out by the experiments will be found to fall easily into their places, and a fairly consistent view of leakage conduction will be obtained. The research divided itself quite naturally into two parts corresponding to the two significant parts of the characteristic curve. The investigation of the second or breakdown part of the complete curve (see Fig. 1) is still in the preliminary stage, and the present paper deals mainly with the first part up to the point or region of inflexion.

2. Method of Investigation.

To avoid encumbering the paper, methods of experiment will only be described so far as they are essential. As a preliminary, a few words must be said here in order to remove any misapprehension as to what it is that goes by the name "insulation resistance." When a conductor resistance is measured care is taken to avoid the introduction of any extraneous electromotive forces due to polarization, induction, capacity, or thermo-electric junctions. By so doing, the result of the test is a true measure of an inherent property of the conductor, namely the ohmic resistance apart from any other kind of resistance or opposition to the passage of an electric current. But with insulating materials similar precautions are not generally possible, and all that can be done is to measure the ratio of applied potential difference to the resulting current, V/I, and call that the insulation resistance. We may measure the two factors either separately by means of a voltmeter and a galvanometer, doing the division sum ourselves; or both may be measured at once by an ohmmeter which does the division sum for us. Either way the result is the ratio of pressure to current. It is customary to express this ratio in ohms or megohms, and there is no harm in doing so provided we realize that the "ohms" so obtained are not necessarily of the same nature as the ohms in a metallic conductor. Of course the true ohmic resistance of the insulator (if it has such a property) is included in the result of a resistance test, but it is so entangled with surface leakage, the effects of electrostatic capacity, and the penetration of electric charges into the substance of the insulator, that we are often obliged to be content to lump all these things together when we undertake the measurement of insulation resistance.

Resistances of very high value are often measured by charging the system under test and then observing the gradual fall of potential as the charge leaks away. But this method, being based on the assumption that the resistance of an insulator is independent of the potential difference, begs one of the principal questions the author set out to answer. Obviously it was essential to measure either the resistance or the leakage current.

In dealing with so unstable a quantity as insulation resistance there are obvious advantages in making direct measurements of resistance, and perhaps the greatest advantage of the ohmmeter method is the detection of instability immediately it occurs. But it was desirable to have the means of measuring up to about one million megohms at 500 volts, and at present the galvanometer is the only instrument possessing the required sensibility. The use of ohmmeters was therefore confined to tests which came well within their range, and the greater part of the work was done by means of a Broca galvanometer made by the Cambridge Scientific Instrument Company.

The galvanometer method gives no evidence of instability until the ratios of pressure to current are worked out at the conclusion of a series of tests, and the consequence of this lack of timely warning was that in many cases it proved to be impossible to plot a curve from the observations, just because the insulation had been in an unsteady condition during the tests. For this reason alone much fruitless labour would have been avoided had it been possible to use an ohmmeter throughout the investigation.

The pressure was supplied by a battery of secondary cells giving about 500 volts, and in a few cases this was supplemented by a small testing generator giving 1,000 volts. It should be mentioned that when leakage conduction is to be detected or measured, continuous current is essential. Quite apart from the greatly inferior sensibility of alternate-current instruments, the alternating current due to electrostatic capacity is generally much larger than the leakage current, so that the latter is difficult to disentangle and easily escapes detection altogether. Methods have been suggested by which the two currents might be separated and what is now impracticable may one day come into use, but at present continuous current has no competitor in this field.

Guarded insulation—the method of Price's guard wire extended to include every material insulating point in the testing apparatus—is now universal in insulation testing. This happy invention was of course used throughout the present investigation, and hence the current measured was in every case the current it was intended to observe and nothing else.

Before quitting the subject of methods of experiment, a minor precaution may be referred to. Every insulator has some electrostatic capacity, however small. In most cases it was inappreciable and the charging current could be ignored. But in every case in which a charging current

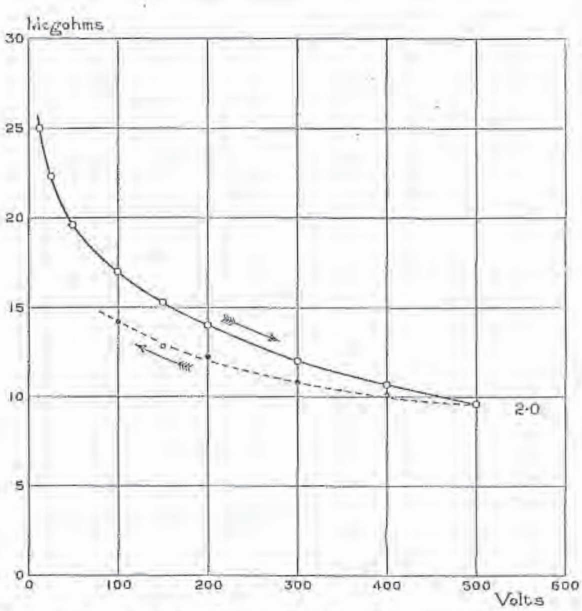

FIG. 2.—Insulation resistance of a Dynamo Armature, showing hysteresis effect.

was observed, ample time was allowed for it to die away to a negligible value before taking a reading of the leakage current.

Electrical measurement is capable of such precision that it was not easy to avoid aiming too high in this respect. Upon the whole the precision of the apparatus was much greater than the nature of the investigation required. The discrepancies that frequently occurred were almost entirely due to rapid and unavoidable changes in the insulator under test. Hence the accuracy of any set of tests was

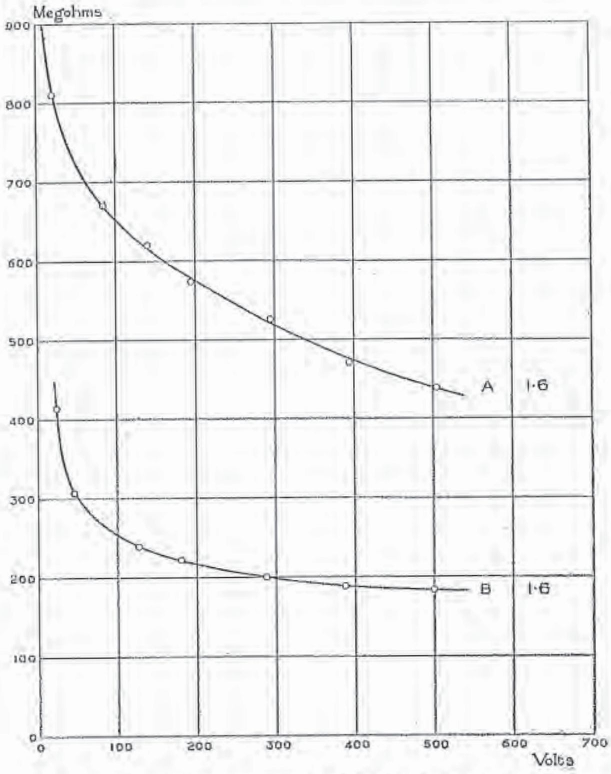

FIG. 3.—Insulation resistance of Field Coils: A, in dry weather; B, on a damp day.

often a matter of luck, and it was only upon a general review of a large number of similar tests that any sound conclusions could be reached. These remarks are all the more necessary because it is no uncommon thing to see insulation resistance expressed by a long row of figures, of which perhaps the first digit has something to do with the leakage current (and often much more to do with the charging current) and all the others have obviously been born of the slide rule.

3. TYPICAL EXAMPLES OF INSULATION.

Although it is impossible to predict the insulation resistance of any piece of apparatus, yet if each of the insulating materials had a resistance as constant as that of a metal we might reasonably expect the insulation as a whole to follow Ohm's law. A few typical examples will show how little ground there is for any such expectation. In the choice of examples it does not matter what kind of insulators are involved; so long as their resistance is within the range of measurement they will nearly all tell the same tale of a gradual fall in the resistance as the testing voltage is increased. Characteristic voltage-resistance curves, obtained from things which happened to be at hand, are given in Figs. 2 to 7.

It will be seen that in every case the resistance falls as the potential difference rises, although the curves differ in shape a good deal and the decrease in the resistance is therefore much less marked in some cases than in others. It will be shown later on that these obvious variations in the curves indicate differences both in the kind of material used for insulation and the condition as regards moisture. For example Fig. 2 is a typical moisture curve, indicating that the insulation is entirely composed of absorbent

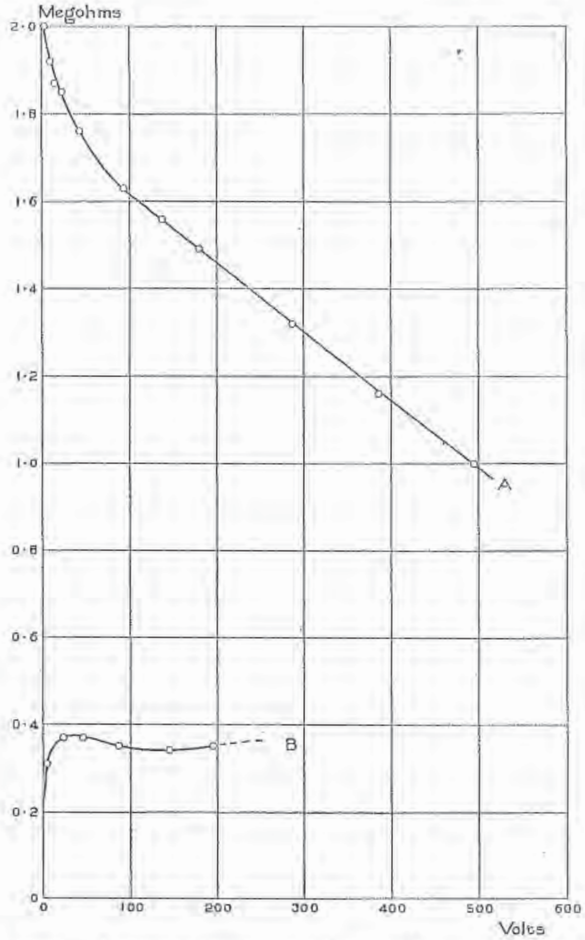

FIG. 4.—Insulation resistance of Lighting Circuits: A, in dry weather; B, in very wet weather.

materials. It is important to note that when the curve was retraced backwards a kind of hysteresis effect appeared. With absorbent insulators this effect is nearly always to be found if one chooses to look for it. The two curves in Fig. 4, one traced on a wet day and the other after a spell of dry weather, show that a large excess of moisture not only lowers the general level of the resistance but also brings about an entire change in the character of the curve. In the lower curve three things which are characteristic of conduction by moisture are struggling for the mastery. On a wet day every solid insulator is covered with a film of water which if it were in stable equilibrium would conduct according to Ohm's law and give a horizontal straight line. But instability is a marked feature of films when they are exposed to the air, and hence in practice the curve is never a simple straight line. In addition there is some typical

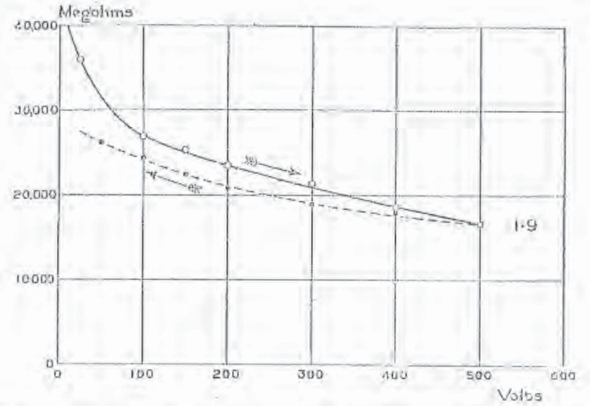

FIG. 5.—Insulation resistance of a moving-coil Ammeter in which the ebonite insulation had become defective from an accumulation of dirt.

conduction through absorbent insulators, and the curve is the resultant of all three effects.

In Fig. 5 the resistance was in an unstable condition, several discrepancies being noticed in the course of the tests. This curve being retraced backwards from 500 volts also shows the hysteresis effect.

The curve in Fig. 6 is typical of insulation that is made up of an absorbent insulator in series with one which has a more nearly constant resistance, and when the nature of moisture conduction has been examined we shall see how the resistance of these two components may be separated and an approximate value assigned to each. In short, we shall arrive at the tentative beginnings of a rough diagnosis of insulation. Fig. 7 is remarkable because it shows that the resistance was affected by polarity. When the testing

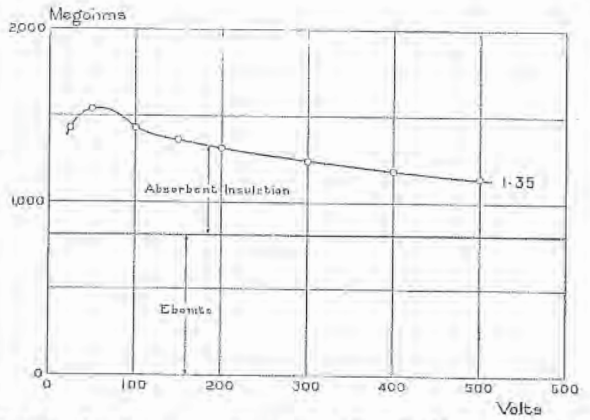

FIG. 6.—Insulation resistance of a Supply Meter, a typical example of absorbent insulation in series with a non-absorbent insulator.

generator was so connected that the circuit wires were positive and the earth negative, the resistance was 8·7 megohms; whereas when the polarity was reversed the resistance fell to 5·7 megohms; both readings being those taken at 500 volts.

The polarity effect which has just been noticed in connection with Fig. 7 is a strongly marked characteristic of earthenware insulators, and although it has nothing to do with the characteristic curve some account of it seems to be called for in a paper on insulation resistance. But the subject cannot be dismissed in a few lines and to avoid a long interruption in our main argument the effect of polarity has been dealt with in an appendix under the heading "Insulation Valves." The matter is one which closely concerns everyone who has occasion to test insulation in which earthenware of any kind is used as an insulator.

Before any general hypothesis can be framed to account for the characteristic behaviour of insulation in ordinary

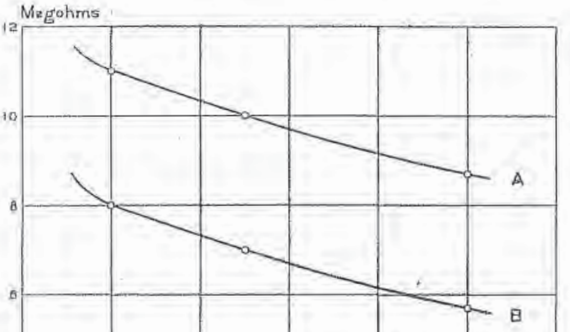

FIG. 7.—Insulation resistance of Interior Wiring, showing polarity, or "valve," effect (Ohmmeter test).

A, with wires *positive*, earth *negative*.
B, with wires *negative*, earth *positive*.

use, it is clearly necessary to know something about the individual behaviour of different insulating materials. For this purpose a brief outline will be given of the prolonged experiments that were made on a large number of materials which are in common use for insulating purposes. The materials included rubber, gutta-percha, micanite, porcelain, cotton, paper, silk, oils, and varnishes. Not a tithe of the work done can be recorded here, but it will be sufficient to describe a few of the more important experiments made on insulators which are typical of their class.

4. DIELECTRIC RESISTANCE.

Our object being to learn something about conduction through moisture, any dielectric leakage there may be through the substance of the insulators can only be ignored if we first show that dielectric resistance is enormous in comparison with the resistance of the leakage paths which are formed by traces of moisture.

Figures may be found in the text-books for the specific resistance of various insulators. What may be called good insulators vary from about 80 million megohms for mica up to about 50,000 million megohms for vulcanized rubber—the centimetre cube being the datum. Such figures as these convey no more meaning to the mind than the distance of a star expressed in miles; we do not want figures so much as relative magnitudes. The consideration of an example of dielectric conduction will therefore be a useful preliminary because it will afford some insight into a subject which is but little understood outside the test room, and at the same time serve to create a proper sense of proportion.

The only non-absorbent insulators which were tested in the course of the work recorded here were gutta-percha and rubber. These are both non-absorbent in the sense that what little water they may be capable of absorbing is entirely unable to form leakage paths through the insulator. Submarine cables insulated with these materials have been lying on the bottom of the sea for half a century or more, and, so far as the author is aware, no trace of conduction by absorbed water has ever been detected in a sound cable.

Rubber as an insulator for cables is so extensively used in every branch of electrical industry that it is naturally the example chosen for illustration. The test sample was a rubber-covered flexible cable made up of 64 6-mil wires, insulated in accordance with the standards of the Cable Makers' Association, and guaranteed to have an insulation resistance of not less than 600 megohms for one mile after one minute's electrification. The rubber is between 35 and 37 mils in thickness, and consists of one layer of pure Para and two layers of vulcanized rubber. This flexible is used by the author's firm for the interior connections of naval gear and for that purpose it is supplied without any covering outside the rubber; it was therefore in suitable form for an under-water test. A length of this cable—equal to $\frac{1}{16}$th of a mile—was put into a bucket of water, where it remained for 40 days. The tests which were made during that period consisted in charging the cable at about 500 volts and observing the total current flowing into it at intervals of time, so that a time-current curve might be drawn. Tests were also made by discharging the cable and observing that part of the discharge current which passed out through the galvanometer. It should be noted that whereas during the charging of the cable the entire charging current traverses the galvanometer, no equivalent statement can be made about the discharge current. During discharge there are three parallel paths for the current: through the galvanometer, through surface leakage paths at the exposed ends of the cable (the guard wires being ineffective during discharge), and lastly the dielectric leakage paths through the rubber. Hence the discharge as recorded by the galvanometer does not agree exactly with the charge.*

Suppose the cable is charged through a resistance of r megohms by a battery giving V volts, the dielectric resistance being R megohms. Then the leakage current will be $V/(R + r)$ micro-amperes, and the initial value of

* For the purpose of this paper it is not necessary to describe the ordinary method by which the leakage current is arrived at by deducting the discharge current from the total current flowing into the cable.

the charging current will be V/r micro-amperes. The charging current dies away, rapidly at first then more and more slowly. Ultimately, possibly after many hours, it will have fallen to a value which cannot be distinguished from zero, and the only appreciable current passing through the galvanometer will be the true dielectric leakage, namely $V/(R+r) = I$. Since R is always very large compared with r the latter may be

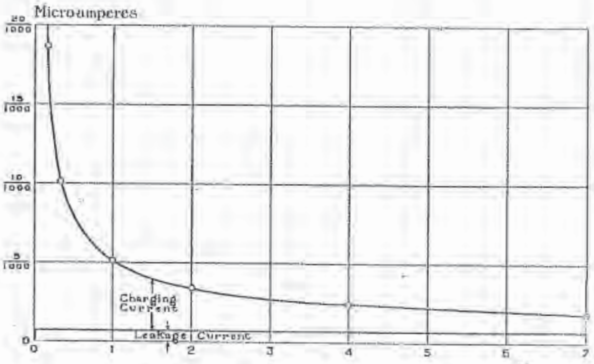

FIG. 8.—Leakage current plus charging current flowing into a rubber cable, from 0 up to 7 minutes.

neglected and V/I will correctly express the dielectric resistance at voltage V—provided the patience of the observer has not been exhausted before the final subsidence of the charging current to zero. The actual result of a test of this kind, made after the flexible had been in the water for 10 days, is shown in Figs. 8 and 9. In Fig. 8 the time-current curve is given from 10 seconds up to 7 minutes after the closing of the charging circuit; while Fig. 9 shows the same curve from 3 minutes up to 420 minutes (7 hours).

Incidentally these two diagrams afford a good illustration of the misleading appearance of curves of this class. Judging from Fig. 8, one would infer that within 4 or 5 minutes the current was already nearly approaching its final steady value: "Well round the bend of the curve" is a phrase often used in this connection. But we have only to change the time scale from minutes into hours, and magnify the current scale by a substantial amount, and the curve conveys a very different impression. Looking at Fig. 9, and again judging by eye, we now draw the inference that instead of a few minutes an hour or more must elapse before the current can be said to be "well round the bend of the curve."

The charge was continued for 27 hours without a break, and by that time the current had fallen to 0·00072 micro-amperes at 525 volts. This was assumed to be the true dielectric leakage current and its value is indicated on each of the diagrams by a horizontal line, in order that the relative magnitudes of charging current and leakage current may be seen at a glance.

It has been the custom ever since the early days of submarine telegraphy to observe the total current at the end of the first minute, and to call the ratio of the charging voltage to that current "the insulation resistance after one minute's electrification," a custom which is still adhered to by cable-makers. Inspection of the curve in Fig. 8 shows that at one minute 86 per cent of the total current was charging current, only 14 per cent being true leakage current. Hence when a cable-maker specifies the resistance of cable similar to this as so many megohms, his statement only contains 14 per cent of the whole truth. Economy of truth, however, is on the side of honesty in this instance, and the buyer is doubtless aware of the customary method and sometimes understands what it implies.

In this paper we are more concerned with fact than custom. Fig. 8 shows that at one minute the total current was 0·0051 micro-amperes at 525 volts, hence the value of what may be called the "customary resistance" was $525/0{\cdot}0051 = 103{,}000$ "megohms" for $\frac{1}{16}$th of a mile of cable; and the customary resistance of one mile of similar cable would be 103,000/16, or roughly 6,000 "megohms." The final value of the current being 0·00072 micro-amperes, the real dielectric resistance was $525/0{\cdot}00072 = 730{,}000$ megohms for $\frac{1}{16}$th of a mile, equivalent to a dielectric resistance of 45,000 megohms for one mile of similar cable.

With these figures as a guide let us ascertain the relative importance of dielectric leakage and moisture leakage in some installation of interior wiring in which rubber insulated wires are used. The circuits which gave the characteristic curve shown in Fig. 7 afford a good example, being carried out with rubber-covered wire insulated to the same standard as the flexible we have just examined. The conductors also are of the same diameter in the two cases. The installation contains 380 yards of wire, coupled up in the usual way to a number of fittings in which porcelain is used exclusively as the insulator. Assuming the covering

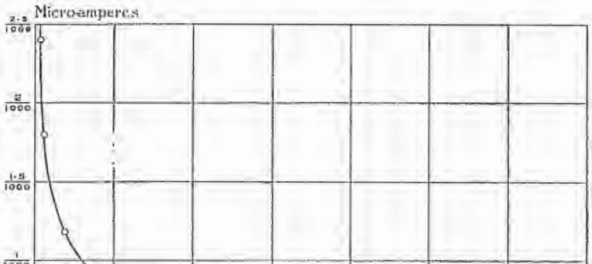

FIG. 9.—Leakage current plus charging current flowing into a rubber cable: continuation of the time-current curve in Fig. 8, up to 7 hours.

of the wires to be undamaged, the dielectric resistance of 380 yards of wire to earth will be about $45{,}000 \times \frac{1760}{380} = 200{,}000$ megohms, and the customary resistance would be about $6{,}000 \times \frac{1760}{380} = 28{,}000$ "megohms." We need not attempt to decide which of these values is to be taken, because it is only necessary to look at Fig. 7 to find that the resistance of the installation as a whole was but a paltry 6 megohms, even when tested in dry weather. The relative importance is now obvious; leakage through the dielectric rubber is nothing, leakage at the fittings is everything.*

What has been demonstrated in the case of rubber must be equally true with regard to any insulator which has a resistance in any degree comparable with that of good rubber. The resistance of such materials as ebonite, sulphur, glass, mica, gutta-percha, shellac, dry paper, and dry cotton, is in every case enormous; like rubber their specific resistance is measured by millions of megohms, and in most cases by thousands of millions. Hence dielectric leakage will be ignored in what follows. In a later section the conduction through a porous insulator is compared with the quantity of absorbed water it contained an experiment which incidentally gave another convincing proof of the relative insignificance of dielectric leakage.

5. Moisture Curves.

Cotton.—Although this material is so largely used as an insulator for wires the opportunity for observing its

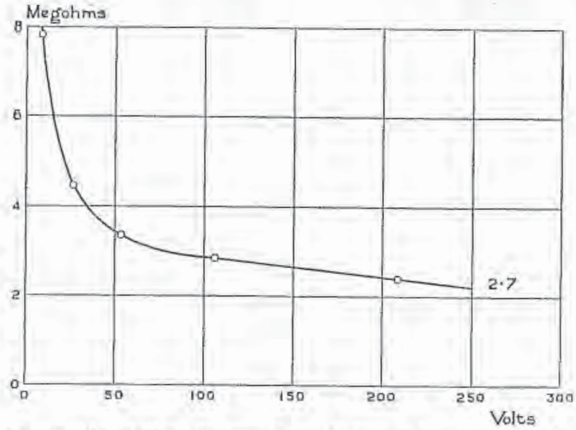

FIG. 10.—Insulation resistance of Cotton which contained a normal quantity of moisture.

resistance seldom or never arises in practice. Several test-pieces were therefore made up for the purpose, each consisting of two cotton-covered wires wound side by side in a single layer on a well glazed porcelain bobbin so that leakage from one wire to the other could only take place through the cotton coverings. One of these cotton test-pieces when tested for insulation resistance from one wire to the other gave the curve shown in Fig. 10. After being dried in an oven at 150° C. for a couple of hours, and then allowed to cool, this test-piece gave the curve shown in Figs. 11 and 12. The resistance is now five or six times greater as the result of the partial evaporation of the moisture originally contained in the cotton, but the general character of the voltage-resistance curve is unaltered. It will be noticed that at 500 volts the resistance has fallen to

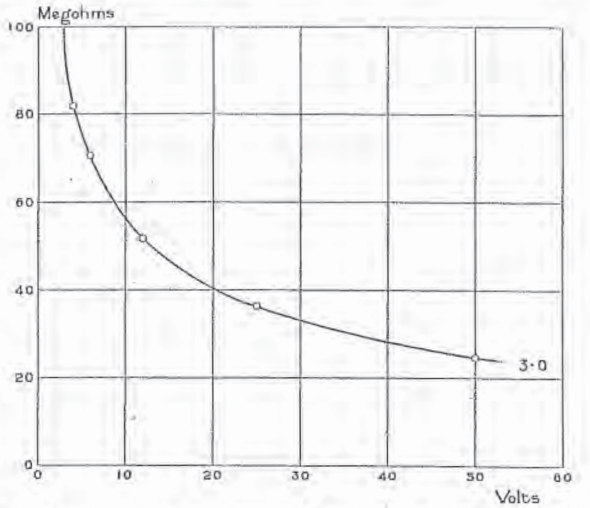

FIG. 11.—Insulation resistance of Cotton; the same test-piece as in Fig. 10, but partially dried by baking.

about one-third the value it had at 50 volts, or to put it shortly $R_{50}/R_{500} = 3$.* This is a rough-and-ready way of comparing curves which, although following similar laws, look very different to the eye simply because they are plotted to different scales. In the diagrams the value of the ratio R_v/R_{10v} is marked at the end of each characteristic curve so that different curves may be readily compared, and it will be found as we proceed that in the case of absorbent materials this ratio is more commonly nearer 2 than 3. After further drying at 150° C. for some hours, this

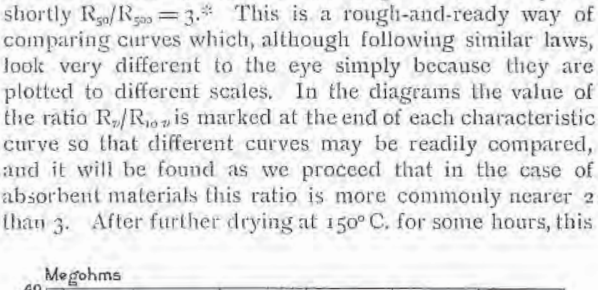

FIG. 12.—Insulation resistance of Cotton; continuation of the curve in Fig. 11 up to 500 volts.

same test-piece gave the curve shown in Fig. 13. The effect of the drying process has been to increase the resistance to something like 80 times the initial value, but

* It may be remarked in passing that the average resistance per leakage point is a useful criterion for the insulation of wiring. In the case of the resistance from wires to earth, the switches, fuse-blocks, ceiling roses, lampholders (if they can leak to earth), and other places where the conductors are fastened to leaky insulators, constitute the leakage points. For resistance between the wires with the switches closed and the lamps removed, the lampholders alone are to be counted; and for resistance between the wires with the lamps in place and the switches open, the switches are the only leakage points that count.

In the example considered in the text the resistance to earth was about 6 megohms, and there were 62 leakage points, hence the average resistance per leakage point was $6 \times 62 = 372$ megohms. Remembering that one switch base of good quality may have a resistance as low as 100 megohms, it is evident that the installation as a whole was in excellent condition as regards insulation.

Rules based solely upon the number of lamps are frequently too remote from the facts to afford much guidance.

* The exact value of the ratio is 2·8 in this example.

notwithstanding the great diminution in the quantity of water in the cotton, the curve retains the characteristic shape. The reason for this remarkable persistence in the law of moisture conduction under widely varying conditions will be found in a later section.

Paper.—Although cotton exhibits all the phenomena of conduction by moisture, it is not the most convenient material for experiment. Paper lends itself very much

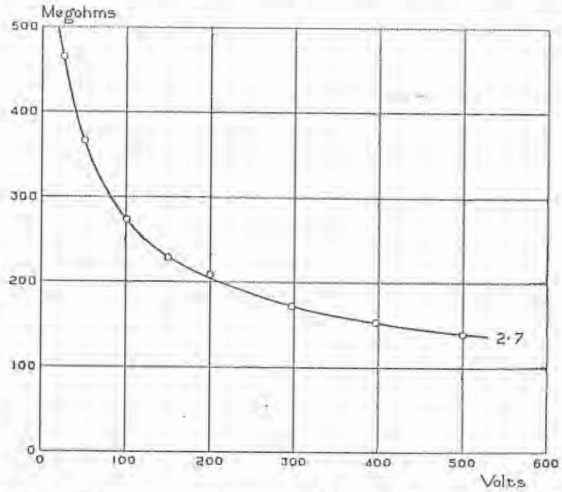

FIG. 13.—Insulation resistance of Cotton; the same test-piece as in Figs. 10, 11, and 12, after further baking.

better to exact conditions as regards the area and length of the insulator interposed between the two conductors. Various kinds of paper under a variety of conditions as regards moisture, compression, length, and area, were

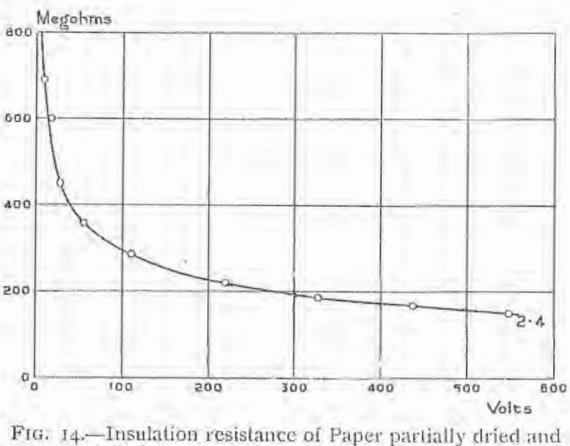

FIG. 14.—Insulation resistance of Paper partially dried and tested at a compression of 2·8 lb. per sq. inch.

exhaustively tested. The test-pieces were each composed of several sheets of paper cut to a suitable size and shape and laid in a pile on a flat copper plate which served as one electrode. A second copper plate on the top of the pile of paper acted as the other electrode, and by putting the complete test-piece in a small screw press any compression could be obtained, from that due to the weight of the upper electrode to about 100 lb. per square inch. As might be expected, paper behaves in much the same way as cotton. The two curves shown in Figs. 14 and 15 were obtained from drawing paper of good quality. In both cases the paper was in a normal state as regards moisture.

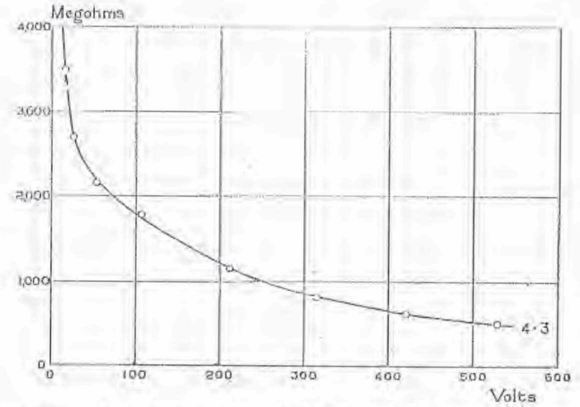

FIG. 15.—Insulation resistance of Paper; the same test-piece as in Fig. 14, but tested at 0·1 lb. per sq. inch.

The law of the characteristic curve is considerably affected by the degree of compression to which the absorbent material is subjected. The curve in Fig. 14 corresponds with a pressure of 2·8 lb. per square inch, whereas in the case of Fig. 15 the pressure was only 0·1 lb. per square inch. The corresponding values of the ratio R_{50}/R_{500} were 2·4 and 4·3. The latter figure is abnormally high and nothing approaching it has been observed in any tests of insulation under working conditions, probably because in practice absorbent insulators are always under a greater mechanical pressure. In Fig. 16 the connection between compression and the ratio $R_v/R_{10\,v}$ is traced from zero up to 40 lb. per square inch.

The degree of moisture in an absorbent material, like paper, may be varied within wide limits without much

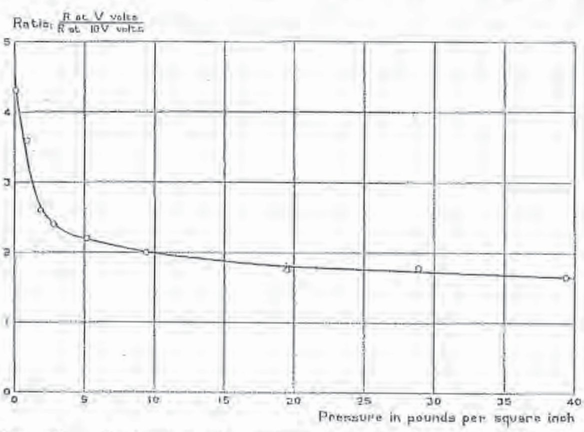

FIG. 16. —Influence of compression on the shape of "the "moisture curve" of Paper and similar insulating materials.

affecting the law of the moisture curve, although the corresponding variations in the resistance will be enormous. But when the material contains a considerable excess of moisture, so that it is sensibly damp, the law begins to change; the ratio $R_v/R_{10\,v}$ gradually approaching unity as a limit and the curve subsiding into a horizontal straight line. In other words when an absorbent insulator

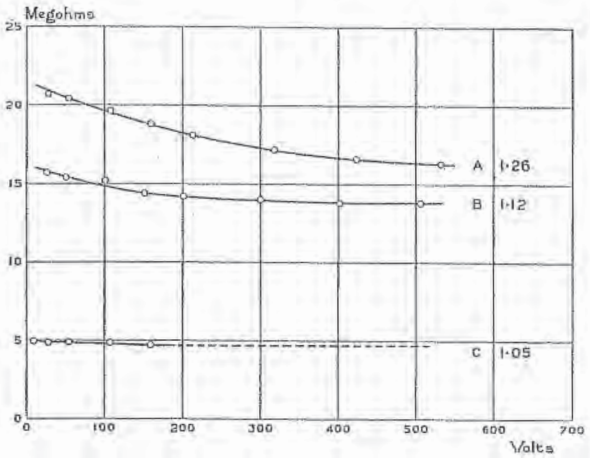

FIG. 17.—Moisture curves of damp Paper, showing gradual change from moisture conduction to Ohm's law as the Paper becomes sodden with water.

is sodden with water its resistance follows Ohm's law. This gradual change from a moisture curve is illustrated in Fig. 17, the curves being obtained from paper in which increasing quantities of water had been absorbed. Owing to the very low resistance of the wet paper, curve C could not be continued beyond about 160 volts.

Micanite Cloth.—The test-pieces for examining this material were made up by wrapping a single thickness of the cloth round a piece of smooth iron pipe, and then winding a single layer of cotton-covered wire tightly over it. The cloth was therefore tested under much the same

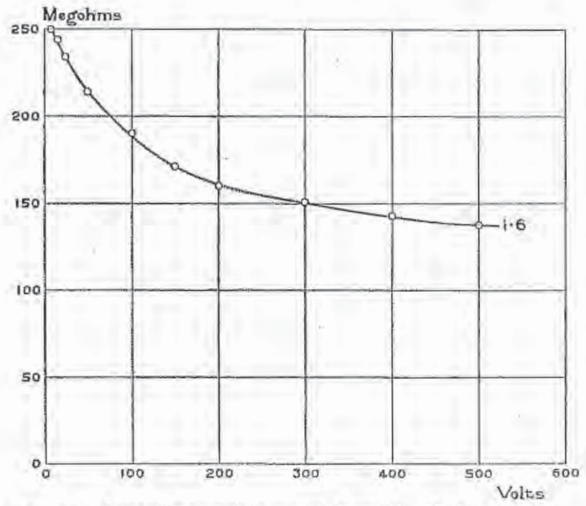

FIG. 18.—Insulation resistance of Micanite Cloth which contained moisture absorbed from the air.

conditions as are commonly met with in practice, micanite cloth being largely used as an insulator for windings. Of course in ordinary use there may be leakage over the surface of the cloth in addition to that which takes place through the insulating material; but as it was intended in these experiments to investigate conduction *through* the micanite apart from any other leakage, guard wires were tightly twisted round the cloth which projected beyond the winding at each end of the test-piece.

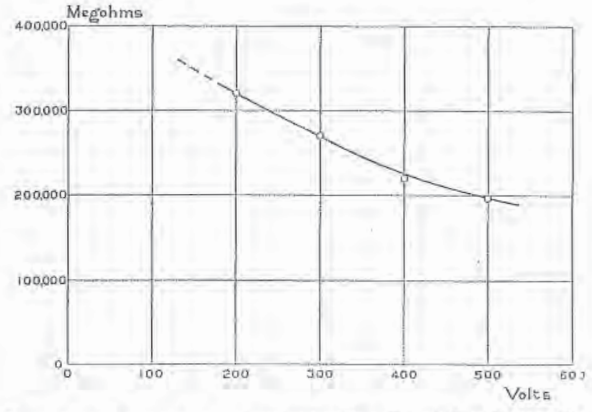

FIG. 19.—The same test-piece as in Fig. 18 tested 24 hours after being dried in an oven. *Note:* One hour after removal from the oven this test-piece had a resistance of 1,300,000 megohms at 500 volts.

One of these test-pieces, immediately after being wound and before being dried, gave the curve shown in Fig. 18. Notwithstanding the presence of the layer of mica the curve indicates conduction by moisture. The rather low

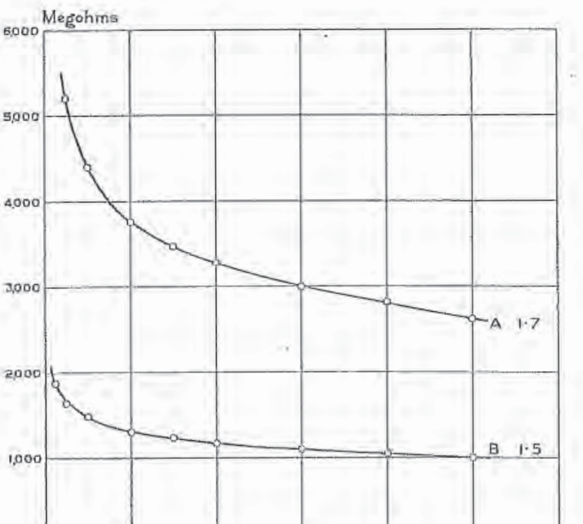

FIG. 20.—The same test-piece as in Figs. 18 and 19, tested after exposure to the air for (A) 5 days, and (B) 90 days.

resistance suggested that there was a good deal of water absorbed in the cloth, and the test-piece was therefore baked for about four hours at 150° C. In one hour after removal from the oven the test-piece was cold and its resistance was then about 1,300,000 megohms when tested at 500 volts. It was then left exposed to the air of the experimental room in order to find out to what extent micanite cloth acted as an absorbent of atmospheric moisture. At the end of 24 hours' exposure the curve reproduced in Fig. 19 was obtained, showing that the resistance had fallen, although it was still barely within the range of easy measurement. The two curves given in Fig. 20 were obtained after exposure to the air for 5 days and 90 days respectively.

It is by no means surprising to find a laminated substance like mica acting as an absorbent body, and in the form which it necessarily takes in micanite cloth there are innumerable capillary spaces available for the formation of leakage paths. It should be noticed that in these curves the ratio R_{50}/R_{500} is much less than 2; the average value deduced from seven curves obtained from micanite cloth test-pieces is 1·47.

Many other more or less absorbent insulators might be added, but the three examples which have just been examined are typical of the whole. The composition of the insulating substance seems to be of little importance. So long as the structure of the material is such as to provide capillary spaces to harbour moisture, leakage will take place in the characteristic manner. Of course the difficulty of maintaining adequate resistance in absorbent insulators is fully realized, and they are seldom used without an attempt being made to exclude moisture by means of some non-absorbent insulator applied as an oil or a varnish and intended to close all the capillary channels. In the following sections the effect of filling up the pores of absorbent materials is dealt with in connection with oiled paper and varnished windings.

6. Conduction through Oil.

Oils are good insulators in themselves, but they are capable of absorbing traces of water. An investigation was therefore made to ascertain whether water when absorbed in oil behaved in the same way as moisture in an absorbent solid. For the purpose of the test a glass beaker was fitted up with two flat copper discs, one above the other, to act as electrodes. The upper disc was adjustable up and down by a micrometer screw so that the electrodes could be set accurately to any required distance. Several different kinds of oils and varnishes (and also liquids which are used as solvents in varnishes) were tested in this apparatus and in every case Ohm's law was followed, the resistance proving to be a constant quantity not varying with the potential difference between the electrodes. It was necessary to know whether the same thing applied to oil in which water had been absorbed. The oil used for the test was a heavy hydrocarbon sold as a lubricant for gas engine cylinders. It had the disadvantage of a rather low resistance—about 2·5 million megohms for a centimetre cube*—but it was chosen because a large store of it was available, and hence uniform samples might be relied on. A trace of distilled water was dissolved† in the oil by putting a few drops into a bottle containing a pint of oil and stirring for many hours. The oil was then left at rest for about 48 hours in order to allow the suspended water to settle down. The slightest trace of water in suspension is apt to cause instability in the resistance because all the suspended particles are slowly drawn in between the electrodes by the electrostatic force, and when there they tend to form conducting chains from one electrode to the other. The result of a test with oil containing absorbed water is shown in

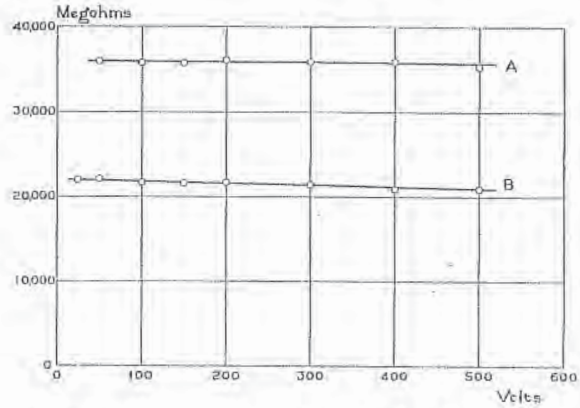

Fig. 21.—Resistance of Cylinder Oil: A, when dry; B, containing a trace of absorbed water.

Fig. 21, the upper curve being obtained from cylinder oil freshly drawn from the storage tank and the lower curve from the same oil after absorbing water. Notwithstanding some irregularity due to water in suspension, the effect of the absorbed water is evident in the marked lowering of the resistance. But of any effect like that due to moisture in absorbent solids there is no trace. In both curves the resistance is practically constant, Ohm's law being followed well enough.

7. Oil-impregnated Paper.

Paper containing moisture may be saturated with an insulating oil without producing any effect on the leakage paths formed by the water. The curve shown in Fig. 22 was obtained from drawing paper which, while in a

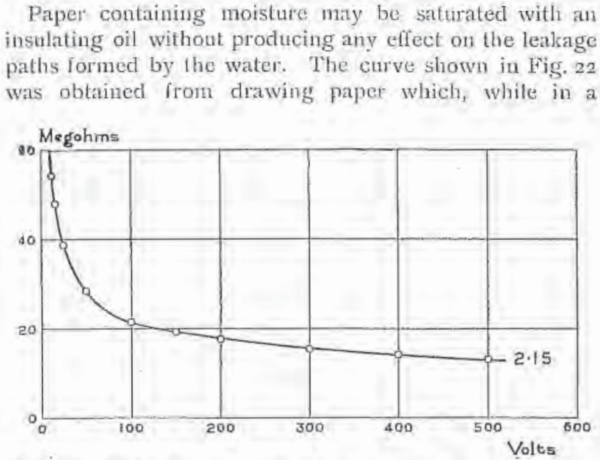

Fig. 22.—Insulation resistance of Paper which had been soaked in dry Cylinder Oil for a week.

normal state as regards moisture, was immersed in dry cylinder oil and left to soak for a week before being taken out and tested. The resulting curve does not differ in any way from an ordinary moisture curve, the ratio R_{50}/R_{500}

* The oil used for impregnating paper cables has a specific resistance of about 700 million megohms, at 15° C.

† The water may not be in solution in a chemical sense, but it is permanently absorbed in the oil, whereas any water in suspension or forming an emulsion with the oil, ultimately separates out and falls to the bottom of the vessel.

being 2·1 for the oiled paper. It is evident that the oil does not displace the water, or break up the conducting paths, or interfere in any material way with the characteristic conduction due to the moisture which was present in the paper before the entrance of the oil.

The converse, however, does not hold good. Water will not only find its way into paper which has been dried and soaked in oil, but will so far displace the oil as to form leakage paths. As is well known, paper impregnated with oil easily absorbs water from the air. Hence the necessity for the lead covering and soldered joints of an impregnated-paper cable. To ascertain whether moisture absorbed by an impregnated paper cable was able to form leakage paths of the same kind as those in other absorbent solid materials, a short piece of lead-covered impregnated-paper cable was left with both ends open and exposed to the air of the experimental room. The curve shown in Fig. 23 was obtained when the cable had been open to the air

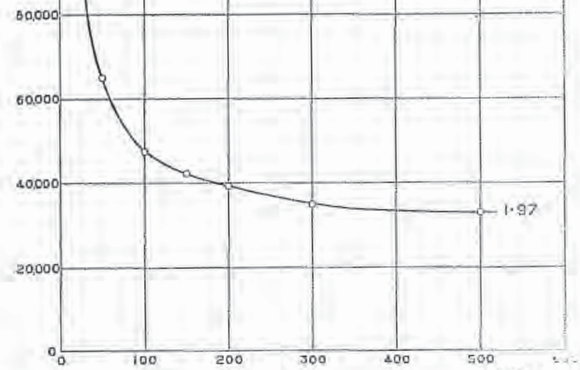

FIG. 23.—Insulation resistance of Oil-impregnated Paper Cable with the ends open, after exposure to the air of the Experimental Room for 13 months.

for 13 months. There is nothing to distinguish it from the characteristic curves of more ordinary absorbent insulators. The ratio R_{50}/R_{500} is 1·97, quite a normal value for a moisture curve when the absorbent material is under a moderate compression.

Although water ultimately finds its way into impregnated paper, the process of absorption is extraordinarily slow. The piece of paper cable when first tested had a resistance of about one million megohms at 500 volts, and although this high value was not maintained for more than a month or so, it required nearly 9,000 hours' exposure to the air to reduce the resistance to 33,000 megohms. Had the cable been insulated with dry paper (not impregnated) the resistance would have fallen to the same extent—in other words, the same quantity of water would have been absorbed—in four or five hours at the most.

The experiments on oiled paper lead irresistibly to the conclusion that the mode in which absorbed water forms conducting paths is substantially the same whether the insulator is saturated with oil or not. The water may be in the insulator before impregnation with oil or it may be very slowly absorbed afterwards, but once inside it will conduct electricity just as though the oil was not there.

8. VARNISHED WINDINGS.

Varnish is intended to prevent water from forming leakage paths. To do this it must either keep out water by closing all the pores at the external surface of the insulator, or it must interpose a solid and impervious layer of the body of the varnish between the conductors and the porous insulator. Applying varnish by a brush aims at the first alternative, vacuum methods aim at the second. It need hardly be pointed out that when a porous body is saturated with a liquid varnish, and the solvent is then dried out, the solid body of the varnish remaining in the insulator is necessarily insufficient in quantity to fill up the pores. They can only be entirely filled up by soaking the insulator in oil, or in a melted wax or in some equivalent solid insulator which can be liquefied by heat. Hence a porous insulator, even when varnished, is likely to have many channels available for the reception of water. Whether water can find its way into them depends on how far the varnish has been able to stop up the pores on the outside of the insulator.

Experiments on varnished windings occupied many months, and in several cases varnished test-pieces have been kept under observation for over two years. Their outcome can be summed up in a sentence. Varnish reduces the extent to which moisture is absorbed, but it seems powerless to stop absorption altogether if the windings are subjected to the temperature variations which occur in ordinary use. This failure to exclude moisture was exhibited in every trial, both by test-pieces varnished by a vacuum method and by those which had received coats of varnish applied by a brush. A couple of tests will illustrate the whole series.

The vacuum method consisted in first baking the test-piece at 150° C. for several hours; then putting it into the vacuum chamber and exhausting down to a few mms. pressure; then running in the varnish until the test-piece was completely submerged, the vacuum pump being kept going and the varnish boiling for half an hour or so. Next, air was admitted to the vacuum chamber and the test-piece was left under atmospheric pressure for an hour or more in order to give ample time for the varnish to be forced into the insulation. After this the test-piece was baked for several days at a temperature not exceeding 150° C., and after cooling, the resistance tests were begun. One of the test-pieces, composed of two cotton-covered wires wound on a porcelain bobbin, had an initial resistance of 34,000 megohms after being varnished by this method with a black plastic varnish of good quality. The resistance followed Ohm's law, being constant at all pressures up to 500 volts, thus indicating conduction by the varnish and the absence of moisture conduction. Yet after exposure to the air of the experimental room for 9 days this test-piece gave a perfectly normal moisture curve with a ratio R_{50}/R_{500} equal to 2·1, and the resistance had already fallen to less than one-fourth of the initial value. This fall in resistance and change in the law of conduction are shown in the two curves in Fig. 24. The resistance continued falling for several months and ultimately settled down round about 2 or 3 megohms, rising and falling with the changes in the humidity of the air. A striking experiment was made on this test-piece by boiling some water in an open vessel in a room adjoining the experimental room. Upon opening the communicating door so as to admit air laden with water vapour, the resistance of the test-piece immediately began falling and continued doing so for half an hour. At the end of this interval the boiling

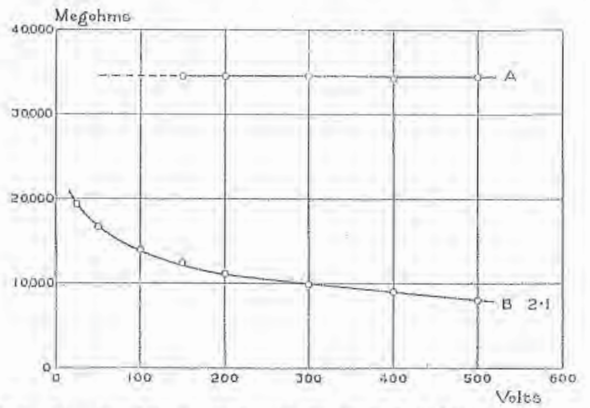

FIG. 24.—Insulation resistance of varnished Cotton: (A) 12 hours and (B) 9 days after baking. Showing the change from Ohm's law (when the test-piece was dry) to moisture conduction after a few days' exposure to the air.

water was removed and the windows of the experimental room were opened in order to restore the air to its original state. Within 3 minutes the fall ceased and the resistance began rising as steadily as it had fallen, until, in about 50 minutes from the time when the boiling water was removed, it had recovered its initial value. One could not have clearer evidence of the ease with which moisture is absorbed by a well-varnished winding.

The history of this test-piece affords a direct proof that the characteristic shape of the first part of the voltage-resistance curve is the result of leakage through moisture. In its initial state, when all moisture had been expelled by prolonged baking, we have a high resistance, and what little leakage there is follows Ohm's law because the varnish itself conducts in that way. But a few days' exposure to the air is sufficient to bring about a complete change in the mode of conduction, and in place of Ohm's law we have the characteristic curve which is common to all absorbent insulators. Finally, we see the resistance falling when the air is artificially charged with water vapour, and rising when the air is restored to its normal condition.

The other test to be described was made on one of the windings used for testing micanite cloth. Two coats of the plastic varnish were applied by a brush to the outside of the winding, and the test-piece was then baked at 150° C. for 32 hours, by which time the varnish was quite dry. After allowing the test-piece to cool, the resistance from the winding through the micanite cloth to the iron core was about a million megohms. This high value was not maintained for long. Within 20 days after removal from the oven a decrease was noticeable, and by the 74th day the resistance had fallen to 33,000 megohms. The curve obtained on that day is given in Fig. 25. It should be compared with the curves given in Fig. 20 for a similar micanite cloth test-piece which had not been varnished. Both curves indicate leakage through moisture, but the varnish has in this case greatly reduced the amount of moisture which the insulation can absorb.

There can be little doubt that the failure to exclude moisture altogether is due to insufficient elasticity in the body of the varnish. Unless this is a highly elastic substance it is unable to follow the expansions and contractions of the windings, and ultimately the continuity of the coat of varnish is broken up, leaving numerous crevices by which moisture can enter.

9. Volume of Water in the Leakage Channels.

The first stages in the investigation of any phenomena are necessarily qualitative. Arithmetical quantity only comes when an attempt is made to fit the phenomena into some kind of ordered scheme. It is difficult to apply arithmetic to so elusive a quantity as the resistance of absorbed moisture, but at this point questions naturally arise as to the volume of water which is utilized in forming leakage paths, and what sort of relation that volume bears to the total volume of water in the absorbent insulator.

To find some answer to these questions experiments were made on the resistance of an absorbent insulator containing known quantities of water of a measured specific resistance. The insulator was composed of a number of circular discs of chemically pure filter paper, 12·5 cm. in diameter, piled up into a pad and moderately compressed between two flat metal electrodes. The pad of paper had an area of 122 sq. cm., and its thickness (under the compression) was 0·53 cm., so that the pad occupied a volume of 64·8 cubic centimetres. The specific resistance of the water used in this experiment was 2,500 ohms.

To begin with, a quantity of the water was put into the

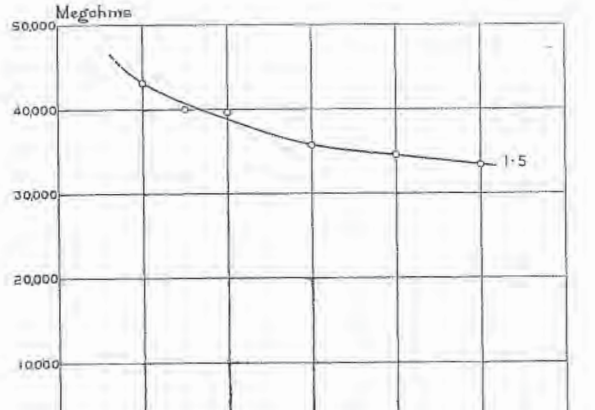

FIG. 25.—Insulation resistance of varnished Micanite Cloth (compare with Fig. 20).

paper and left to distribute itself uniformly. The method of experiment was to measure the resistance of the pad and weigh it immediately afterwards. Next, to allow some of the water to evaporate and then to repeat the resistance test and the weighing. Proceeding slowly step by step, the water was finally dried out and the net weight of the dry paper ascertained. In this way a number of corresponding values were obtained for weight of water in the paper and resistance of the pad. The figures are given in Table I, the volume of water in cubic centimetres being taken as equal to the weight in grammes.

TABLE I.

Test-point	Volume of Water in the Pad of Paper c.c.	Resistance of the Pad at 500 volts (megohms)	Estimated Volume of *Resistance Water* c.c.	Ratio of *Resistance Water* to Total Water, expressed in Parts per million	Percentage Volume of Water in the Pad of Paper
A	1·68	93	188×10^{-6}	112	2·59
B	1·55	131	134 "	87	2·39
C	1·48	179	98 "	66	2·28
D	1·43	226	78 "	54	2·20
E	1·29	369	48 "	37	1·99
F	1·14	845	21 "	18	1·75
G	1·08	1,280	14 "	13	1·66
H	1·00	1,870	9·4 "	9·4	1·54
I	0·59	23,600	0·74 "	1·3	0·91
J	A trace	$11·7 \times 10^6$	—	—	0

Remembering that the resistance of a centimetre-cube of the water was only 2,500 ohms, it is obvious by inspection of the figures in the second and third columns that the resistance of the pad is out of all proportion to the volume of water it contains. Let us analyse one of the tests and see how the two things may be reconciled. Test H is a convenient example, because there happened to be exactly 1 cubic centimetre of water in the paper. The problem is to utilize that volume in such a way as to give the water as a whole a resistance of 1,870 megohms. We must begin by using some of it to make a conducting path of the required resistance and of sufficient length to go from one electrode to the other by a rather tortuous route; tortuous, because it must thread its way through a maze of capillary channels in the paper. Having formed the necessary resistance channels we may dispose of the rest of the cubic centimetre of water by storing it inside the paper as an entirely detached body or bodies, so that it can play no part as a conductor. By these arbitrary proceedings the water will have been divided into two very unequal portions, which may be called *resistance water* and *dormant water*.

Still dealing with Test H how much resistance water will be required to make up the observed value of 1,870 megohms? To answer this question some reasonable guess must be made at the length of the tortuous current path. Now the current will certainly take the shortest available route, and there are such an enormous number of intercommunicating channels in the paper that the average length of all the available paths is unlikely to be more than two or three times the distance between the electrodes. It would require a highly artificial arrangement of the fibres in the paper to compel the current to travel anything like ten times the shortest distance, and in the following calculation it will be assumed that the average path is five times the distance between the electrodes. The electrodes being separated by the thickness of the pad of paper—namely 0·53 cm.—the assumed average length of current paths will be 2·65 cm.*

The volume of a conductor of given resistance length and specific resistance is $\rho l^2/R$ so that at test-point H we have—

$$\text{Volume of } \textit{resistance water} = \frac{2500 \times 2·65^2}{1870 \times 10^6} = \frac{9·4}{10^6} \text{ c.c.}$$

Compare this volume with the total quantity of water in the paper, namely 1 c.c., and we arrive at the figure given in the fifth column of the table:—Under the conditions at Test H the proportion of resistance water to total water was only 9·4 parts in a million.

The reader will distinguish between the observed quantities recorded in the table and the figures which are the result of calculation based on certain assumptions, tacit and otherwise. Thus, the average length of the leakage paths has been assumed to be five times the distance between the electrodes; the dormant water has been assumed to occupy blind alleys entirely off the paths of the leakage current; and the conductivity of the water in the pad of paper has been assumed to remain constant notwithstanding evaporation. Let us see in what direction these assumptions affect the magnitude of the estimated volumes given in the table.

First as regards length. Since the volume of a conductor of given resistance is directly proportional to the square of its length, it is obvious that any underestimate in the length of the leakage path will result in an underestimated volume; and if we choose to double the assumed length, then the volume figures must be multiplied by 4.

Now as to the disposal of the dormant water. In Test H, the calculated volume of resistance water was $9·4/10^6$ c.c., and the length of path 2·65 cm. Translated into more familiar units the resistance water in the innumerable leakage channels was equivalent in the aggregate to a single thread of water rather over an inch in length, and a little more than three-quarters of a mil in diameter.† Let us take some of the dormant water and distribute it along this thread in the form of detached drops, like dew on a spider's web. Each drop, owing to its comparatively large volume, short-circuits the portion of thread to which it clings. To fix our ideas, we can suppose the drops occupy half the entire length of thread and therefore reduce the resistance to one-half. To bring up the resistance to the observed value it will be necessary to reduce the sectional area of the remainder of the thread by one-half, and that part of the leakage path which remains effective as resistance will now have a volume equal to one-quarter of the value reckoned on the assumption that dormant water might be left out of account. It is clear,

* Let the engineer who has never used a factor of safety cast the first stone at this arithmetic.

† At test-point I, the thread of water, which is the equivalent of all the leakage paths, had been reduced to less than one-quarter of a mil in diameter.

then, that this assumption leads to an overestimate of volume, and if the whole of the dormant water is shunted into sidings or blind alleys the volume of resistance water as calculated from the observed resistance is overestimated to the maximum extent.

The drops of dormant water which we have supposed to be distributed along the path of the leakage current might just as well be collected together to form one or more larger bodies of water. The principle is the same, and all we have to bear in mind is that the length of resistance thread which remains intact will be greater or smaller according to whether we choose to imagine the masses of water to be disposed along the current path or across it. To take an extreme case, if the whole of the dormant water which was present in Test H could be spread over the surface of one electrode it would form a layer 1/122 cm. in

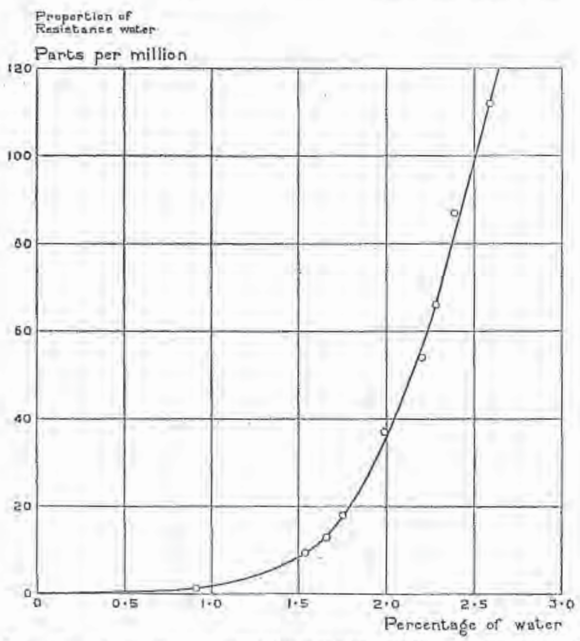

FIG. 26.—Proportion of *resistance water* to the total quantity of water in a pad of paper (see Table I).

thickness—about 3·2 mils. The resistance thread (which was about 1 in. long) would therefore be decreased in length by 3·2 mils, necessitating an equally insignificant decrease in its sectional area in order to maintain the observed resistance of 1,870 megohms. The dormant water would now be wholly in the current path in the form of a very thin sheet, but as its resistance would be much less than 1 ohm we may still regard all the water which is not in the resistance thread as dormant, in the sense that it does not form an appreciable part of the observed resistance.

Finally as regards evaporation: When water evaporates the electrolytic ions generally remain behind, and hence the number of ions in a unit volume of the remaining water increases and the specific resistance falls. But the volume of a conductor of given resistance is directly proportional to the specific resistance, and hence by neglecting the effect of evaporation the volume of resistance water has been again over-estimated.

Taking all these matters into consideration, the figures given in Table I seem rather more likely to be overestimates of volume than underestimates. At all events they may be accepted as of the right order of magnitude, and the significance of the experiment stands out clearly in spite of some unavoidable guesswork: A vast proportion of the whole volume of water in an absorbent insulator is dormant in the sense just defined. The resistance of the leakage paths through the insulator is determined by an exceedingly small fraction of the absorbed water.

The relation between the volume of resistance water and the total volume is shown as a curve in Fig. 26. The total volume of absorbed water in the paper is here reckoned as a percentage of the volume occupied by the pad of paper.

10. DIELECTRIC CONDUCTION IN DRY PAPER.

Incidentally the weighing experiment affords another example of the relative importance of moisture conduction and dielectric conduction. Referring once more to Table I, we see that when the absorbed water was reduced to a mere unweighable trace, the resistance of the pad of filter paper rose to nearly 12 million megohms, corresponding to a specific resistance of about 2,700 million megohms (cm. cube). This is far below the specific resistance of more thoroughly dried paper, which is certainly not less than 26,000 million megohms. The author is indebted to Mr. Welbourn for this figure; it is a value obtained by the British Insulated and Helsby Cables Company in their test room with carefully dried paper, but even in this case it is doubtful if every trace of water had been removed.

Accepting 26,000 million megohms as at all events a lower limit, it is evident that in Test I moisture conduction was at least 5,000 times greater than dielectric conduction, and in Test A when the pad of paper was much nearer a normal state as regards the quantity of absorbed water, moisture conduction outweighed dielectric conduction more than a million times.

11. THE LAW OF THE MOISTURE CURVE.

The experiments on absorbent insulators suggest that underlying the phenomena there is some ascertainable law of conduction by moisture. The fact, which the wary reader will have perceived already, that it has been possible to compare one curve with another without taking potential *gradient* in the insulator into account, is sufficient proof that the curves have some simple property in common. And so they have; for in every case in which moisture conduction alone controls the resistance curve, it is found that over a considerable length along the curve the ratio R_v/R_{10v} is fairly constant whatever may be the value of v in volts. Hence although the insulators have varied widely in thickness, the ratio R_{50}/R_{500} has served quite well as a rough guide for comparing the different curves.

A good example of this property is afforded by the moisture curve for cotton given in Figs. 11 and 12. The fact that in this case a line drawn through the plotted observations forms a smooth curve over a very wide range of potential difference is of itself an indication that disturbances were absent, and hence we are justified in looking here, if anywhere, for a simple law. Table II gives half a dozen ratios of R_v/R_{10v} read off from this curve, and considering the inevitable discrepancies due to instability the figures are remarkably constant and point to a definite law.

TABLE II.

Voltage Points for which Ratio is reckoned	Ratio R_v/R_{10v}
5 to 50	3·0
10 „ 100	3·1
20 „ 200	3·1
30 „ 300	2·9
40 „ 400	2·8
50 „ 500	2·8
Mean value of ratio R_v/R_{10v}	2·95

The law would be expressed empirically by the formula—

$$R = k\sqrt[x]{\frac{1}{v}};$$

and since in this particular curve the ratio R_v/R_{10v} is only a little less than $\sqrt{10}$, the exponent x must be a number not much greater than 2.

But Nature generally declines the Procrustean bed of formula. Just as in the case of fluid friction she has persistently declined to limit herself either to the first power or to the second power of the velocity (the only alternatives offered to her by the mathematical descendants of Procrustes), so here she refuses to abide by any one exponent. But in each particular case a value may be chosen for x which will express the law of the individual curve over a great part of its length, and hence when the ratio R_v/R_{10v} has been found by experiment, the formula may be applied to ascertain any other ratio R_v/R_{nv} for values of n lying between 1 and 10. Beyond this modest degree of practical utility the formula is only useful as an indication of the general character of the moisture curve. Further analysis of the characteristic curves may prove useful in suggesting causes for the wide variations from the ideal curve, but in the present stage it is safer to be guided by average results.

12. COMPOUND INSULATION.

If the examples which have come under review in the foregoing pages are divided into two groups according to whether the insulator was composed of absorbent materials alone, or on the other hand built up of some non-absorbent dielectric insulator in series with an absorbent insulator, then their characteristic curves will be found to exhibit a marked difference in curvature, the decrease in resistance being much larger in the first group than in the second. Figs. 2, 22, and 23, are examples of wholly absorbent insulation, and Figs. 3, 6, 20, and 25, all relate to what may be called compound insulation. In 47 curves obtained from insulation, composed entirely of absorbent materials, such as cotton, paper, cardboard, fibre, and other things, both varnished and unvarnished and including oil-impregnated paper, the average value of the ratio R_{50}/R_{500} was 2·20.

This figure is confirmed by the results of a number of insulation tests on absorbent materials carried out by Mr. E. H. Rayner at the National Physical Laboratory.* The materials included presspahn, Manila paper, oiled paper, oiled board, oiled linen, Excelsior paper, Excelsior linen, and fibre, some of them being tested both in their ordinary condition and after varnishing. The insulators were tested under a compression of about 5·8 lb. per sq. in., and a reference to the compression-ratio curve in Fig. 16 shows that the ratio R_v/R_{10v} might be expected to be about 2·1. But as the resistance of each insulator was tested first at 200 and then at 1,000 volts, the value of R_v/R_{10v} may be more closely estimated from the observed value of R_{200}/R_{1000} by an application of the empirical formula. Mr. Rayner gives 17 tests within the range of measurement, and taking the whole of these the average ratio R_v/R_{5v} is 1·71. In arriving at this figure all the readings taken at 200 volts *after* the application of 1,000 volts have been excluded, as in nearly every case they showed a marked hysteresis effect. Now the formula shows that $\log (R_v/R_{10v})$ will be equal to $\log 1{\cdot}71/\log 5$, and hence we find that in Mr. Rayner's 17 tests the average value of the ratio R_v/R_{10v} was 2·15, compared with the author's figure of 2·20 deduced from 47 curves. The figure 2·2 may therefore be regarded as a good average value for the ratio R_v/R_{10v} for insulation which is wholly composed of absorbent materials, used under a moderate degree of compression.

But in the case of 12 curves obtained from compound insulation, that is to say insulation in which dielectrics like mica or ebonite were used in series with an absorbent material, the same ratio had an average value of a little less than 1·4. The difference is easily accounted for. The law of moisture conduction in any given absorbent material must be the same, whether there is a dielectric insulator in series with it or not, and assuming the dielectric has a constant resistance the absorbent insulator alone is responsible for the curvature of the resistance line. For an example turn to Fig. 6, which is the characteristic curve obtained from a supply meter in which the absorbent insulation of the windings is in series with the ebonite that serves to insulate the working parts from the case of the instrument. As it stands the ratio is only 1·35, but suppose we draw a new horizontal line at such a distance below the curve as will make the ratio R_{50}/R_{500} as deduced from measurements from this line to the curve, equal to the average for absorbent materials, namely 2·2. Then ordinates measured from the new datum up to the curve will represent the resistance of the absorbent insulation of the windings, and the distance from the new datum line down to the original base line will represent the resistance of the ebonite.† The height at which to

* *Journal I.E.E.*, vol. 34, p. 621, 1905.

† It may be the resistance of a conducting film on the surface of the ebonite, for external films have in several cases been found to follow Ohm's law. The point requires further investigation.

draw the new datum is easily found by trial and error, or it may be found at once from the following formula:—

$$\text{Constant part of resistance} = (\text{total resistance at 500 volts})\frac{a-n}{a-1}$$

where n is the observed value of the ratio R_{50}/R_{500} and a is the value of this ratio for the absorbent insulator by itself. In the present example the observed resistance at 500 volts was 1,140 megohms, n was 1·35, and we may take for a the average value 2·20. With these figures the resistance of the ebonite alone is found to be 810 megohms, and a datum line has been drawn in Fig. 6 to represent this value. The only uncertainty here lies in the value we choose for a, the ratio for the absorbent part of the insulation. Now although we have seen how mechanical pressure on the absorbent material may cause this ratio to vary from about 1·7 up to as much as 4·3, yet such wide variations have not been found to occur in practice. Probably absorbent materials are always used under compression, but however that may be, the ratio for absorbent insulators under the ordinary conditions of use does not seem to exceed 2·6, and it is frequently as low as 1·8. If these extreme figures are substituted for 2·2 in the above calculation the resulting values for the resistance of the ebonite will be 890 and 640 megohms respectively, instead of 810 megohms. Such variations as these do not in any way affect the utility of this method by which the two components of an insulation may be separately estimated. In general, if the curve of a compound insulation of the kind we are considering shows a ratio as high as 2 we may be sure that the resistance of the dielectric component has fallen to something approaching zero, either because it has broken down in itself, or because it has been shunted by some kind of absorbent dirt. An example of this happens to be available in Fig. 5. This curve was obtained from an ammeter having absorbent insulation in series with ebonite, yet the ratio is nearly 2 and the resistance is much below the normal value for insulation of the kind.

Upon removing the cover of the instrument the ebonite was found smothered in a mass of fibrous dirt which in the course of a dozen years or so had found its way there through a small hole in the case. Upon removing this highly absorbent shunt and cleaning the ebonite the resistance rose to over one million megohms.

It must be remembered that a non-absorbent dielectric in series is not the only cause of a low ratio value. We have already seen in Fig. 17 how the curve flattens out when there is enough absorbed water to form paths of constant resistance in parallel with those which give a typical moisture curve. But under such circumstances the resistance curve will be so very far below the average level which it occupies under more normal conditions that there is no likelihood of the low ratio that is associated with wet insulation being attributed to the presence of a non-absorbent dielectric in series with the absorbent materials.

The percentage degree of absorption at which leakage paths of constant resistance begin to form inside a porous insulator must naturally vary widely in different cases. Judging from the shape of the curves obtained from paper it would appear that so long as the absorbed water does not exceed the amount which is naturally absorbed from the air, leakage through paths of variable resistance is paramount and the normal moisture curve will be obtained. How far paper is typical of absorbent insulators in general remains to be seen.

The experiment of weighing the water has already shown us how small a proportion of the absorbed water is actually utilized in forming the leakage paths which determine the resistance of an absorbent insulator. Referring once more to Table I, we see that under quite ordinary conditions the dormant water may easily outweigh the resistance water by at least 10,000 to 1. The exact proportion is of little importance, but when once the principle governing the disposition of absorbed water inside a porous insulator has been grasped, the confusing phenomena of leakage through moisture begin to arrange themselves in some sort of order.

13. Electric Endosmose in a Model Insulator.

So far the investigation had not suggested any rational explanation of the moisture curve; possibly because the importance of the principle just referred to was not recognized until after the model insulator, which is now to be described, had given a visible demonstration of the cause of the gradual decrease in resistance with increasing potential difference. The explanation given in the following pages was ultimately arrived at, not as the result of previous experiment, but by first considering what was likely to happen when atmospheric moisture condensed inside a porous insulator, and then putting the notion to the test of experiment.

When condensation takes place on the surface of a solid body it first makes its appearance to us in small detached drops clinging to every roughness, every scratch on the surface. If we suppose the solid body to be an insulator of infinite (or at all events immeasurable) resistance, the presence of detached drops of water will not make any appreciable change in that resistance, and the same holds good for the maze of internal surfaces inside a porous insulator when moisture condenses there. But, as we have seen, the absorption of a mere trace of water brings about a vast decrease in resistance; reduces it from an immeasurable value to one easily within the range of our instruments. We cannot suppose the drops to coalesce in order to form a continuous leakage path, because in that case conduction would be simply that of an electrolyte and would follow Ohm's law, leaving the moisture curve unexplained. We must therefore look for connecting links between the drops to establish a complete conducting chain. It would be natural to suppose the links to be films of some kind condensed on the surfaces of the capillary passages in the insulator, and to account for the characteristic curve the films would have to be endowed with a property analogous to that of the electric arc; with increasing electric pressure they must increase their sectional area either by reason of the leakage current they carry, or in consequence of some effect which, like endosmose, depends on the potential gradient. At the time this hypothesis was first outlined it hardly appeared any more likely to contain the germ of truth than half a dozen others that had suggested themselves in the course of research, only to break down on trial. Nevertheless it was put to the test of experiment, and has proved itself capable of accounting for the facts.

To experiment with a series of drops and connecting films deposited on any kind of exposed surface would have led to almost certain failure, owing to the difficulty of protecting the films against currents of air. This liability is almost non-existent inside a porous insulator, where any considerable change in the humidity of the air occupies a comparatively long time, and the consequent changes in the films and their resistance are not too quick for experiment. To imitate this condition of moderate stability it was decided to construct a model insulator by drawing a series of drops of water and bubbles of air into a capillary glass tube, so that each bubble should constitute an enclosed region within which a film could form on the internal surface of the tube and remain there entirely undisturbed by air currents. Glass was not only an obviously convenient insulating material for the purpose, but as it was intended to look for some visible effect of endosmose a transparent tube was essential.

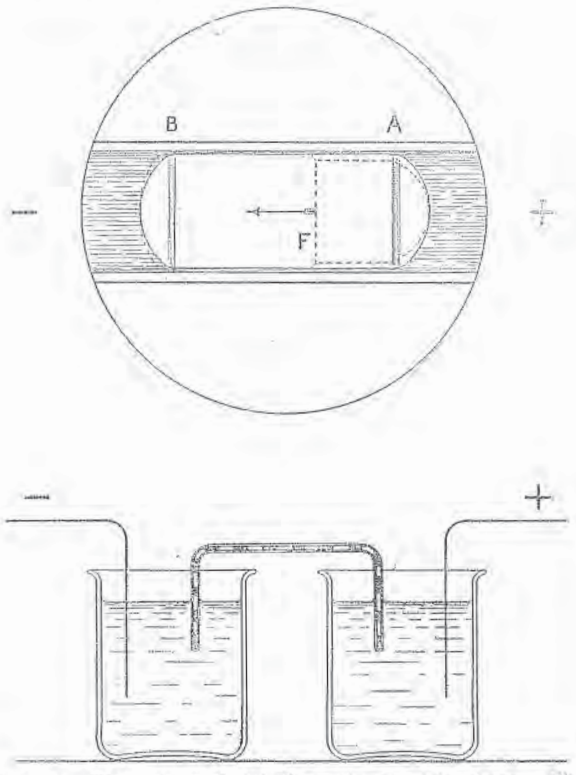

FIG. 27.—Elementary Model of an absorbent insulator. The upper figure represents one of the air bubbles as seen in the field of a microscope.

The glass tube, which was about a couple of inches in length with a bore of 12 or 14 mils, had its ends bent downwards so as to dip into water contained in two small beakers. Before placing the tube in position it was completely filled with a succession of drops of water separated by bubbles of air, the bubbles having an average length equal to four or five times the bore of the tube. Two copper wires, one in each beaker, served as the electrodes. The complete arrangement, as shown in Fig. 27, was fixed under a microscope in such a position that portions of two adjacent drops, with the whole of the air bubble in between them, came within the field of view, as indicated in the upper part of the same figure. At A and B dark transverse lines, corresponding to "Newton's rings," were seen at the end of each drop where the water-air surface approaches the glass at a capillary angle. These lines formed convenient gauges for estimating the initial thickness of the film of water deposited on the glass, and it was apparent that in the neighbourhood of the capillary edges of the drops the thickness of the film did not exceed one-quarter of the mean wave-length of light.

To understand the behaviour of this tube it is necessary to have the principle of electric endosmose clearly in mind, and as this effect is almost inseparable from electricity and water a short account of it may not be out of place in a paper which is so largely concerned with the passage of a leakage current through moisture.

To begin at the beginning. When an electrically-charged body is placed in an electric field it is attracted one way or the other according to whether the charge it holds is positive or negative, the attractive force being proportional to the potential gradient (volts per centimetre). It does not matter what the attracted body is made of; water will do as well as anything else, and, given the proper conditions as regards voltage gradient and so on, it will move. For instance, water which is lying on an insulator in an electric field will be urged towards the negative side of the field and will flow in that direction if it is free to do so. A little scrap of paper jumping up from the table towards an electrified stick of sealing-wax is a more familiar example of the same action. The electrification of the sealing-wax provides the potential gradient, and the scrap of paper moves upwards if the gradient is steep enough.* Both the scrap of paper and the water move for the same reason, and the only difference lies in the mode by which they receive the necessary charge of electricity. In the case of the scrap of paper the charge is induced by the sealing-wax; whereas the water becomes charged by *contact* with the insulator, just as zinc becomes charged by contact with copper. But although no real difference in principle is involved the action goes by very different names in the two cases. When the scrap of paper jumps we are content to say that it does so because it is attracted, whereas when the water moves because it is similarly attracted the action is called endosmose.

Any liquid would exhibit the phenomena of electric endosmose provided two essential conditions were fulfilled. These are that the liquid must be either electropositive or negative to the channel which contains it, otherwise there will be no charge and no force; and its specific resistance must be very high, otherwise it will be impossible to maintain a steep potential gradient inside the liquid without overheating by excessive current. Let an attempt be made to propel mercury by endosmose, and a gradient of something like 50 volts per centimetre would be required to overcome friction. But by the time the gradient had reached 2 or 3 volts per centimetre the resulting current flowing in the mercury would have raised it to boiling-point and the experiment could not go on.

Water, and especially pure distilled water (or condensed

* Thales (500 B.C.), to whom we are indebted for the sealing-wax experiment, does not seem to have laid any particular stress on potential gradient as an essential factor.

water), happens to possess both the essential properties in a remarkable degree. It is strongly electro-positive to all insulators (with the one doubtful exception of hair); and its resistance is from 20 million to 2,000 million times greater than that of mercury, so that it is possible to maintain a potential gradient of several hundred volts per centimetre without any overheating by electric current.

Endosmose may be made visible in a short glass tube connecting two water vessels. By contact with the glass the water in the tube acquires a positive charge which occupies a cylindrical layer of water next the wall of the tube, being held there by the corresponding negative charge in the glass surface. When a potential difference of several hundred volts is maintained between the water vessels, the charged water in the tube is strongly attracted towards the negative vessel and moves in that direction down the potential gradient. This movement is confined to the charged layer and such water as it can drag along with it, and when the bore does not much exceed half a millimetre the whole of the water will be set in motion and may be seen travelling slowly towards the negative end of the tube.

Endosmose has been chiefly studied as it appears in glass tubes and in the capillary passages inside porous materials; hence the name, which may be clumsily translated "within-propulsion." But the name must not mislead us. It is not essential to have the water *within* anything; all that is necessary is that the water should be lying in contact with an insulator and forming a conducting path between two electrodes. Then, if the voltage gradient between the electrodes is steep enough, and the water is free to move, it will find its way towards the negative electrode whether there is any definite channel for it to run in or not. But without some kind of trough or tube the water is apt to go by all sorts of devious ways towards its goal, and the confused motion becomes difficult to follow by eye.

To return to the experimental tube with its chain of drops and films. On applying an electromotive force to the electrodes in the two beakers the effect of electric propulsion or endosmose was at once apparent. On closing the circuit the surfaces of the two drops visible in the field of the microscope instantly changed their curvature, the positive surface A pushing its edge out towards the negative side of the field of view, and the negative surface B decreasing its curvative by withdrawing its edge inwards. The dotted lines in Fig. 27 indicate the general nature of this effect, but grossly exaggerate the extent of the change. If the film connecting the two drops happens to be visible* every part of it is seen to experience a sudden force pushing it towards the negative side. The effect of the hydraulic pressure produced in the drops by the electric propulsion is seen at the same time; a stream of water is forced out from the edge of the positive drop and flows rapidly towards the negative drop, increasing the thickness of the film as it goes along. The advancing wave front (F in Fig. 27) of the travelling water is clearly visible, and if the potential difference is gradually increased, the growing thickness of the now moving film is made apparent by its assuming, one after another, the colours characteristic of thin films.

The sectional area of the films is of course exceedingly small compared with that of the drops and hence the resistance of a complete tube of given diameter is determined almost entirely by the aggregate length and mean thickness of the films, the resistance of the drops being negligible by comparison. The visible increase in the thickness of the film will therefore be made evident also by a concurrent fall in the resistance of the tube, and if a series of tests be made at gradually increasing potential differences the characteristic curve of the tube as an absorbent insulator may be drawn. In Fig. 28 a curve of this kind has been plotted from tests made on a glass tube about 1·5 in. long and 13·5 mils bore, containing water separated by 12 bubbles of air, each of which provided a film length of about 70 mils. The early part of the curve is smooth enough, but the current became increasingly unsteady as the voltage was increased and accurate observation was impossible at the higher readings.

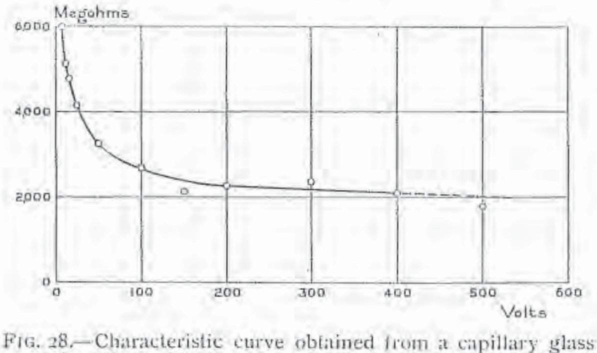

FIG. 28.—Characteristic curve obtained from a capillary glass tube filled with drops of water and bubbles of air, and arranged as shown in Fig. 27.

When the electromotive force is cut off, the surfaces of the drops are instantaneously restored to their normal shape. The surplus water in the films then withdraws very slowly into the adjacent drops, until, after a period which may be hours rather than minutes, the films are reduced to their initial thickness and the resistance of the tube recovers its initial value. The extreme slowness both of the initial formation of the films and their recovery after the application of any considerable potential difference, was not fully realized until the results of all the tests made on tubes were collated some time after the conclusion of the experiments. It then became apparent that the majority of the tests made with single tubes had been carried out before the films had settled down into a normal condition, and their instability naturally led to large discrepancies, particularly at the higher voltages.

But a single tube, one capillary channel, could hardly be expected to give a faithful imitation of a real insulator. Much better results have been obtained from models composed of a number of similar tubes connected in parallel, particularly when they have been given ample time to settle down into a normal condition. The three curves in Fig. 29 were obtained from a model made up of 13 tubes in parallel, curve A being taken 20 hours after filling the tubes, and curves B and C at 44 and 98 hours respectively. In these tests leakage along the external surfaces of the

* The film is only visible when parts of it are thick enough to give some of the colours of Newton's rings. If its thickness is much less than a quarter of a wave-length the film cannot be seen

tubes was eliminated by guarding each tube, and in order to ascertain whether the guard wires upset the uniformity of the potential gradient, a fourth curve D was taken at 113 hours with the guard wires removed. This curve so closely follows curve C that to avoid confusion the mean values of the observations in the two tests have been plotted in Fig. 29 as a single curve representing both C and D.

Reckoning from the average of these four curves the ratio R_{50}/R_{500} is 2·1, a figure which agrees surprisingly well with the average ratio 2·2 obtained from absorbent insulators.

Hysteresis, which is such a marked feature of the moisture curves of real insulators, is equally characteristic of the model. In each series of tests upon the model the return curve obtained by retracing the voltage steps from

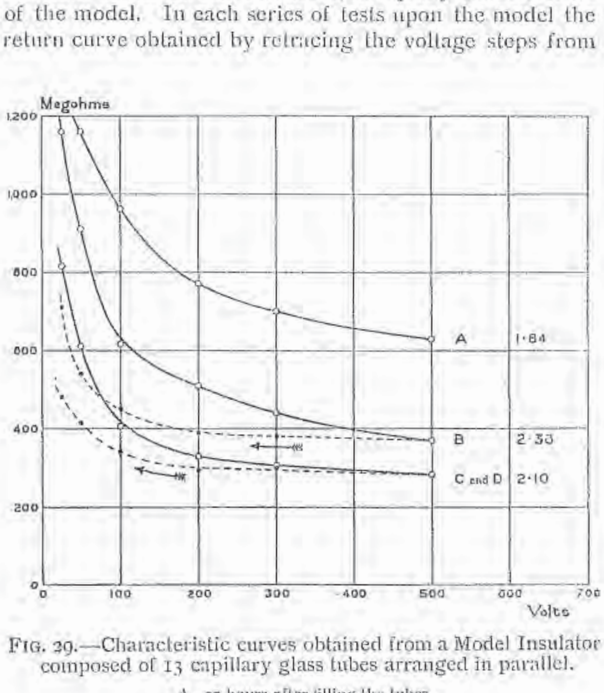

FIG. 29.—Characteristic curves obtained from a Model Insulator composed of 13 capillary glass tubes arranged in parallel.

A 20 hours after filling the tubes.
B 44 ,, ,, ,, ,,
{C 98 ,, ,, ,, ,,
{D 113 ,, ,, ,, ,,

500 back to 25 volts has indicated a pronounced hysteresis effect. The return curves obtained immediately after curves B, C, and D, have been included in Fig. 29, and should be compared with the examples of hysteresis in real insulators which have been given in Figs. 2 and 5.

The general resemblance of the curves given by glass models to those which are characteristic of absorbent insulators is evident. In the decreasing resistance with increasing voltage, in the extent of the decrease, in the slow recovery or hysteresis, even in instability, the films and drops possess properties which are common to every absorbent insulator. The dormant water which we found in the pad of paper is here in the drops, and the resistance water is visible in the films which link the drops together into a conducting chain, and provide the high resistance.

But in one matter a simple model composed entirely of open tubes differs fundamentally from a porous insulator. The first effect of heating an absorbent insulator is to bring about a very large decrease in resistance. Heat this too simple model, and the expanding air bubbles lengthen the films and increase the resistance.

But, after all, the structure of the model is not much like the real thing. For the tangled maze of interconnected channels in a porous insulator the model substitutes a number of parallel channels, each going without a break from one electrode to the other; it contains no blind alleys and no cross-connections. Hence in the model the proportion of dormant water falls far below the proportion which we have found by weighing the water in the real insulator. How far below can only be estimated when the thickness of the films is known.

14. THICKNESS OF THE FILMS.

The net resistance of a measured length of film in a glass tube containing drops of water of known conductivity enables the thickness of film to be estimated, on the assumption that it is uniform. Reckoned in this way the films in the tube which gave the curve shown in Fig. 28 had a thickness not exceeding 10 millionths of an inch. The films are of course very far from being uniform in thickness and hence this figure is only a rough estimate.

One of the films in the same tube was measured by the method of Newton's rings, which gave the value 5·5 millionths of an inch.

The two measurements were made at the same time, the films having the maximum thickness corresponding to a potential difference of 500 volts. The two values do not differ more than one would expect, and as the second method is the more accurate we may say that in this tube the thickness of the films was about 6 millionths of an inch when swollen by the action of endosmose. Hence judging by the concurrent decrease of resistance, their initial thickness must have been about 2 millionths of an inch. This is so much less than one-quarter of a wave-length of light that in the initial state the film had no perceptible colour by which to estimate thickness.*

15. DORMANT WATER IN THE MODEL.

We can now estimate the proportion of dormant water to film water in the model. Most of the tubes have been about 2 in. in length, and about half the length has been occupied by films and the other half by water. The bore of the tube being about 14 mils, its perimeter is 44 mils. The initial thickness of the film was $2/10^6$ in. $= 2/1{,}000$ of a mil, and the aggregate length of film was about 1,000 mils. Hence the volume of water in the films was about 88 cubic mils.

The sectional area of the drops is 154 sq. mils, and since they occupied about half the length of the tube their aggregate volume was about 154,000 cubic mils. Hence the ratio of dormant water to film water was 154,000/88 $= 1{,}750$. That is to say for one part of water in the films there are something less than 2,000 parts of dormant water.

Now in a real insulator the corresponding proportion is, as we have seen, much more like 10,000 or even 100,000 to 1; from 5 to 50 times as much. To represent reality in this respect it would be necessary to build up a model with

* The wave-length at the sodium line in the spectrum is 23 millionths of an inch. It is worth noting that at its thinnest the film has depth for about 170 molecules.

a very large number of closed tubes in addition to the open or conducting tubes, and to interconnect the two sets, by numbers of cross tubes. When the whole assemblage was filled with water and air it would form one hydraulic system, although electric conduction would still be confined to the open tubes. The whole of the water, both in the open and in the closed tubes, would be attracted towards the negative electrodes, and at every place where there happened to be a convenient junction between a closed tube and an open one, dormant water might be driven out into the latter and assist in swelling the films in the conducting channels.

16. The Properties of a Model Insulator.

Heat this complex model and the expansion of the trapped air * in the closed tubes will drive a large volume of dormant water into the conducting channels. At the same time the expansion of the air in the open tubes may have lengthened or even broken up some of the films, but remembering that the closed tubes may contain perhaps fifty times the volume of air and water, it is evident that the quantity of dormant water forced out from the blind alleys will be enough to flood the conducting channels, quite apart from what may happen to individual films. The flooding of the conducting paths naturally brings about an enormous fall in resistance. Lower the temperature and the air bubbles throughout the system will contract and the flood water will retire into the blind alleys The films then slowly recover their initial thickness as the surplus water is forced out of them by the tension of the water-air surface, and the resistance rises to its former value.†

Another remarkable property of absorbent insulation finds a ready explanation in the model with its tubes full of drops and films. Over and over again in the course of the investigation a number of moisture curves have been obtained under widely different conditions as regards the quantity of absorbed water. Yet the curvature of the characteristic has remained practically unchanged throughout the whole series of tests notwithstanding the enormous changes in the general level of resistance which accompany changes in the amount of absorbed moisture. This permanence in the shape of the curve has already been referred to, and in view of what has been demonstrated by means of a bundle of capillary glass tubes the explanation is clear. Place a damp insulator in a dry atmosphere so that evaporation takes place. Evidently the more accessible films will evaporate first, followed by film after film, and the least accessible and thickest films will be the last to go. But as each film gives more or less the same sort of curve, the curve from a few dozen film channels in parallel would be indistinguishable in shape from the curve obtained when there were hundreds or thousands of films acting as parallel leakage paths. Hence so long as a few film channels are left intact—just enough to carry a measurable leakage current—the resistance-voltage curve will retain its characteristic shape. We now realize why it was that a piece of impregnated paper cable which had absorbed a trace of water, giving a resistance of several hundred thousand megohms, had a characteristic curve of the same shape as that obtained from a dynamo armature the resistance of which was less than a dozen megohms. The curve is characteristic of the film with its adjacent reservoirs of dormant water; the magnitude of the conductance is simply a question of the number of film paths acting in parallel.

The marvellous rapidity with which the resistance alters when a change occurs in the humidity of the air is of course attributable to the extreme tenuity of the films.

All these phenomena should become visible in a complex glass model if only we had skill to make it. But, after all, the necessary complexity is available in every porous insulator, for there we have a tangled system of innumerable conducting channels, cross connections, and blind alleys, ready made; an elaborate natural system which could not be imitated by any artificial arrangement of a few glass tubes. If we direct our mental vision to the inside of a real absorbent insulator we shall see a bewildering number of channels occupied by films and drops in which the same kind of actions are going on as those which are visible in the glass tube; and mingled with the elaborate hydraulic system there will be a quantity of air, some of it—perhaps a large proportion of it—trapped in blind alleys by plugs of dormant water, and always ready to expand when heated and drive the water out into the conducting channels.

17. Summary and Conclusion.

This vision of what goes on inside an absorbent insulator, misty and imperfect as it is, provides an explanation in general agreement with the facts. In putting it forward the author is conscious of difficulties and obscurities which leave the mind doubtful, but the doubts are just those which come from ignorance of the precise structure of absorbent bodies and the mode in which they harbour moisture. In all probability the microscope would dispel a good deal of this cloud of ignorance if it were applied to some typical material like a thread of cotton.

But the facts which have emerged from the investigation leave no room for doubt as regards the main characteristics of insulation resistance under working conditions.

The true dielectric resistance of insulation is enormous compared with the actual insulation resistance obtained in practice, and in all ordinary cases we need only consider the leakage which takes place through films of moisture condensed on the external and internal surfaces of the insulating material. Dielectric leakage is insignificant and may be left out of account.

The quantity of water in the conducting films of moisture is not only very small, but it forms an exceedingly small proportion of the whole volume of absorbed water.

Impregnating an absorbent insulator with oil or varnish delays the absorption of water and no doubt limits the amount absorbed, but it does not prevent the ultimate formation of the moisture films which constitute leakage paths.

Conduction through absorbent insulation does not follow Ohm's law. The relation between the resistance of an absorbent insulator and the potential difference which is

* Inside a porous insulator containing a normal amount of moisture the volume of air will vastly exceed the volume of dormant water, and there must be innumerable bubbles of air trapped inside capillary spaces by drops of water.

† The above explanation of the action of heat on absorbent insulation has its origin in a suggestion made by Mr. A. Campbell and embodied by Mr. E. H. Rayner in the report on Temperature Experiments at the National Physical Laboratory (*Journal I.E.E.*, vol. 34, p. 624, 1905).

applied to it is expressed by a curve which is characteristic of conduction by films and drops.

When the absorbed water exceeds the amount which the material can hold in the form of dormant water and leakage films it begins to form conducting paths of constant resistance. Hence the moisture curve gradually decreases in curvature as absorption goes on, and ultimately when the resistance has fallen to a very low value the curve is reduced to a horizontal straight line, indicating conduction by Ohm's law.

In compound insulation consisting of an insulator in which conduction follows Ohm's law, in series with an absorbent material which follows the law of moisture conduction, the resultant curve has less than the normal curvature.

The degree of curvature in the characteristic curve of compound insulation enables the resistances of the two components to be separately estimated.

In compound insulation a curve of normal curvature indicates failure of the dielectric component. A straight horizontal "curve" (Ohm's law) indicates failure of the absorbent component.

Finally, the broad principle of film conduction in an absorbent insulator is clear; the moisture curve—the first part of the complete characteristic curve—is the direct result of electric endosmose. The electrically produced hydraulic pressure drives dormant water into the films, and their increasing thickness is made evident by the gradual fall in resistance as the potential difference is increased.

At what point leakage through moisture becomes dangerous; whether the ultimate effect of prolonged endosmosis is to safeguard the insulation by driving all the water away from the positive conductor in a continuous-current system, and from both conductors if the supply is by alternating current; whether it is possible to predict the breakdown voltage—these and other questions can only be answered by an investigation of the second part of the characteristic curve. Preparations for this are not yet complete, and so far it has only been possible to extend the curve to the breakdown point in one or two simple cases for which the voltage already available proved sufficient. In these examples the curve began to bend downwards at pressures well below the breakdown value, thus indicating the impending failure without exposing the insulation to the risk of permanent injury. It remains to be seen whether this useful effect is general, or whether, as seems more probable, it is confined to insulating materials in which failure begins along already existing leakage channels. It is a significant fact that in the model insulator breakdown begins in the form of sparking along the films from one drop to another. Questions of this kind go to the very root of the matter. It is customary to account for breakdown by dielectric stress; a blackened hole appears in the insulation and the inference is too hastily drawn that the puncture process was instantaneous and could not have been foreseen by any kind of test. But nothing in Nature, not even an explosion, takes place instantaneously, and the breakdown of an insulator is only sudden to the mind that does not apprehend it.

The time may never come when it is possible, by systematic insulation testing, to forestall breakdown by diagnosis of the disease and removal of the cause. To-day the problem as a whole looks wellnigh insoluble, and with no visible goal ahead of us we must be content to gain a clearer insight as we go along in more or less the right direction. That road is always open to us and the author hopes that facts recorded in this paper may serve as stepping-stones on the way.

NOTE.—The whole of the experimental work has been carried out at Acton-lane works by Mr. S. F. W. Finnis, to whom the author is greatly indebted for the skill and patience with which the laborious and in many cases difficult experiments were conducted. Not the least among many difficulties was the necessity for carrying on the investigation without interrupting the ordinary work of the Experimental Department of which Mr. Finnis has charge. The author also wishes to thank Mr. B. Welbourn of the British Insulated and Helsby Cables Company for his kindness in providing samples of paper cables and the oil and paper used in their manufacture, together with data relating to the specific resistance of these materials. It is always a pleasant task to make acknowledgment of the help which is so freely given by one member of the Institution to another.

APPENDIX.

INSULATION VALVES.

The effect which polarity has on the resistance of some kinds of insulation has been known from the early days of telegraphy in connection with overhead wires run on earthenware insulators. The same effect is frequently met with in testing the insulation resistance of electric-light wiring. So far as the author is aware it was first traced to porcelain insulators by Mr. Bernard Holt. Writing from Perth, West Australia, to the author's firm, Mr. Holt has described some remarkable instances of valve action which he has come across. A new installation of interior wiring, when tested from one wire to the other with the switches open, gave 1·5 megohms with the testing voltage in one direction and 9 megohms when the polarity was reversed. Another installation gave a similar result and, by elimination, Mr. Holt traced the effect to the switches. One of these when removed from this installation and tested for insulation resistance from one terminal to the other, differed in resistance by several hundreds per cent according to the polarity of the terminals. The switch was of the ordinary tumbler pattern mounted on a china base.

The author has had no difficulty in verifying Mr. Holt's tests in every particular. House wiring, whether tested from wire to wire with the switches open, or from the wires to earth, often shows a valve effect. Porcelain base switches of inferior quality have invariably acted like valves. On the other hand, switches of the best quality in which well glazed china is used gave resistances from about 100 megohms up to several thousand megohms, and it was only when the resistance was well within the range of the ohmmeter used for these tests that a valve action could be detected. It is probably inherent in every earthenware insulator. A number of switches of good quality were found to give 10 megohms or so with the voltage applied in one direction, and over 100 megohms when the testing leads were reversed, the rise in resistance being practically instantaneous. Apart from the highly insulating glaze, earthenware is something between a rather good conductor and a very poor insulator, but it need hardly be pointed out that if a switch base were covered in every part, including all screw holes, with a good glaze which was entirely free from cracks, the resistance between terminals or from terminals to earth would amount to several thousands or even millions of megohms. Such high values would indicate a needless perfection and are no doubt unattainable in practice, but when we find many china bases of poor quality giving not more than one or two megohms each, even in dry weather, we naturally begin to inquire why some limit should not be set to the discontinuity of the glaze. A resistance of two or three hundred megohms would at least be an indication that the glaze was well applied and reasonably free from cracks.

To ascertain the cause of the valve action, tests were made on a flat block of porcelain of good quality. The resistance being far too great for easy measurement, the glaze was partially removed by grinding in order to approach the condition of an ordinary switch base and at the same time obtain a smooth flat surface. Three small electrodes, A, B, and T (see Fig. 30), were secured to

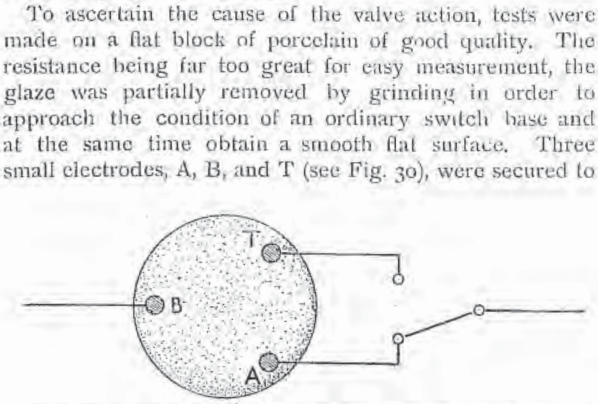

FIG. 30.—Glazed Porcelain Block fitted with three electrodes for investigating the polarity or "valve" effect.

the surface, and the method of experiment was to measure the resistance of the path A B and compare it with that of the path T B, the region round B being common to both paths. Current was never allowed to traverse the path T B for more than two or three seconds at a time—just long enough to allow the ohmmeter reading to be noted—and hence any substantial increase which might be observed in the resistance of this path would be confined to the neighbourhood round electrode B and would be the result of current flowing in the path A B. It was found that when current, flowing in either direction, traversed the path A B the resistance of this path gradually rose until by the time the current had been flowing for half an hour or so the resistance would be twenty or thirty times the initial value. By cutting off the current in A B and immediately taking the resistance of the reference path T B, it was at once seen whether the increase in A B had taken place at electrode B or not. In this way it was proved that when electrode B was positive, practically all the increase in the resistance of A B occurred at or near B; and when that electrode was negative then no material change took place there. That is to say the increase in resistance that results from the leakage current is almost entirely confined to the region round the positive electrode, the conductor where the current enters the earthenware. In one experiment the initial resistance of the path A B was 40 megohms, and on switching on the testing current, which in this instance entered the porcelain at A, the resistance rose to several thousand megohms in the course of two or three minutes. During this time the reference path T B changed from an initial value of 8·0 megohms to a final value of 8·2 megohms. Hence of the enormous increase in the resistance of A B only 0·2 megohm occurred in the region near the negative electrode B; practically the whole increase took place in the region of the positive electrode A.

By making both the electrodes very small, the resistance-change may be made to take place almost instantaneously, no matter which way the current flows. If one electrode has a smaller area than the other then the change will take place more quickly when the current enters the china at the small electrode than it does with the current going the other way. By using one very small electrode and one of fair size, the increase is easily made to occur so quickly when the small electrode is positive that it will appear to take place instantaneously, whereas when the electrode of large area is positive the change may take place so slowly that no material alteration will be detected in the time occupied by an ordinary insulation-test. The word "area" is used here in rather extended sense, for it is clear that a metal piece having a large area in contact with the glazed surface might act as an electrode of small area if there happened to be only a few small cracks in the glaze available for the passage of current from the metal into the body of the earthenware. In this connection it would be more precise to refer to access to the interior of the insulator than to area, although the two sometimes mean the same thing.

Access-area is frequently the result of accidental circumstances. The screw holes in a porcelain base are often insufficiently glazed, and hence the fixing screws for the terminal pieces are apt to have rather easy access to the conducting earthenware beneath the glaze. It is a matter of chance which of two screws will have the better access, and although any individual switch may show a marked valve effect simply because one terminal has a better access than the other, yet a complete installation of similar switches may show no such effect, because they are coupled up to the wiring without any regard to valve direction, and the installation could only show a polarity effect if there chanced to be more valves opening one way than the other.

But chance is not always the governing factor. Where there is some systematic difference in access-area, arising out of constructional features and accompanied by a systematic coupling to a circuit, there the circuit as a whole will show the valve effect. An overhead telegraph line is a good example. At every insulator the line wire, and its binding on the well-glazed surface of the insulator, has a far smaller access-area than the fixing bolt embedded inside the earthenware. Such a line will have a higher insulation resistance to earth when the line is made positive than it has when the polarity is reversed. Electric wiring when tested from circuit to earth will show the valve effect for much the same reason.

The increase in resistance at the positive electrode seems to be due to the clogging of the leakage channels, both the cracks in the glaze and the capillary passages in the body of the earthenware, by the products of electrolysis. But it is significant that the valve effect is almost as great when platinum electrodes are substituted for the usual brass pieces. In this case oxygen alone is produced at the positive electrode, but some chemical change evidently takes place in the region near the electrode because even with platinum the earthenware is observed to become discoloured, and the resistance remains at the increased value for 24 hours or more after cutting off the leakage current. This seems to point to some solid non-conducting substance choking the pores of the insulator. The action of endosmose in driving moisture from the positive towards the negative electrode must not be overlooked. If in this way the water were driven out of the cracks in the glaze near the positive electrode, a very large increase in resistance might easily take place. But upon the whole the facts point to clogging by the chemical action accompanying electrolysis, although endosmose may play a subordinate part.

An installation of wiring, which when new may have no valve action when tested from wire to wire, will soon acquire it if the supply is by continuous current. In this case the positive side of every porcelain switch base becomes so clogged by the prolonged electrolysis which goes on whenever the switch is open, that a systematic difference in access-area comes about, the positive terminals in contact with the clogged earthenware acting as the electrodes of small access-area.

The insulation valve is thus seen to be closely related to other well-known electrical valves which depend for their action on the two electrodes having widely different freedom of access to an electrolyte. Glazed earthenware seems peculiarly well adapted to produce a valve effect, but no doubt other porous insulators may be found to act in the same way.

As to the question whether the normal resistance or the abnormal is to be taken as correct, the answer must be that both are real, both are effective in preventing leakage. In a continuous current system the higher value is the one which actually governs leakage if the polarity of the system remains unchanged. But in telegraphy this is not always the case, and it is no doubt advisable to carry out insulation tests on overhead lines with the line wire negative and use the lower resistance value, so obtained, in estimating the signalling capacity of the circuit.

NOTE.—In introducing the paper the author gave an experimental demonstration of the moisture effect by means of a mirror ohmmeter having a scale 30 feet in length and easily visible to a large audience. Measurements of insulation resistance were made at a series of ascending voltage of (1) a dynamo, (2) a varnished winding, (3) the skin of the hand, and (4) a model insulator composed of a bundle of capillary glass tubes filled with water and bubbles of air. Two moisture curves plotted from the readings so obtained are given in Fig. 31. The readings were noted by Mr. E. B. Vignoles.

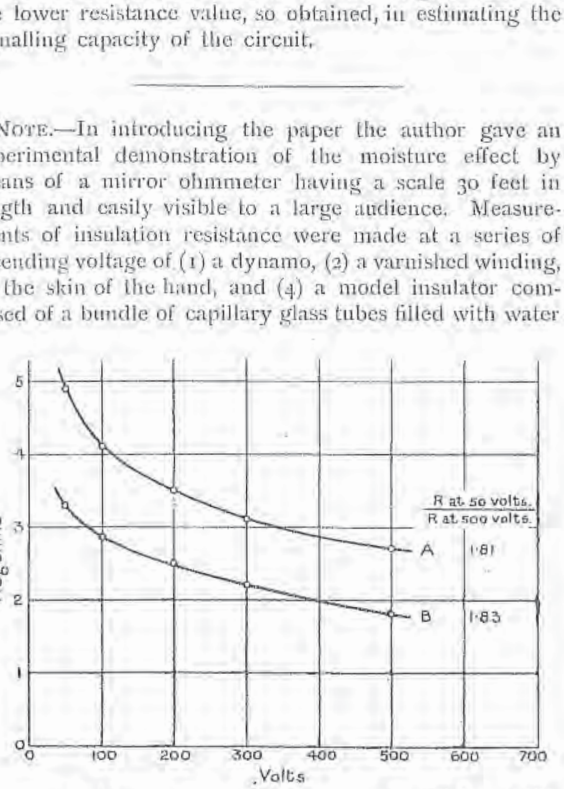

FIG. 31.—Moisture Curves plotted from readings taken in the course of the experimental demonstration at The Institution of Electrical Engineers, on 27th November, 1913.

Curve A: Insulation Resistance of a Dynamo, lent for the experiment by Mr. W. Clark.
Curve B: Resistance of a Model Insulator prepared by Mr. Littlejohn, composed of a bundle of capillary glass tubes.

DISCUSSION BEFORE THE INSTITUTION ON 27TH NOVEMBER, 1913.

Professor Silvanus Thompson.

Professor SILVANUS P. THOMPSON: I think that Mr. Evershed's paper will be, at any rate for some years to come—if not for more than some years—a standard of reference, and we shall look back upon it as a very definite and notable contribution to our knowledge of a very ill-explored but important branch of our science. We have known all too little about the conductance of insulators, and I think we shall be particularly indebted to Mr. Evershed for having directed our attention to what is very rightly called the characteristic curve of insulation resistance. It may be that we shall not always express ourselves in the same terms; it may be that we shall perhaps not always take exactly the ratio of the apparent resistance at 500 volts and at 50 volts; but at any rate, whatever we do in the future, we have now a datum to start from. Mr. Evershed suggests the measured resistances at 50 volts and 500 volts as furnishing a pair of points of reference, with a curve joining them which we can compare as between one substance and another to see whether they behave alike in their conducting properties; and for that definition, if for nothing else, I think this paper is valuable. It will be our own fault if, having now the means of measuring the insulation resistance in other cases and with other materials, we do not choose to follow the lead that Mr. Evershed has given us, and produce characteristic curves which shall be comparable, in the way in which they are made and plotted, with his. He has laid the foundation, therefore, for a certain definite advance in our knowledge and our means of expressing our knowledge on this subject. When I have said that, I have not said what is perhaps even a greater matter for those of us who have listened to Mr. Evershed; again and again throughout his paper he has given us excellent suggestions, hints, and points to excite our curiosity and our imagination as to what it is that is going on—as to what are the physics of this particular process of the leakage of electricity through the substances which are commonly called insulators. We must all have been impressed, for example, Professor Silvanus Thompson.

with that exceedingly beautiful arrangement of films of water in capillary tubes to imitate by known appliances the behaviour of the water in the pores of solids. When he asked us to think of these porous channels ramifying about in all manner of tortuous directions, having blind ends and holding dormant water which could not take any part in the conductance because it led nowhere, when he gave us this *aperçu*—this vision, as it were—of the interior of a solid, surely we carry away with us a picture in our minds which we can fill up at leisure as more knowledge comes, and we shall be better able to grasp what is going on in materials when we make measurements in the laboratory or in the workshop.

One of the most important points comes out strongly; that is, how very little of the water that is absorbed by an insulator takes any part in the operation. Although it may be that only one-millionth part of the whole of the water is really conducting the leakage current through it —and how difficult it is to stop that millionth!—is it not a most remarkable fact that no chemical substance has yet been found with which to impregnate paper or any of those cellulose materials so as effectively to stop those minute channels? We may parchmentize the material and get rid of its fibre; we may what is termed vulcanize it; we may impregnate with vitriols, oils, fats, and all manner of varnishes, etc.; but we are continually eluded by the water which for ever manages to permeate through the cellulose material. It may be that some day a chemical discovery will be made which will enable us to impregnate paper so that it shall not conduct; but that discovery has yet to be made. How many of us would be glad of a paper product which would insulate, say, as well as ebonite, to say nothing of gutta-percha, or ivory, or amber.

Among the things that come out clearly in this paper, and from what Mr. Evershed calls the instability of the liquid film, is that we do not get a constant insulation resistance or insulation conductance of moisture unless a considerable number of channels are in parallel. The significance of that, if we analyse it, is surely that conductance in a liquid is connected with movement—with the movement of the liquid itself, of the molecules or ions; because such liquids never conduct without being ionized. There is always chemical action in that sense going on, and that means movement. We may have looked in old text-books at the pictures of molecular chains across an electrical cell, and perhaps we have looked in vain for them through our microscopes: yet something very closely akin to this may be seen. If we place on a slip of glass in a microscope a film of a liquid which includes minute particles of, say, gamboge paint (a resin), or minute globules of milk, and examine the liquid when a current is passed through it, we should not see molecular chains, although we shall see small particles; but these are not in rows as represented in text-books. On the contrary we should notice lively movements, chains of twos and threes dodging about. Conductance through a liquid is always a phenomenon of lively movement, and that is going on in these tubes. Unless we can obtain a sufficient number of paths to regularize out the movement in any one chain, then, of course, we get instability. We only get statistically a kind of stability that will permit of steady measurement.

In Fig. 5 Mr. Evershed showed us the decrease of the resistance as the voltage is increased, and how the curve returns back on itself with what he, in a rash moment, described as a kind of hysteresis. We must be very careful about the use of the word "hysteresis." To my mind, if one wishes to study hysteresis one must pursue a phenomenon right round a cycle. But what would happen if the voltage were repeatedly raised to 500 and reduced to zero? Would a loop be obtained? A zigzagging curve would result until a stable bottom was reached. Mr. Evershed assures me that ultimately a loop is obtained. I am pleased to hear that, because we may be able to calculate something from that loop. I should like Mr. Evershed to deal with that point in his reply.

There is one important criticism I should like to make. I must protest most emphatically against the notion that there are any substances which do not obey Ohm's law. Ohm's law is true under all circumstances for every kind of conductor, or insulator, or current, or anything else. It depends entirely on the definition of "resistance." I do not know any way of ascertaining the resistance of a body except by passing a current through it; the name "resistance" is given to the ratio between the electromotive force that is supplied and the current which results. That is Maxwell's definition. What Mr. Evershed undoubtedly meant, and what those people mean who say that something does not obey Ohm's law, is that the resistance is not constant. When conducting a current the resistance of some substances changes because the molecular condition is being altered. If we think of a liquid carrying a current, and of all the molecular movement that is going on, can we expect the resistance to be constant whether the current is flowing or not? No, the resistance decreases as the current is increased; but Ohm's law is still true, for E/R still equals I. It is sometimes said that Ohm's law is not true if there is a back electromotive force; but so long as we do not disregard the back electromotive force Ohm's law is still true. Some people, again, get the idea that Ohm's law is not true for an alternating current merely because they neglect to insert in the equation the back electromotive force due to the reaction of self-induction. I do not know a single thing that does not obey Ohm's law. Not even in the voltaic arc is Ohm's law violated.

In conclusion, I venture to suggest to the world of electricians that to shorten the phrase "insulation resistance" we should use the term "insulance."

Mr. Beaver.

Mr. C. J. BEAVER: While the paper is of more direct interest to makers of electrical machines, instruments, and apparatus than to cable-makers, we are all very much indebted to the author for his collation of facts and the very interesting demonstrations he has made, particularly those with the model insulator. Most of the phenomena referred to in the paper are familiar to cable-makers, who have always recognized the necessity for protecting fibrous insulation by non-absorbent coverings such as lead, and thereby sealing off the insulating material from contact with moisture. They have always recognized that it is impossible to maintain efficient insulation resistance in absorbent dielectrics, however well dried and impregnated these may be originally, unless such seals or barriers against moisture are employed. The absorbency of fibrous materials is due to capillarity, which means a much greater susceptibility to moisture than would be due to other effects such as condensation, Mr. Beaver.

deliquescence, etc. The capillarity of fibrous materials such as those mentioned in the paper is due not only to the structure of the paper or woven fabric as a body, but also to the capillarity of the individual fibres themselves. The sequence of events demonstrated by the characteristic curve for cotton (Fig. 1) corresponds exactly to the cable-makers' experience as to what happens during breakdowns from moisture faults. The osmotic effects illustrated by the first part of the curve merge into the formation of electrolytic products in the dielectric and incipient charring in the second part, passing to final breakdown in the third part of the curve. With regard to the general character of the moisture curves shown for the various kinds of absorbent insulation and moisture films, I would point out that the fall in resistance with increase of testing voltage is simply a matter of the electrodes not making contact with the virtual conductor contained in the non-conducting mass of fibrous material. Imagine a range of materials varying from conductors, through absorbent and therefore imperfect or variable insulators, to non-absorbent insulators. At each end of the range we get a constant relation between resistance and voltage, but in the intermediate materials we apparently do not. The reason obviously is that the conducting component of these materials moves about in the cellular structure; in other words, the insulating and conducting components do not form a homogeneous mixture and are not uniformly distributed, therefore we do not make efficient contact with the conducting component and do not get a conductivity proportional to the resistance of the two components. To take a simple parallel, if we set out to measure the resistance of a stranded conductor, say of aluminium, the strands of which are making bad contact with one another, we should have to connect up every wire of the strand to the test leads before we obtained a true result. The reason for the difference between the curve for oil containing water (Fig. 21) and oil-impregnated paper also containing moisture (Fig. 22) becomes obvious when viewed from this standpoint. In the former we have a homogeneous mixture, and in the latter a collection of substances, the conducting component of which cannot make contact with the test electrode.

The "valve effects" referred to by the author have been well known in cable practice for very many years. It is because of these effects that factory tests on cables are always made with a negative current. In Government and other standard specifications it was customary until a few years ago to specify that cables should be tested with both positive and negative currents, and the results compared. A difference of not more than 5 per cent in the insulation-resistance figures thus obtained rendered the cables liable to rejection. The custom lapsed because in course of time cable manufacture arrived at such a stage of perfection that the test with negative electrification could be solely relied on. The various hysteresis effects noted by the author are probably closely connected with "valve effects." In relation to Fig. 8 the author refers to the real dielectric resistance of cables as compared with what he calls the customary resistance. It may be of general interest to point out that the customary method of testing the insulation resistance of cables by "loss of charge" is the only practical method. The real dielectric resistance is much greater than is indicated by the nominal grade or guaranteed figures. It may also be pointed out that the steadiness of the rate of "loss of charge" gives a valuable indication as to the soundness or otherwise of a cable under test, which is quite independent of the observed value at the end of the standard one-minute electrification. It is obvious that to measure the real dielectric resistance can give no advantage for cable-testing purposes over the conventional method, and the enormous difference in time required would necessitate the ratio of works area to test room area being inverted. Porcelain has been referred to in the paper and the appendix as an absorbent material, but it is not necessarily so. Porcelain can readily be obtained which is so thoroughly vitrified throughout its mass that it is non-absorbent and does not depend on its glazing for non-absorbency.

Finally, I can hardly agree with the statement contained in the author's conclusions, that it is customary to account for breakdown by dielectric stress. As a matter of fact the primary cause of a breakdown is hardly ever dielectric stress *per se*. In the vast majority of cases, whatever the primary cause, the presence of moisture is almost invariably found to be the chief contributory cause, and as the author's work appears to confirm very conclusively my opinions in this direction, the logical conclusion to my mind is that absorbent materials should be used as little as possible for general insulating purposes unless they can be either absolutely protected—as in the case of the paper-insulated cable—from access of moisture, or free to dry out under working conditions. There are other electrical points of view from which this is highly desirable, but they do not come within the scope of this paper.

Mr. Wordingham.

Mr. C. H. WORDINGHAM: The author has referred to "blind" tests, by which he means applying a high pressure and not knowing what goes on. I quite agree that such tests are very unsatisfactory and very unscientific; but I must say that, in my experience, I have found them exceedingly useful, and I am content to wait, as I have been waiting for a great many years, for Mr. Evershed to provide means to enable us to know what is going on. I should like to ask Mr. Evershed what is the date of Mr. Holt's experiments in Australia with the switches with porcelain bases. I know that about 1892 or 1893 Dr. John Hopkinson, with Professor Ernest Wilson's help, rather carefully looked into the effect of electric endosmosis, and I know that for some months after I had a good deal of experience with electric endosmosis on underground mains, largely on rubber cables in pipes. Reference has been made to porcelain being porous. Vitrified porcelain can certainly be obtained, and so far as I knew up to the present it was not porous; I have hitherto attributed all moisture effects to moisture on the surface of the insulator. The author does not seem to make any distinction in his paper, and probably quite rightly, between the conduction of the moisture within the material and the conduction of the moisture on the surface; but I think a great deal of the moisture must undoubtedly be on the surface. At all events, if long surface leakage paths are provided we all know that very much better results are obtained than with short paths, even though the distance measured through the dielectric may not be longer, or substantially longer, in one case than in the other.

Mr. Welbourn.

Mr. B. WELBOURN: As I read this paper I could not help thinking of a well-known quotation from Browning, lbourn. "Oh but a man's aim should exceed his grasp." I thought of this particularly at the end when Mr. Evershed suggested that the problem of forestalling breakdowns by systematic testing is nearly insoluble. Perhaps it is so, but with our present knowledge a great deal of systematic mains testing is being done, and a large proportion of insipient faults are removed from mains networks by regular testing without the consumer knowing anything at all about it. An extremely useful tool which has been provided for all mains engineers is the "Megger," for which I think Mr. Evershed is responsible, and which is an enormous advance on the old ohmmeter and generator. This in itself is a very good illustration of the rapid advance of knowledge. The author mentions, in a footnote on page 51, the flash test. I do not know whether the flash test is a "method of barbarism," but in my opinion it will not disappear very rapidly. I should like Mr. Evershed to suggest an alternative because all electrical circuits are liable to sudden pressure rises, and I do not know of any test which is in any way comparable with the flash test for showing up the suitability of the insulation to withstand these rises. I should also like to ask Mr. Evershed whether all the curves have been taken at uniform atmospheric temperatures, and whether artificial means were adopted to ensure that the insulating material was always at the same temperature, or whether the increasing dielectric loss due to the rise of the potential was allowed to heat up the dielectric. To all cable-makers especially it has been an exceedingly interesting problem to theorize as to why the insulation resistance of a cable should fall when pressure is applied and when the dielectric heats. This paper has thrown considerable light on the problem, and the author has convinced me that the theory put forward originally by Mr. Campbell and communicated to this Institution some years ago by Mr. Rayner and acknowledged by Mr. Evershed in his paper, is correct and that the effects are mainly due to moisture and air. I should further like to ask Mr. Evershed whether the fall in dielectric resistance is *only* due to moisture and air. The paper and impregnating oil themselves have physical properties which possibly change when electrical pressure is applied, and it may be that that also has some influence on these curves; but as far as I can discover from the paper the author gives no indication of his views on that point.

Now, for reasons given by the author, all the tests described in the paper have been made with continuous current, and some of them illustrate the causes of effects well known to all those whose work lies in the distribution of electricity by continuous current, such as the "valve" effect and the collection of dust and moisture through endosmosis. It reminds me of a particular use of the low-tension triple-concentric cable originated some years ago by Sir Alexander Kennedy where he made the core of the triple-concentric cable the negative pole instead of the positive pole, as is the usual practice, and I think it was effective in getting rid of some of the low insulation troubles with the neutral conductor on distribution networks. In these days when alternating-current work is so much to the fore, it would be very useful if the author could spare the time to make some tests with alternating current, and publish the results. There is no doubt whatever that the faults on alternating-current networks are far fewer—in fact almost non-existent—than on continuous-current networks. To mains engineers, the application of alternating-current pressure for some hours is a well-known method of temporarily getting rid of low insulation on continuous-current mains if alternating current is available. I think some engineers might draw the inference from this paper that if we could get rid of all the moisture and air in absorbent insulators we should approach a sort of electrical millennium; but I would ask the author if he has considered whether it is really advisable to get rid of all the moisture and air. Every attempt that cable-makers have made to get rid of moisture has only resulted in brittle paper and the destruction of that flexibility which is so essential in handling cables. Mr. Welbourn.

Under the general title of "Characteristics of Insulation Resistance" one can rather range outside the exact contents of the paper. I have been very much impressed in the last few weeks in re-reading Dr. Russell's paper read before this Institution in 1907.* In that paper a characteristic of insulation comes out in which moisture in a cable appears to play very little part, namely, the different behaviour of a given thickness of insulation with conductors of varying radius. In connection with Fig. 8, Mr. Evershed calls attention to the test taken after electrification for one minute, and this has already been referred to. The result is understood by all cable men as only being qualitative, but it gives an approximate idea of the true state of the insulation. Longer tests could be made if required, but, as Mr. Beaver has just indicated, there are limitations of time and space in every works.

Professor A. SCHWARTZ: On page 55 the author mentions that the only non-absorbent insulators which were tested in the course of his work were gutta-percha and rubber. He states that "these are both non-absorbent in the sense that what little water they may be capable of absorbing is entirely unable to form leakage paths through the insulator." While this statement may be quite true as regards gutta-percha and vulcanized rubber, it is hardly correct for pure rubber. The classical experiments of Thomas Hancock, which extended over 30 years—from 1826 to 1856—in which he hermetically sealed 12 ounces of water in a rubber bag and watched its evaporation from year to year, shows conclusively that at ordinary atmospheric pressure water is capable of being absorbed by, and of passing through, pure rubber. Pure rubber will absorb about 25 per cent by weight on prolonged immersion in water and increases considerably in volume; there is no doubt also that in its passage through pure rubber water very much affects the insulation resistance. In 1907 I tested some pure rubber flexible cables of 2,000-megohm grade; a 10-yard length was tested in air with a pressure of 550 volts, and the insulation measured between the conductors was found to be 6,000 megohms. On immersing the cable in water the insulation fell almost at once to 80 megohms; in a week to 40,000 megohms; and in 8 days it broke down with a pressure of 400 volts. A piece of vulcanized flexible cable put through a similar test showed, as in the author's case, that no appreciable effect was obtained. The amount of water that is absorbed by pure rubber depends partly on the character of the rubber, that is, on the amount of resin or oil which it contains, and partly on the physical condition of the rubber. Freshly Professor Schwartz.

* *Journal I.E.E.*, vol. 40, p. 6, 1908.

Professor Schwartz.

manufactured pure rubber absorbs water readily, but if the rubber is allowed to rest it becomes hard and comparatively inextensible, and in that condition it is more resistant to the absorption of water. Mr. Lester Taylor told me some time ago that he had had a pure rubber flexible cable feeding a 100-volt lamp for several months without any trace of breakdown, although immersed in water all the time.

I should like to refer to this question of the physical condition of rubber a little more in detail, because some of the changes that may take place in it are so considerable, and take place within such a small range of temperature, that when Mr. Evershed comes, as I hope he will do, to investigate the lower part of his curve, I think it would be interesting if he could consider the effect of these changes. (The speaker then exhibited the behaviour of a strip of rubber under the action of heat.) It is evident that the molecular condition of rubber undergoes a very considerable change at a comparatively low temperature; in determining the linear coefficient of expansion of a "rested" strip I found that this change takes place between 33° and 35° C.; up to 33° C. the rubber is in a hard and inelastic state, and above 35° C. it is in a plastic state. The author has described the state of things that obtains in the inside of a porous insulator. I have been interested in this subject from rather a different point of view, namely, in connection with the problem of the rise of sap in trees; and as a good many of our porous insulators are vegetable in origin, and since many of our inorganic insulators have a capillary structure, I think perhaps it would not be without interest if we consider very briefly what results have been reached by the physicists and the botanists who have been experimenting in this somewhat different field. In the first place we do not find in plants a continuous system of water channels; we find the bulk of the channels are intersected with innumerable longitudinal and transverse partitions dividing them up into very small compartments. It is rather curious, considering that the function of these channels is to take water from the roots to the leaves, that we should find them intersected nearly all the way up by numerous transverse partitions. We find, however, in the cells numerous air bubbles present, just as in the author's experimental tubes, and these bubbles, alternating with drops of water form Jamin's chains. The botanists consider that 10 to 50 per cent of the channels are filled with air, but I think that Mr. Evershed's resistance measurement method will help them in estimating more closely than they have been able to do by the microscope the proportion of channels which are filled with air. Now it is evident that whatever movement takes place in these chains of air and water—whether it is by endosmosis or by any other agency—the bubbles will not be able to pass through the partitions, and where we have long cells a bubble forming in one of these will put a large proportion of the conducting tube out of action, or at any rate it will introduce a very high resistance in the conducting tube. But by dividing the conducting tube up into a number of small cells by means of transverse partitions we have the size of the bubbles limited, and we see that if a cell is put out of action, or has extra resistance introduced into it by means of an air bubble, the length of the high-resistance film is limited by the length of the cell. The fact that the bubbles are confined in very small cells by longitudinal partitions means that only an infinitesimal portion of the whole of the conducting area of the circuit is interfered with by a bubble. An interesting reference was made by Professor Silvanus Thompson to the question as to whether we should ever be able to get material with pores small enough to prevent the ingress of water. I am afraid that the work of botanists shows us that the smaller the pores the more easily the water-vapour gets into them. Messrs. Brown & Escombé* found in 1900 that the diffusion of water-vapour through a number of minute pores in an impermeable membrane will be greater than through one large aperture having a cross-section equal to the area of the pores. This is due to the increased efficiency of transmission at the periphery of the aperture as against the efficiency of the transmission at the central portion of the orifice, and as the size of an aperture is reduced the relation of its margin to its area is increased. The prevailing idea in botanical circles as to the rise of the sap is that it is due to tension in the water induced by evaporation. I do not know that the possibility of an electrical cause has been considered, and I should like to ask the author in this connection what is the lowest voltage at which he has found endosmosis take place.

Mr. Rayner.

Mr. E. H. RAYNER (*communicated*): Those of us who have worked on insulation know that the labour apparent in any paper on insulation is only a small proportion of the amount which has actually been spent, a large proportion of the experimental work being the unmentioned preliminary experiments, which give the author the moral authority to publish the results of such final experiments as he deems of value. Before turning to the one point upon which I especially desire to dwell, I should like to suggest that notes on the effect of a few degrees' change of temperature would be instructive. Without experimental experience it is difficult to realize how greatly the resistance of an absorbent insulator may change with quite a small variation in temperature. The possibility of moisture being associated with mica is mentioned on page 60. When testing mica under a high voltage I have often noticed that the violence of the brush discharge on the surface diminishes after the first few minutes, which I have ascribed to driving off a surface film of moisture. Some further details as to the dimensions of the apparatus used in measuring the resistance of oil would be of use. Do the numbers in Fig. 21 refer to the actual resistances as measured, or to the value per cubic centimetre? The absorption curve for the oiled paper cable is very interesting. Does the author think the same resistance would be obtained if the paper were absent and the same quantity of water associated with oil only? And does the paper plus oil absorb much more moisture from the air than the oil alone would? Some note as to the "natural" amount of water in the paper used for the experiments in Table I would be of interest. There is no mention as to whether this condition falls within the limits of the experiments described. It is very satisfactory to find that the results of my own work mentioned on page 65 agree so well with those of the author.

I now turn to one particular point which has been

* BROWN & ESCOMBÉ. "Static Diffusion of Gases and Liquids in Plants." *Philosophical Transactions of the Royal Society*, B, vol. 193.

Mr. Rayner. mentioned by Mr. Wordingham and other speakers. On page 51 the author asks, "What is the margin between working voltage and breakdown? That is the fundamental question at the root of every inquiry into the properties of insulation. To conduct tests without any means of ascertaining what is going on in the insulator as the breakdown voltage is approached, without either observing the current or, better still, the resistance, is to shut our eyes and deliberately avoid looking for the cause of failure." And again (on page 71) he asks "whether it is possible to predict the breakdown voltage. . . . a blackened hole appears in the insulation and the inference is too hastily drawn that the puncture process was instantaneous. . . . The time may never come when it is possible, by systematic insulation testing, to forestall breakdown by diagnosis of the disease and removal of the cause." Within certain, possibly wide, limits I think the answer is already in the affirmative. It *is* possible, with *simple apparatus*, to test insulation of an organic and absorbent nature under an alternating voltage, and to see exactly what is happening; to learn whether the insulation is likely to withstand the voltage indefinitely, whether and how soon it is sure to fail, with the great advantage that the pressure test may be stopped before permanent damage is done. Some method of determining whether an electrical plant is insufficiently dried out for running for the first time after erection could not but be of great commercial value.

As the author states, alternating-current measurements are useless in showing the leakage current through insulation, as it is exceedingly small compared with the capacity current. An alternating-current wattmeter will give the required information; but it is hardly a practicable workshop instrument. It is, however, practicable, while applying a high-voltage alternating test pressure to insulating material, to add in the circuit a much lower continuous potential which will find its way through the weak places in the insulation, more especially where the conductivity is greatly increased by any local heating at dangerous spots. In testing small pieces of insulating cloth ample warning is given of the approach of breakdown. Whether the method can be as usefully employed for finished machines can only be determined by trial. The apparatus consists merely of a sensitive moving-coil ammeter (a micro-ammeter by R. W. Paul) and a battery inserted at any convenient part of the circuit. Small cells for pocket lamps can be mounted compactly, so that a battery giving a pressure of 100 volts weighs about 12 lb. Fig. A shows a diagram of the connections and the result of a test on three thicknesses of Empire cloth wound on a cardboard tube with tinfoil electrodes, the area being 130 sq. cm. The alternating voltage was 2,500 and the continuous voltage 100. The continuous voltage alone produced no perceptible current in the instrument. On switching on the alternating current the ammeter indicated 4 micro-amperes, which increased in 6 minutes to 21 micro-amperes. On switching off the alternating voltage the reading falls to 1 and diminishes still further. On switching on again, the alternating voltage causes instantly a great increase in the continuous current, and failure rapidly takes place.* The very great drop in the continuous current on switching off the alternating voltage is important. It shows the futility of assuming that the insulation resistance of a high-voltage machine under working conditions can be assumed from tests made by much lower continuous potentials. Fig. B shows the result of a similar test at a lower voltage (2,000), which was applied for 40 minutes and then raised to 2,250. As in the previous experiment, the alternating voltage was switched off for half a minute and the experiment was stopped a minute after switching on again a few seconds before actual failure occurred. The material has become

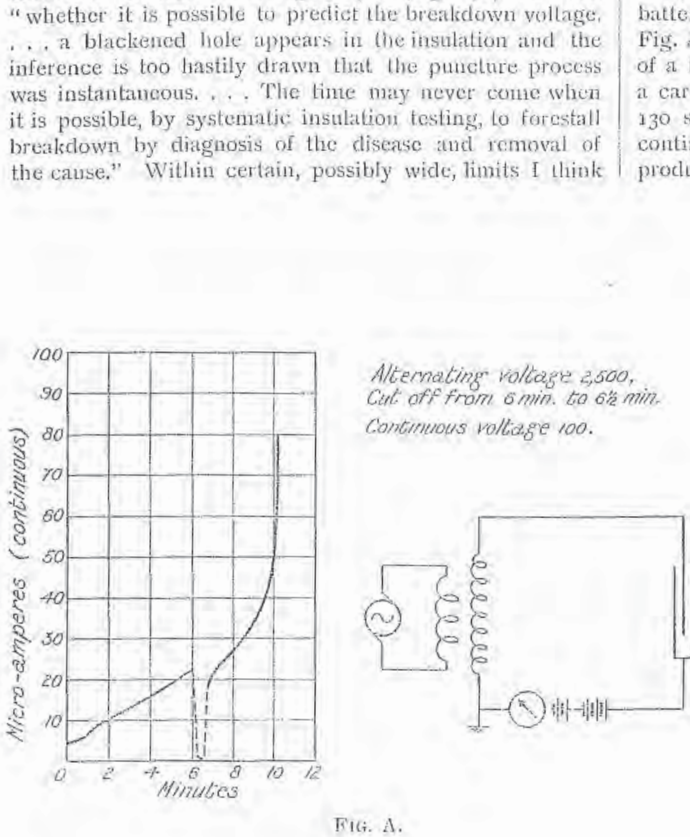

FIG. A.

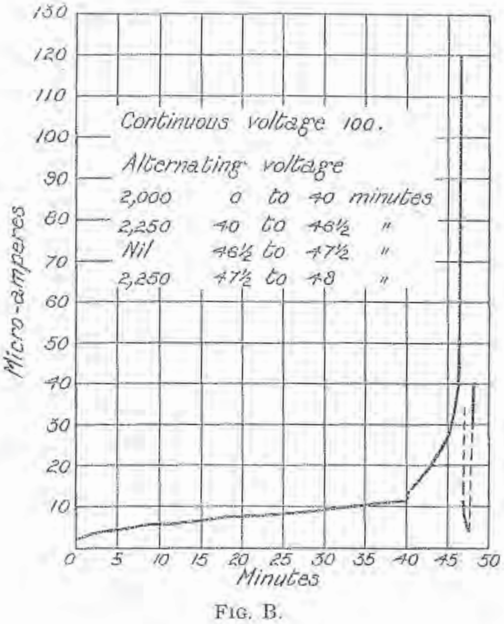

FIG. B.

* E. H. RAYNER, "High-voltage Tests and Energy Losses in Insulating Materials." *Journal I.E.E.*, vol. 49, p. 47, 1912.

Mr. Rayner. darker locally over an area of a few square centimetres, but actual puncture has not taken place. I do not know that the method has been tried on finished machines. It will be seen that the alternating current traverses the continuous-current instrument and causes some vibration of the pointer unless this is very stiff. The only difficulty would appear to be the alternating capacity current, which would be much larger than when testing a comparatively small piece of insulating material. No doubt a specially rigid moving system would be of considerable help and might suffice. The instrument might have a very large inductance added to it, say the primary of a switchboard potential-transformer, and the ammeter and inductance be shunted by a large condenser through which most of the alternating current passes. Mr. Irwin tells me that he has found an inductance of 4 henries and a capacity of 20 microfarads successful. The condensers should be protected by a spark-gap, as the full voltage would come on them if failure occurred in the insulation under test.

Mr. Sparks. Mr. C. P. SPARKS (*communicated*): Mr. Evershed raises an interesting question: "What is the margin between working voltage and breakdown?" and suggests that the problem should be determined by continuous-current insulation tests rather than by the application of an alternating-current pressure test; the difficulty of using any sensitive instrument with alternating current is pointed out in Section 2 of the paper. While I am in agreement as to the advantage of using an indicating instrument, this has yet to be evolved for alternating current, and until this is possible I am in favour of continuing the use of alternating-current testing, not in the form of a flash test referred to in his note, but in the form of an alternating-pressure test applied for short periods. At present this is the only feasible method of testing high-pressure apparatus, and is a more reliable indication of the condition of the plant than can be obtained by a continuous-current insulation test carried out with a pressure of a few hundred volts. Section 4 of the paper refers to the relative importance in wiring between the leakage through the dielectric used to insulate cables, and the leakage through fittings. The importance of the leakage from fittings was appreciated by the Institution Wiring Rules Committee when amending the rules some years since, as is shown by the following extract from Rule 121:

"121. The insulation resistance to earth of the whole or any part of the wiring must, when tested previously to the erection of fittings and electroliers, be measured with a pressure not less than twice the intended working pressure, and must not be less in megohms than 30 divided by the number of points (par. 32) under test. For this purpose the points are to be counted as the number of pairs of terminal wires from which it is proposed to take the current, either directly, or by flexibles, to lamps or other appliances."

Section 13 of the paper deals with a model insulator tested with continuous current. Have similar tests been made with alternating current? These should show the breaking up of the films between the separate drops of moisture, thus increasing the insulation resistance. In conclusion, Mr. Evershed's paper will be welcomed by all, as it demonstrates the initial reason why alternating-current cables and other apparatus are far less troublesome to maintain than continuous-current apparatus when worked under equal dielectric stress.

Mr. Bartlett. Mr. A. T. BARTLETT (*communicated*): I welcome the research described in the paper as one of great value, not only for the actual results already obtained but for what it may, and I hope will, lead to. Such methods and knowledge should help us to select our insulation materials in a more rational manner and, it may be, to produce new and more satisfactory forms of flexible insulators; but from the dynamo and motor manufacturers' point of view I must in common with two other speakers protest most emphatically against the author's condemnation of the flash test. I believe that few engineers understand the real object the plant manufacturer has in view when he fixes and applies a definite flash or pressure test. It is not applied, as many seem to imagine, simply to find out whether the insulation will stand a definite pressure between, say, the windings and the shell—having provided a factor of safety, he knows it will, unless the material has been damaged or has faulty spots which could not be detected before use. If any such weak points occur he wants to discover them, and I know of no other method which can approach the pressure test for this purpose, because it is not only necessary to know that such weak points exist, but they must be located, and even in "a costly piece of electrical apparatus" it is cheaper in both time and cost to burn the fault out; at this stage he is not concerned with what actually happens to the damaged insulation at the moment of breakdown. To emphasize the real object of the flash test, I may say that it has been my practice to fix the voltage of the flash test quite independently of the working voltage, *e.g.* in the case of a low-voltage, say 50 volts, generator, if I know that the insulation materials in that machine are identical with a machine built for a working voltage of 500 volts, as is frequently the case, I test for damage to the insulation with a 2,000-volt pressure test, which may appear to be heroic, but is good sound practice; I should imagine that cable-makers have probably the same object in view. Anyone who has had experience on the test-beds knows that an insulation test even when applied at a more or less high pressure by means of a 1,000-volt testing set often fails to reveal the presence of air-filled cracks in the insulation, simply because there is not sufficient power behind the test. Hundreds of cases have occurred in which machines have broken down under a pressure test after having just previously shown high-insulation results with high-voltage testing sets. The plant manufacturer can no more forgo his pressure test than can the crane- and lift-builder or boiler-maker forgo his overload stressing tests.

To the plant builder the experiments on the varnish-impregnated cotton-covered wire are of great interest, and my own experience agrees with the results obtained, viz. that the effect of such impregnation is quite ephemeral. I have for years unsuccessfully advocated that all field coils of such machines as are to work in an ordinary weather-proof building should be wound dry and varnished only on the outside layer, or taped over and varnished. Impregnating such coils has practically no effect on the dielectric strength to earth, and reasonably dry cotton is ample insulation between the turns and layers in a well-designed coil. I have seen a number of the old field coils of ancient two-pole machines unwound in which the cotton was in excellent condition, although wound dry. On the other

Mr. Bartlett. hand I have seen a number of cases of impregnated coils giving trouble owing to the varnish breaking down and acquiring an acid reaction; this is a real danger and one which in my opinion it is quite unnecessary to run. The author mentions stoving his varnished materials at 150° C., which I do not think can be recommended; he referred to a special varnish which he uses, and if he has a varnish that will stand this temperature not only on a thin coil such as he used, but in a normal field coil—in which the solvent in the interior takes many years to evaporate or oxidize—then I hope he will disclose it as it might be of great value in such cases where impregnation is advisable.

Mr. Campbell. Mr. A. Campbell (*communicated*): As one who attaches great importance to consistent nomenclature, I regret to see that the author uses the term "characteristic curve" quite out of its ordinary meaning (*i.e.* volt-ampere curve). To give any scientific term a double meaning reduces its efficiency by much more than 50 per cent. The author's theory appears to be well supported by many experimental results, and in particular by the behaviour of his beautiful model, but I fear that the examination of a wider variety of absorptive insulating materials will make the theory more difficult to accept. Some years ago in experimenting on fibrous insulating materials (like paper) at various temperatures I came to the conclusion that the effects observed had their origin in the tubular structure of the fibres. Not long afterwards I found that solid cellulose behaved very much like ordinary paper. Now the solid cellulose is a fibreless colloidal material (like a sheet of glue), and its pores must be of a quite different order of magnitude from those of paper. Since reading Mr. Evershed's theory I have had a few rather hurried experiments made on some colloidal materials, which have given the following values for the "Resistance Ratio" for V_{40}/V_4:—

Solid cellulose	2·7
Celluloid	1·2
Cellulose acetate...	1·0

The third material is the well-known flexible enamel now so much used for covering wires; it is somewhat absorbent of moisture, but not nearly so much so as any form of cellulose. It will be noticed that the other two colloids show "Resistance Ratios" greater than unity, and yet their gluey structure does not suggest porosity in the ordinary sense. It appears to me, therefore, that the effect of moisture is mainly molecular, not explainable by the assumption of water films working in microscopic channels. Cellulose and other similar colloids appear always to have (at any given temperature and pressure) a certain proportion of water associated with them, part of which may be in loose chemical combination, and the remainder, as it were, in solution in the colloid. The tubular structure of some of the fibrous forms of cellulose no doubt must have considerable influence on their behaviour as insulators, but any theory must take account of the ultimate colloidal nature of the material. I hope the author will examine the behaviour of some of the non-fibrous absorbent insulating materials (Bakelite for example) and if necessary widen his theory to include them all.

Mr. Bairsto. Mr. G. E. Bairsto (*communicated*): I should like to ask the author whether in the analysis of his results he has fully taken into account the nature of the contact used in his experiments. He uses copper plates interleaved with the sheets of dielectric. Now it has been shown by Mr. Appleyard,* and recently in more detail by myself,† that in using tinfoil, which is obviously even better suited than copper plates for producing a more intimate contact with the dielectric, an increase of voltage has a very considerable influence in producing an apparent decrease in the resistance as the voltage is increased. This will take place even with a very high compression of the dielectric, say 15 or 20 lb. per sq. in. The more rigid copper plates used in the present experiments would tend to enhance this effect. There are two points described in the paper which make me suspect that the imperfect contact is responsible to a certain extent for the rapidly falling characteristic curve shown in most of the figures. The first is in Fig. 5, in which we have a so-called hysteresis effect depending upon whether the voltage is increasing or decreasing. Now this hysteresis effect is well known to those who have studied tinfoil contact with ordinary dry dielectrics, and is due to the influence of the voltage in pulling down the electrodes into contact with the dielectric. The second point is illustrated by Fig. 17, where the change of characteristic from a gradually falling curve to a straight line, as the dielectric becomes sodden with water, is explained as a change from "moisture conduction" to conduction by Ohm's law. It could, however, be explained in quite a different manner. Starting with a dielectric having a resistance independent of the voltage, curve A may be taken to represent the influence of voltage in bringing about a more intimate contact as has just been described. In curve C, however, the paper being now sodden with water will have a surface film of moisture, allowing the current to creep along the face of the dielectric from the points at which the electrode is in contact, to, and through the parts of the dielectric which are not touching the electrodes. That is to say, the effect of the presence of the moisture film is to produce a contact which is almost as good as if every part of the dielectric were in thorough contact with the electrodes. We should then get, as in curve C, a straight line showing a resistance independent of the voltage. I do not maintain that all the effects described in the paper are due to this effect, but I feel sure that it has had a considerable influence. It cannot be separated out, and the only way in which comparative tests can be made is by employing mercury electrodes. I may mention that in a long series of experiments made at University College it has been found that at low-potential gradients up to about 5,000 volts per cm. there is no variation of resistance with voltage, and this is true for such widely different dielectrics as mica and celluloid, using ordinary dry materials and mercury electrodes. As the potential gradient is still further increased the resistance falls away in a manner similar to that depicted in the lower portion of Fig. 1. Supposing, however, that the results obtained by the author represent the state of affairs for damp insulation, then it must be agreed that what we are discussing is not the characteristics of insulation at all, but rather the characteristics of water in insulation.

Mr. Gifford. Mr. R. D. Gifford (*communicated*): It is apparent that this paper is the outcome of a very thorough investigation. It is probably only those who have had to make resistance

* *Proceedings of the Physical Society of London*, vol. 19, p. 724, 1905.
† Ibid., vol. 25, p. 301, 1913.

Mr. Gifford. and breakdown tests on insulators who can really appreciate how fully the factors which usually go to obscure the truth have been recognized and taken account of. There is one point, however, to which I should like to call the author's attention, as I do not see it mentioned in the paper. He says, on page 53, that the source of current was usually a 500-volt battery, and occasionally a small 1,000-volt generator. The author has emphasized in several places in the paper how greatly the true value of the insulation may be masked by the capacity current, which effect must be considerable where we are testing the insulation resistance of a cable or network of feeders. Now the E.M.F. of a battery may be represented by a smooth line, but surely the E.M.F. of a generator cannot be so represented; it must have a surface ripple, since it is made up of a number of commutated waves. Under these circumstances it is apparent that a capacity current will be superposed on the insulation current, vitiating the results to a greater or lesser degree. Moreover, the ripple will be much more conspicuous in the case of the small generator E.M.F. than in an ordinary continuous-current supply, as the number of commutator segments is necessarily relatively few. I shall therefore be glad if the author will state whether he made any tests, such as with an oscillograph, to ascertain the magnitude of these ripples, and also if the results obtained when using the generator were consistent with those obtained when using the battery.

Mr. Cottle. Mr. P. J. COTTLE (*communicated*): Mr. Evershed's paper is of great interest to telephone engineers who are confronted with the problem of maintaining the insulation of dry-core cables. The pictorial representation of the action of moisture in reducing the insulation resistance of absorbent insulators may throw some light on many desiccation problems. In this country it is usual to desiccate paper-core cables with dry air, but French telephone engineers have recently extensively employed dry CO_2 for this purpose. Apart from considerations of cost and inconvenience it is claimed that a certain volume of dry CO_2 is more efficient than an equal volume of dry air for raising the insulation of a paper-core cable. It is found on the completion of desiccation with CO_2 that the insulation has been raised by an amount quite equal to that obtained by using an equal volume of dry air, but that in the former case the insulation resistance continues steadily to rise after the completion of desiccation. Does the author consider that owing to the greater density, and the consequent slower rate of diffusion of CO_2, this gas should be more effective than air in reducing the proportion of water in the paper which acts as a conductor?

Dr. Ashton. Dr. A. W. ASHTON (*communicated*): In adopting the conclusions arrived at by the author we must not lose sight of the fact that the testing pressure was continuous and that the materials tested gave results mainly determined by the amount of moisture absorbed. In cases where the leakage is neither due to absorbed moisture nor surface moisture the true dielectric leakage is proportional to the applied voltage. In the paper this is shown to be true in the case of cylinder oil (see Fig. 21, Curve A) and varnished cotton (see Fig. 24, Curve A). This true dielectric leakage, determined by prolonged charging at a steady pressure, is only of use as an indication of the presence of conducting impurities in the dielectric. On the other hand the apparent conductivity after one minute's electrification is, I believe, much more important in the case of a good dielectric than it is generally considered to be. According to what may be called the Pellat-Schweidler-Hopkinson theory of dielectric absorption, there is a direct relation between the charging current after one minute's electrification and the energy loss under an alternating E.M.F. If this theory is true the so-called insulation resistance in the case of a cable free from faults gives an indication of its capability of withstanding the prolonged application of an alternating voltage, where breakdown is probably due to an increase in temperature caused by dielectric losses. Dr. Ashton.

With regard to "blind" tests of breakdown voltage, there are two factors for the determination of which the breakdown test is of use, viz. the effect of the geometrical form of the insulator and the strength of the dielectric to resist disruptive discharge. The application of the flash test will detect the presence of faults due to design or to manufacture, and will determine whether the dielectric is able to withstand the unavoidable transient pressure rises due to switching on, etc. On the other hand the prolonged pressure test during which the material is kept under observation by measuring the energy dissipated, will enable the possibility of changes in the dielectric due to electric stress or to temperature rise to be investigated.

Mr. S. EVERSHED (*in reply*): The discussion has extended a good deal beyond the area covered by the paper, and the many interesting matters touched upon by the several speakers serve to remind us of the enormous area as yet unexplored in the field of insulation. In replying to the discussion I must, however, confine myself to those points which bear directly upon the facts recorded in the paper. Mr. Evershed.

Dr. Thompson spoke of the extraordinary difficulty there is in keeping water out of an absorbent body. At present, as he said, it seems quite impossible to keep it out, and until the great discovery, which he referred to, is made we must put up with what Nature has given us. I should like to point out that but for the marvellous power an absorbent body has of stowing away almost the whole of the absorbed water in an electrically dormant state much of the work we now do would be commercially impossible. If the whole of the absorbed water took part in making leakage paths, low-tension networks as we know them would be useless. In such networks we do not measure insulation by megohms, but by amperes sometimes a great many amperes; for the leakage current depends on all sorts of circumstances—and on the mains engineer. But if Nature had allowed all the absorbed water to conduct, then for every ampere leaking under present conditions we should have had a leakage current of many thousands of amperes. Nature is sometimes on our side. I was very much interested in what Dr. Thompson said about the inevitable instability, the complex motions, of water which is carrying an electric current. When we look through the microscope at the films in our little glass model the unstable motions are going on under our eyes. We see why individual tubes are often so extraordinarily unstable. At one moment the film water will be travelling along in one channel, and the next moment, for no apparent cause, it will divert itself into another path altogether. But this of course refers to water films on glass, and I suspect that the extremely smooth surface of the glass accentuates the

Mr. Evershed.

instability. It may well be that in that respect glass is not truly representative of other insulators. Dr. Thompson asked whether the moisture curves obtained by first ascending and then descending the voltage range formed loops or not. They certainly make a loop, and there is an accompanying waste of energy. When the potential difference is applied the hydraulic force of endosmose is utilized (1) in overcoming the quasi-elastic capillary force of the film into which the dormant water is driven, and (2) in overcoming the fluid friction of the moving water. Upon switching off the pressure, the surface tension or capillary force of the film very slowly forces the surplus water out of the film into the adjacent water drops, and in so doing the reversible energy stored in the form of surface tension is all frittered away in overcoming the fluid friction incurred in driving the surplus water back into the dormant drops. Hence in going through a complete voltage cycle the whole of the energy due to the endosmose action is lost—degraded into heat. And since the surplus water retires into the drops with extreme slowness, and the flooding of the film may be made to take place almost instantaneously if we choose to apply a high potential difference, the area of the loop and waste of energy may evidently be reduced to any extent by performing the cycle with great rapidity. The analogy with magnetic hysteresis is evident. There is the "lagging behind" and the waste of energy, and if only we had the power to perform a complete *magnetic* cycle so quickly that Ewing's little magnets had barely time to move, the magnetic loop could doubtless be reduced in area to the same extent as the loop in a rapidly executed cyclic moisture curve. But the analogy must not be pushed too far.

Ohm's law is a perennial stumbling-block. I was taught to believe that it is comprised in the statement that "a current through a given conductor is proportional to the E.M.F. which drives it."* When we find a conductor in which this proportionality does not hold good (notwithstanding the fact that the conductor undergoes no apparent change in its dimensions or in its temperature), then we are justified in saying off-hand that it does not follow Ohm's law. But we do not for a moment believe that Ohm's law has failed us. On the contrary we suspect at once that our "given conductor" has in some occult way altered its electrical dimensions and changed its resistance. When we examine the case of the absorbent insulator we discover that the absorbent body which we assumed to be the "given conductor" is not a conductor at all. We find that the actual conductor is made up of a number of films of water and that each film has its sectional area increased as the potential difference increases. And in this way the apparent failure of a law which we believe to be universally true is accounted for. I have never heard the universal truth of Ohm's law more clearly expressed than it was by Dr. Thompson, and although he and I do not speak the same language I agree with every word of his statement. But I shall continue to speak the language I have been accustomed to all my life, the free and easy speech of everyday intercourse. I shall continue to say the sun rises, although I know perfectly well that he only appears to rise because I happen to live on a revolving planet.

* OLIVER J. LODGE. "Modern Views of Electricity," p. 69, edition 1889.

I quite agree with Mr. Beaver that it is commercially impracticable to measure the insulation resistance of rubber-covered cables, since each test might occupy 24 hours. I do not object to the cable-maker measuring the charging current plus leakage current at the end of one minute if the test gives him useful knowledge, but I confess I should like to see the phrase "insulation resistance" restricted to its proper use, undiluted by charging current.

Mr. Wordingham expressed the hope that means would some day be forthcoming by which it would be possible to see what was going on while the insulation is undergoing a pressure test. The means have been available for many years past, but we have not chosen to take advantage of them. All that is necessary is a high-tension continuous-current dynamo, and a galvanometer to give timely warning of latent defects. So far from being averse to high-pressure tests, as a manufacturer I regard them as absolutely indispensable. But I want to see an improvement in the usual mode of conducting them; let us have our eyes wide open. Mr. Wordingham also drew attention to the effects due to moisture on the external surfaces of insulators. In the early stages of our research we made several attempts to investigate the law of conduction in films on external surfaces, but experimental difficulties have so far prevented us from arriving at any useful results. External films are unlikely to give a moisture curve because in the absence of drops on the surface there is no dormant water available to flood the film. No doubt the action of endosmose, if sufficiently prolonged should result in an increase in the resistance of the film, provided the water is driven away from the positive electrode at a greater rate than that at which fresh water is being deposited out of the air.

I was very glad to hear what Mr. Welbourn said about the systematic testing of distribution networks. It is indeed good to know that already a large proportion of latent defects are discovered and removed; to know that in a great many cases breakdown is forestalled. But when I refer at the close of my paper to the problem as a whole seeming almost insoluble I am thinking of the complete system, from the plant in the power house to the installation on the consumer's premises. The mains may be cut up for the purpose of testing, but it is impossible to cut up the generator and transformers, and it is in such things that the difficulties of diagnosis are greatest. It is there hat our aim exceeds our grasp. Mr. Welbourn referred to a number of interesting phenomena which are familiar to the cable-maker and the mains engineer, such as the marked difference between the number of faults occurring on continuous-current and alternating-current networks, and the use of alternating current as a remedy for low insulation. These things are but vaguely known to those who, like myself, are interested in tracing the causes of such effects, and I feel sure there is room for a good descriptive paper on the subject written by someone who has first-hand knowledge.

Professor Schwartz drew our attention to the difference between pure rubber and vulcanized rubber as regards absorption of moisture. Hancock's experiment has never appealed to me as conclusive because I have never come across any rubber that did not perish after two or three years' exposure to the air, or to water containing air in

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solution. After such exposure the rubber is full of minute cracks. The poor insulation results obtained with flexible cables insulated with pure rubber are, I think, as much due to imperfect joining of the rubber strip round the conductor as to porosity of the rubber. What Professor Schwartz told us about the structure of the capillary passages up which the sap finds its way in a tree-trunk (and I suppose in any plant) cleared away some of the obscurities as to the disposition of the dormant water. There are evidently plenty of cells—blind alleys—to harbour it. But where are we to place the conducting films, with all those cross-partitions apparently blocking the way at intervals along the passages? I think the answer is that since the sap goes through the partition they must be porous; and in the pores are the films, with bodies of dormant water lying close at hand on both sides of the thin wall. A disposition of that kind is particularly well adapted to produce the endosmose effect, as Mr. Finnis and I have already discovered by experiments on thin porous tubes. I can only answer the question Professor Schwartz put to me about the limit potential gradient below which endosmose will not take place by saying that I do not think there is any limit. The lowest gradient at which I have actually seen the water pouring out from a drop into the film was about 25 volts per cm.; but judging by the decrease of resistance, the effect begins a long way below that point.

While I have been investigating the first part of the characteristic curve, Mr. Rayner has been at work at the National Physical Laboratory on the last part of the breakdown curve. His method of testing by superposing alternating current on continuous current is very interesting, and the resulting effects are quite new to me. He was kind enough to communicate the preliminary results to me a few days ago, and I asked Mr. Finnis to carry out similar tests on a piece of vulcanized rubber flexible. With defective cable we get just the same kind of effects as those which Mr. Rayner has described to us. What the explanation may be is another matter. And this reminds me that several speakers have referred to the effect of temperature on the characteristic curves. When the insulator is near the breakdown point it may easily be that a large amount of power is being spent in heating it. This has already formed the subject of an interesting paper which Mr. Rayner gave us last year.* But throughout the moisture curve the power spent is almost immeasurably small, and hence there is no sensible heating of the insulator. We have never observed any appreciable rise of temperature in making tests on the first part of the characteristic curve. Replying to Mr. Rayner's question, the resistance values in Fig. 21 are those actually measured; the test was purely qualitative.

Mr. Campbell tells us that since reading the paper he has carried out "a few rather hurried tests" on colloidal materials, and he gives us the resistance ratios obtained. These are, however, no criterion for a voltage-resistance curve, in the absence of any knowledge of the shape or law of the curve. I hope Mr. Campbell will continue his investigation of colloidal insulators and give us curves based upon a prolonged experience of their behaviour.

* *Journal I.E.E.*, vol. 49, p. 3, 1912.

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Mr. Bairsto refers to the effects occurring at the contact between electrode and insulator. In the earlier stages of our research Mr. Finnis and I attempted to find an explanation of the moisture curve at the terminals, but like many other hypotheses which occurred to us, it entirely failed to provide an explanation in agreement with all the facts. It was not until we directed our attention to the inside of the absorbent insulator that we made any progress at all.

Mr. Gifford mentions the small capacity current due to the ripple superposed on the E.M.F. of a testing generator. This is of course an alternating current and does not affect the reading of the galvanometer, or ohmmeter, one way or the other.

Mr. Sparks refers to the Institution Wiring Rule No. 121 as it now stands. This rule is based on the number of pairs of terminals from which it is proposed to take current. This is very far from being the same thing as the number of leakage points, and, as I have pointed out in the footnote on page 57, it is the average resistance per leakage point which enables us to judge whether an installation is in good or bad order. Incidentally I may suggest that the ordinary wireman would more easily multiply the ohmmeter reading by the number of leakage points than perform the simplest division sum. I share his weakness. Mr. Sparks suggests that the application of an alternating potential difference should break up the films in the model insulator. I have not tested the model with alternating current, but I have little doubt that Mr. Sparks is right. I think the film water would tend to collect in a heap halfway between the surfaces of the adjacent drops; but *fiat experimentum*.

Fiat experimentum. Perhaps that is the best answer to those friendly critics of my paper who have expressed a healthy scepticism with regard to my theory of moisture conduction. Let them test a few typical absorbent insulators. Let them make up a bundle of capillary tubes and test them. Put a tube under a microscope and watch the behaviour of the drops and films. They may then feel more confidence in taking the step which I have taken; the step from what I have seen in the tube to what I infer in the absorbent insulator. On the other hand they may unearth fresh facts which give my theory its quietus. Time will show.

In conclusion, I can only say that Mr. Finnis and I shall go forward with the investigation of the breakdown curve, greatly encouraged by the cordial reception which has been given to this paper.

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