The Institution of Post Office Electrical Engineers

Properties and Testing of Dielectric Materials

J. F. DOUST and W. J. SULSTON, M.Sc., A.Inst.P.

The Institution of Post Office Electrical Engineers

Properties and Testing of Dielectric Materials

J. F. DOUST and W. J. SULSTON, M.Sc., A.Inst.P.

Properties and Testing of Dielectric Materials

Introduction.

The purpose of this paper is to discuss briefly the dielectric properties of various types of material and the means by which those properties may be measured and compared. For simplicity the materials have been divided into the following classes:—

(a) Plastics.
(b) Waxes.
(c) Ceramics.
(d) Textiles.

A description of some of the more important representative members of each class will be given and their influence, either alone or in combination, on the design of common equipment such as condensers, cables, relays, etc., will be considered.

Although a critical review of the various theories which have been advanced to explain dielectric phenomena would be beyond the scope of the paper, a very brief account of the general trend of modern investigations will be given.

1. PROPERTIES OF DIELECTRICS.

Unidirectional Electric Fields.

Clerk Maxwell[1] defined a conducting substance as one which " when a charge of electricity is communicated to any part of that substance, the electricity is rapidly transferred from places of high to places of low potential till the potential of the whole becomes the same." To substances which did not exhibit this property of rapidly transferring electricity Faraday gave the name of " Dielectrics."

If a slab of dielectric material is placed between two flat conducting electrodes the arrangement forms a simple condenser. If now one electrode is connected to earth and the other is given a charge Q, the latter will be raised to a potential V, with respect to earth where

$$V = \frac{Q}{C}$$

C is defined as the capacity of the condenser, and depends on its geometric form and on a property of the dielectric material known as its Specific Inductive Capacity or Dielectric Constant. The Dielectric Constant of a material may be described as the ratio of the capacity of a condenser having that material as dielectric to the capacity of a similar condenser having a vacuum as dielectric.

Although there is no general drift of electrons through the dielectric from one electrode to the other, a movement of electricity does occur. The electrons, while remaining bound to the positive nucleus of the atom, may, perhaps, be moved from their mean equilibrium positions under the influence of an electric field. When in this state a dielectric is said to be " polarized." The displacement per square centimetre (D) across any cross section parallel to the electrodes is proportional to the dielectric constant (K)

(1) See Bibliography.

of the material and the voltage gradient existing in it. Thus

$$D = \frac{K}{4\pi} \times \frac{V}{d} \text{ electrostatic c.g.s. units,}$$

where d is the thickness of the material.

If the area of the dielectric slab under consideration is A, the total quantity (Q) is given by

$$Q = D \times A = \frac{KA}{4\pi} \times \frac{V}{d}$$

and the capacity (C) of the condenser is,

$$C = \frac{Q}{V} = \frac{KA}{4\pi d} \text{ E.S. units}$$

$$= \frac{KA}{3.6\pi d} \text{ micro-microfarads.}$$

When the potential between the electrodes is reduced to zero by short-circuiting them the condenser is discharged and the displacement disappears.

The current flowing into the condenser considered above was governed by its capacity, the E.M.F. of the source and the resistance and inductance of the circuit as a whole. This may be described as the " normal charging current " for those particular conditions. In practice, dielectrics are not perfect and a small current, called the " normal conduction current," flows continuously while the E.M.F. is applied. It might be expected that when an E.M.F. was applied to a condenser the total current at any instant would be the sum of the normal charging current and the normal conduction current. This is not the case, however, for an additional component which decreases in magnitude with time, makes its appearance.

The third component is not dependent on the specific inductive capacity or on the resistivity of the material and has been called the " abnormal " or " anomalous charging current." Its relative magnitude and its rate of decay vary with different dielectrics; in some cases it may have ceased after a very small fraction of a second and in some cases it may persist even for weeks after the initial application of the E.M.F.

When a charged condenser is short-circuited the normal conduction current ceases and the normal discharging current flows in the circuit. There may be in addition an " anomalous discharging current." This may be regarded as in some sense the reverse of the anomalous charging current although the quantity of energy restored by the anomalous discharge current will not be as great as the quantity supplied by the anomalous charging current. Again the magnitude and time of duration vary greatly. In some cases, where this time is long, if a charged condenser is short-circuited for a short period and allowed to stand, a charge builds up again due apparently to a re-charging of the condenser by the anomalous discharge current. This feature of dielectric materials will be referred to again.

One other phenomenon associated with the behaviour of dielectric materials under the influence of unidirectional electric fields should be mentioned. If

B

the voltage gradient existing in a specimen is gradually increased, a point is eventually reached at which the proportionality between current and voltage is lost and the current begins to increase much more rapidly than before. Chemical and physical changes may also occur in the material. This phenomenon is known as " breakdown," and the power of a material to resist breakdown is specified by its " dielectric strength," which may be defined as the voltage gradient just sufficient to cause breakdown.

The measurement of dielectric strength is, in general, of greater interest to the power engineer than to the telecommunications engineer and no further reference will be made to the subject here.[2]

Alternating Electric Fields.

If an alternating E.M.F. be applied to the simple condenser considered above an alternating current will flow in the circuit, and if the dielectric is perfect the current will lead the voltage by $\frac{\pi}{2}$ radians, no power being dissipated in the material. Even the best solid dielectrics are not perfect, however, and the current will, in practice, lead the voltage by an angle $\left(\frac{\pi}{2} - \delta \right)$, the power dissipated in the dielectric appearing as heat. The angle δ is known as the " loss angle " of the condenser and $\sin \delta$ is its power factor. The engineer dealing with the transmission and utilization of power is concerned with the deviations of power factor from unity while in studying dielectric materials the deviation from zero is more important. The loss angle rather than the angle of lag or lead will therefore be emphasised herein.

Since power is dissipated in the condenser it can be represented as a perfect condenser, say, C_1, in series with a small resistance R_1, or a perfect condenser of capacity C_2 shunted by a high resistance R_2. It can easily be shown that : —

$$\tan \delta = \omega R_1 C_1 = \frac{1}{\omega R_2 C_2}$$

and

$$\frac{C_2}{C_1} = \cos^2 \delta.$$

When determining the capacity of an imperfect condenser it may therefore be necessary to state whether the equivalent shunt capacity or the equivalent series capacity is measured, since if the power factor exceeds 0.1, for example, the capacities C_2 and C_1 will differ by more than 1%.

When a dielectric is subjected to alternating electric fields its power factor always has a larger value than can be ascribed to the normal conduction current. There is little doubt that the power factor is closely connected with the anomalous charging and discharging current phenomena and many theories have been advanced to explain the connection. A discussion of these theories would, however, be beyond the scope of this paper.

It has been pointed out that the anomalous charging current varies with time and it might be expected, therefore, that when capacity measurements are made

with alternating currents the values of capacity and power factor obtained would be dependent on the frequency of measurement. This is, in fact, true, and for this and other reasons it becomes doubtful whether we can specify or measure a dielectric " constant." It is, therefore, usual to describe the specific inductive capacity measured under any particular conditions as the " Permittivity " under those conditions. For calculations of permittivity the equivalent shunt capacity is generally used.

Tests carried out on Dielectrics.

The properties of the dielectric which determine the electrical behaviour of apparatus into which it is built are : —

(a) the Volume Resistivity,
(b) the Surface Resistivity, since in many applications the leakage current over the surface of the material will be more important than that through the body of the material.
(c) the Permittivity under appropriate conditions, and
(d) the Power Factor under those conditions.

The power factor appears to be independent of the form of the specimen and to be solely a property of the material.

The following sections will be devoted to a brief description of certain methods of measuring these quantities which have been found to be convenient and to meet the requirements of the Research Branch of the Post Office Engineering Department.

2. RESISTANCE MEASUREMENTS.

This section deals with the determination of the following properties : —

(a) the Volume Resistivity, which is defined as the resistance between two parallel faces of a centimeter cube of the material, and
(b) the Leakage Resistivity, which may be defined as the resistance between two parallel sides of a centimeter square which could be drawn on the surface of the material. If the volume resistance is large compared with the surface resistance the leakage resistivity reduces to the surface resistivity.

These properties are usually measured under carefully controlled conditions of temperature and humidity and the specimens are tested after conditioning in suitable chambers. The preparation of specimens will be discussed under the headings of the various materials. The testing voltages employed are such that the breakdown voltage-gradient for the materials is not approached.

Insulation Resistance measurements are also made on complete items of apparatus such as condensers, relay windings, cables, etc.

The following are the principal methods of measurements employed.

Direct Deflection Method.

In this method a sensitive reflecting galvanometer is used to compare the current flowing through the specimen when the testing voltage is applied, with the current flowing through a standard resistance (usually

---

(2) See Bibliography.

one megohm) under similar voltage conditions. The method is well known and no detailed description is necessary. Resistances from 10^5 ohms to 10^{12} ohms may be measured satisfactorily, but for the higher values care is necessary to avoid inaccuracies due to stray leakage currents. These can usually be rendered negligible even under comparatively bad atmospheric conditions by mounting the apparatus on clean paraffin wax blocks, and by the use of guard rings where necessary.

Condenser Discharge Method.

An interesting though less convenient method which has been used to check the accuracy of the conventional direct deflection method, is that which depends on the leakage of a charged condenser *via* the resistance under test. If a condenser of capacity C, and a high resistance R, are connected in parallel, and the condenser charged with a quantity q_0, the charge (q) at any subsequent time is

$$q = q_0 e^{-\frac{t}{CR}}$$

Hence if the charge be measured at times 0, and t secs. after charging, the resistance may be calculated. A correction must be made for the residual leak which is present in the absence of the specimen, the capacity of which will, of course, be included in C.

Electrometer Method.

This method is useful for the measurement of resistances from 5×10^{11} ohms to 3×10^{14} ohms. The current flowing through the specimen charges a condenser, the resultant p.d. across which is measured after a given time by means of an electrometer. If the capacity of the condenser is known, the current in the specimen and hence its resistance, may be calculated.

A quadrant electrometer has been used for this purpose, but is difficult to apply to rapid routine measurements. Recently a more stable type of electrometer, due to Lindemann and Keeley[3], has been brought into use. This instrument was developed for use in conjunction with a photo-electric cell for the measurement of light radiation received from stars. The cell was mounted at the focus of a telescope and an electrometer was required which could be fixed rigidly relative to the cell and which would be unaffected by the movement of the telescope.

The electrode system of the Lindemann Electrometer is shown in skeleton form in Fig. **1**. The " quadrants " are four flat brass plates arranged as shown and cross-connected in the usual way. The needle consists of a thin filament of gilded or silvered glass, with a very small crosspiece at one end, and is carried on a very fine fibre of gilded quartz. This fibre is under tension and the movement of the needle is therefore independent of the angle at which the electrometer is held. The supports of the fibre are also of quartz and the effects of temperature on the sensitivity are negligible.

The instrument is very compact, as may be seen in Fig. **2**, the case being about two inches in diameter and about one and a half inches deep. Windows are provided so that the movements of the needle may be

(3) See Bibliography.

measured by means of a microscope, or, as is perhaps more convenient, by projecting an image of the end of the needle on to a ground glass screen carrying a millimetre scale. With ± 17 volts on the plates the sensitivity is about 9 mm. deflection of the image per volt, and with ± 26v. on the plates about 30 mm. per volt. The capacity of the instrument is about
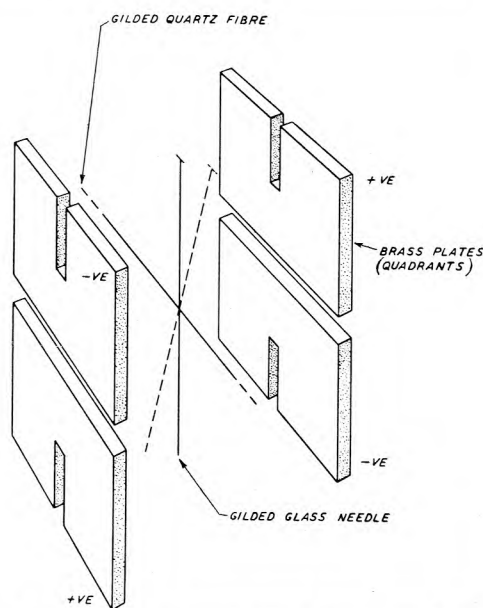

FIG. **1.**—LINDEMANN· ELECTROMETER ELECTRODE SYSTEM.

2 cms. A pneumatically operated earthing switch is provided. Compression of a small rubber bulb, connected to the switch by rubber tubing, pushes an earthed pin into contact with the needle terminal.
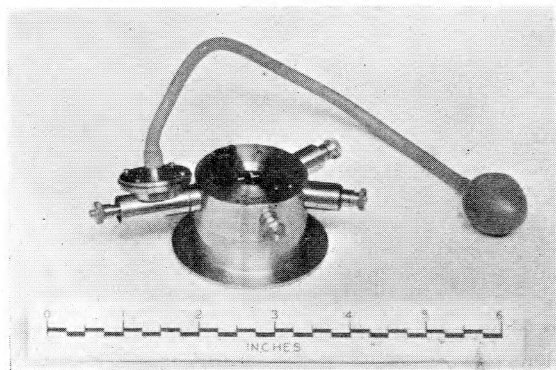

FIG. **2.**

The circuit used for resistance measurements is shown in Fig. **3**.

One end of the resistance to be measured is connected *via* a switch to the positive terminal of a high voltage battery (usually 500v.), the other terminal of which is earthed. The other end of the resistance is connected to the needle of the electrometer and one plate of a high insulation air condenser, the other plate being connected to a potentiometer (P_1) so that its potential may be made negative with respect to earth
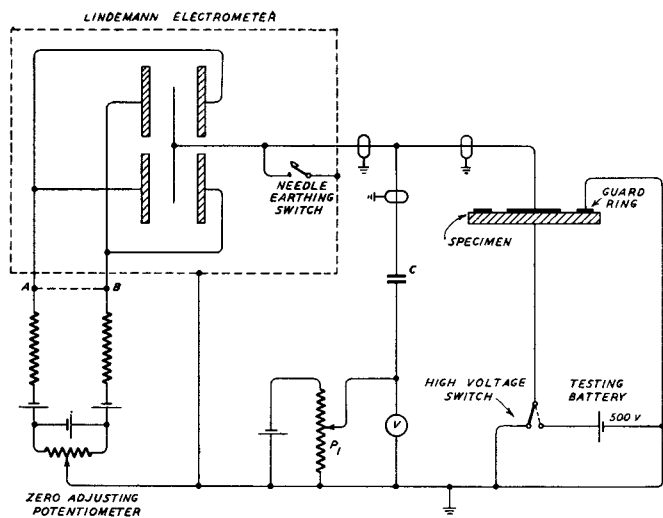
FIG. 3.—ELECTROMETER METHOD FOR MEASUREMENT OF HIGH RESISTANCES.

by one or two volts. When the high voltage is applied to the specimen the condenser begins to acquire a charge and the needle of the electrometer is deflected. This deflection is reduced to zero and maintained there by continuous adjustment of the potentiometer P_1. Then since the needle of the electrometer is still at earth potential the p.d. across the condenser must be equal to the p.d. across P_1, which is measured by the voltmeter.

If the capacity of the condenser is C microfarads and the p.d. across it is v volts after t seconds, the mean current flowing in the specimen is:—

$$I = \frac{Cv}{t} \times 10^{-6} \text{ amperes.}$$

If V be the voltage of the testing battery the resistance (R) of the specimen is

$$R = \frac{V}{I} = \frac{Vt}{Cv} \times 10^6 \text{ ohms.}$$

It might be thought that resistances of very great magnitudes could be measured by increasing t. Owing to apparent variations in the insulation resistance of many materials with the time of application of the testing voltage, however, the adoption of a standard time is necessary if comparative results are required. This time is usually 60 secs.

Before making a measurement the specimen is short-circuited by means of the high voltage switch and the needle earthing switch of the electrometer. The plates of the electrometer are short-circuited at AB and the mechanical zero is adjusted. The short circuit is then removed from AB and the needle adjusted once more to zero by means of the potentiometer P_2. This ensures that the potentials of the two pairs of plates are equal and opposite with respect to earth.

The advantages of this particular method are:—

1. Being a null method the calibration of the electrometer does not enter into the calculation.

2. Since the potential across the specimen remains constant, errors due to its self capacity (which may be considerable when a thin slab of dielectric material is used) are eliminated.

3. The electrometer needle is at earth potential when making a measurement and any leakage across the instrument will not affect the result.

4. The voltage across the condenser is small and if its insulation resistance is reasonably high the leakage across it will have a negligible effect.

3. MEASUREMENT OF CAPACITY AND POWER FACTOR.

Since commercial condensers as well as specimens of dielectric materials have to be tested, it is necessary to make measurements over a range of capacities from a few micro-microfarads to several thousand micro-farads. Fortunately, the range need not be continuous, since it is generally possible to choose condensers of suitable capacity for the purpose, while the capacities of specimens of dielectric materials are always less than 1000 $\mu\mu$F.

For condensers used at power frequencies tests are made at 50 c/s., while for those used at audio frequencies a testing frequency of 800 c/s. is generally employed. It is sometimes necessary, however, to study the performance of a condenser or material over a wide frequency range, which, in view of recent progress in the development of carrier circuits has been extended to at least 500 kc/s.

To meet these requirements the following methods of measurement have been adopted and these represent a compromise between the highest accuracy and convenience in testing.

Measurements on small Capacities at Audio Frequencies.

For this purpose the low tension Schering Bridge[4] is used and is suitable for capacities up to 1000 micro-microfarads with power factors up to about 50%. The arrangement of the bridge is shown schematically in Fig. 4. With the specimen disconnected at S, C_1 set near its maximum capacity and C_4 set at some suitable arbitrary value, the bridge is balanced by adjustment of C_2 and C_3. The switch S is then closed and the bridge is re-balanced by adjustment of C_1 and C_4, C_2 and C_3 remaining untouched.

Then if C_1' and C_4' are the capacities of C_1 and C_4 respectively at the initial balance, and C_1'' and C_4'' are their respective capacities when the bridge is balanced with the specimen connected—

$$C_x = C_1' - C_1'',$$

$$\frac{1}{R_r} = C_1' \omega^2 R_4 (C_4' - C_4''),$$

and $$\tan \delta_x = \frac{1}{R_x \omega C_x} = \frac{C_1'}{C_r} \omega R_4 (C_4' - C_4'').$$

C_1 is a high grade air condenser and is calibrated so that the change in its capacity necessary to secure the second balance can be read directly in micro-microfarads.

C_2 is an air condenser of similar capacity, but since its setting remains constant during the second balance

[4] See Bibliography.

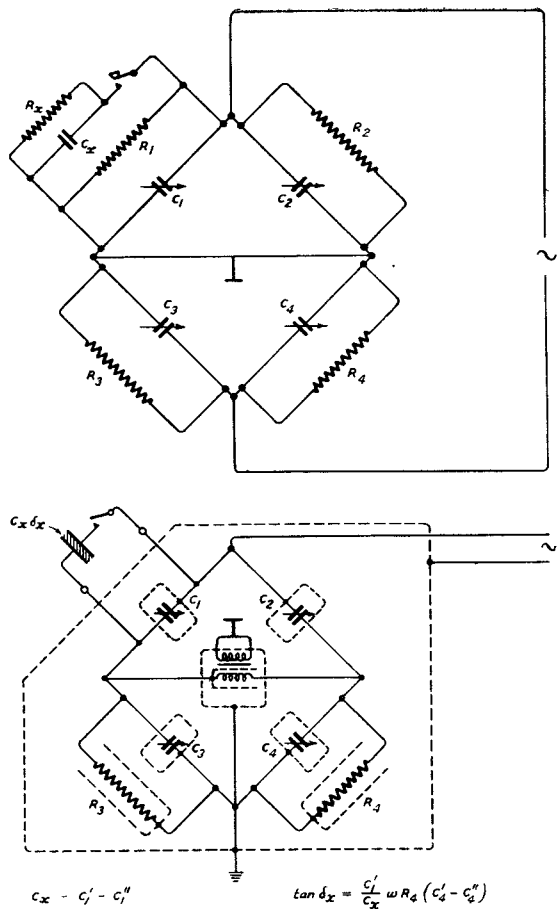$$c_x = c_1' - c_1'' \qquad \tan \delta_x = \frac{c_1'}{c_x} \, \omega R_4 \, (c_4' - c_4'')$$

Fig. 4.—L.T. Schering Bridge.

and since any losses in it are balanced by the initial adjustment of C_3 it need not be of such high quality as C_1. It is usually calibrated in degrees.

C_3 and C_4 are similar air condensers, and being shunted by the 10,000 ohm resistances R_3 and R_4, they need not have particularly low losses. While, however, C_3 is calibrated in degrees, C_4 is calibrated from a suitable artificial zero so that, if the testing frequency is 800 c/s., its reading, divided by the capacity of the specimen condenser, is equal to the power factor expressed as a percentage.

Since this is a substitution method and since the potential distribution is very nearly the same for both balances, errors due to capacity and leakance of leads are avoided. The effect of impurities in the resistances is also reduced, but they should be of reasonably high quality since R_4 occurs in the expression for $\tan \delta_r$.

It is perhaps worth noting also that since C_1 is a high grade condenser its losses at audio frequencies are mainly due to the dielectric and its equivalent shunt resistance will be extremely high and practically independent of its setting. Therefore, although its power factor will vary with its setting in the usual way, no serious error will result.

It will be seen that the screens are connected so that stray capacities are arranged either across the power supply or across C_3, so that they will not impair the accuracy of measurement.

Correction for Edge Capacity Effects.

When accurate determinations of permittivity are required, allowance must be made for the non-uniformity of the electric field near the edges of the electrodes, which causes the measured capacity to be higher than the true geometric capacity required. The best method of overcoming this difficulty is probably by the use of a "guard ring," as shown in Fig. 5.
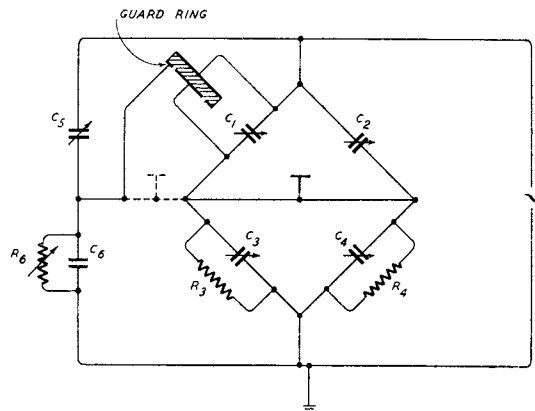

Fig. 5.—L.T. Schering Bridge with Guard Ring.

The ring is connected to a point which is brought to the same potential as the electrode it guards and only the capacity required is measured on the bridge.

Measurements on Condensers of Capacities between 0.02 μF. and 2 μF.

This range of capacities includes paper dielectric condensers and measurements are usually made on condensers of 1 μF. or 2 μF. capacity. The power factor of paper condensers at 800 c/s. ranges from 0.003 upwards. In the case of a 2 μF. condenser a power factor 0.003 at 800 c/s. represents an equivalent series resistance of only 0.3 ohm and care is therefore necessary to ensure that no appreciable additional series resistance is added due to connections. In any case a correction is made for the resistance of the leads.

The bridge is shown in Fig. 6. C_1 is a standard condenser of known power factor. R_2 and R_3 are equal and may be 100 or 1000 ohms, depending on the capacity of the condenser under test.

When balance has been attained—
$$C_x = C_1,$$
and
$$\tan \delta_r = \omega C_2 R_2 + \tan \delta_1$$
where δ_1 is the loss angle of the standard condenser C_1.

By this means the power factor of a 2 μF. paper condenser can be measured with an accuracy somewhat better than $\pm$ 2%.

Measurements on Condensers of High Capacity.

The development of electrolytic condensers having capacities up to several thousand microfarads presented new problems in the measurement of capacity and power factor. The bridge is shown in Fig. 7.
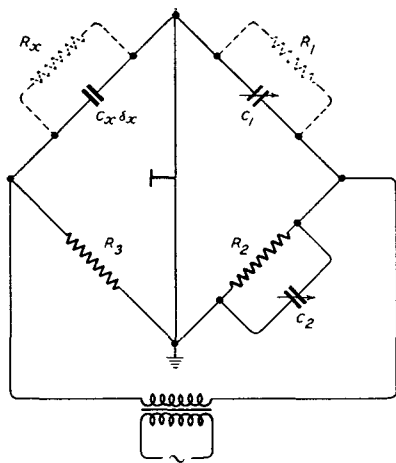
$$c_x = c_1 \qquad \tan \delta_x = \omega\, c_2\, R_2 + \text{LOSS TANGENT OF } c_1$$
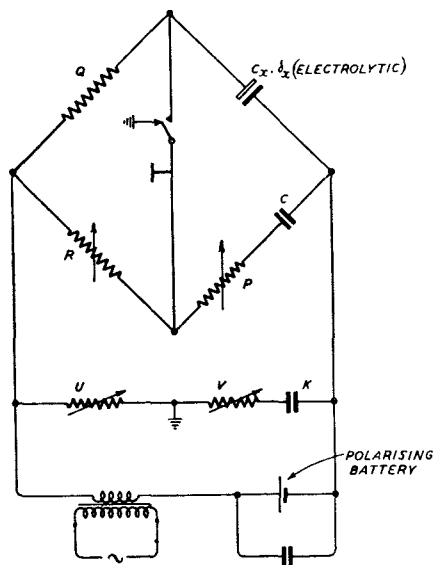
FIG. 6.—BRIDGE FOR MEASUREMENTS ON PAPER CONDENSERS.

When the bridge is balanced

$$C_x = \frac{R}{Q} C, \text{ and}$$

$$\tan \delta = \omega PC.$$

Now the impedance of, say, a 100 μF. condenser at 800 c/s. is about 2 ohms. Q must in any case be a low resistance, and if it is made equal to 2 ohms and if C is made equal to 2 μF. the capacity C_x in microfarads is equal to R. Also $\tan \delta = \dfrac{P}{100}$ at 800 c/s.

$$C = \frac{R}{Q} C, \qquad \tan \delta_x = \omega PC$$

$$IF\ Q = 2\ OHMS, \quad C = 2\mu F, \quad \& \ \omega = 5{,}000,$$

$$THEN\ \ C_x = R(\mu F) \quad \& \quad \tan \delta_x = \frac{P}{100}$$

FIG. 7.—BRIDGE FOR TESTING ELECTROLYTIC CONDENSERS.

P is therefore an adjustable resistance with a maximum of 100 ohms in steps of 0.1 ohm.

Since the bridge is of low impedance it may be used satisfactorily at 800 c/s. in spite of its lack of symmetry. At higher frequencies, however, stray capacities become important and it is necessary to employ a Wagner earth connection as shown in Fig. 7. In order to check measurements at high audio frequencies a bank of paper condensers of 50 μF. was made up and a series resistance added so that the combination simulated an electrolytic condenser. The capacity and resistance of the combination were measurable on the bridge to an accuracy of $\pm$ 1% up to a frequency of at least 6,400 c/s.

A.C. Potentiometer Method.

A method is available in which an alternating current is passed through the condenser in series with a non-reactive resistance and the relative magnitude and phase of the resulting voltages across the resistance and condenser are measured by means of an A.C. potentiometer. The circuit arrangement is shown in Fig. 8.

An oscillator and a polarizing battery of suitable voltage are connected to the condenser under test and a non-reactive one ohm resistance in series. Part of
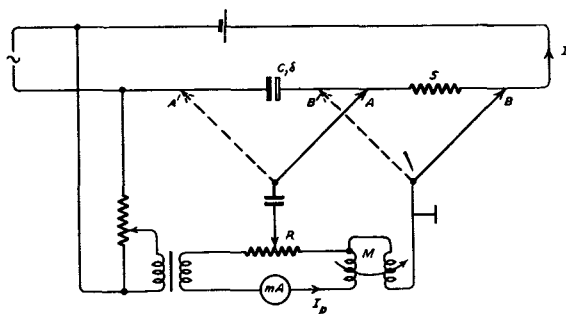
$$c = \frac{R_s^2 + \omega^2 M_s^2}{s\omega^2(R_s M_c - R_c M_s)} \qquad \tan \delta = \frac{R_s R_c + \omega^2 M_s M_c}{\omega^2(R_s M_c - R_c M_s)}$$
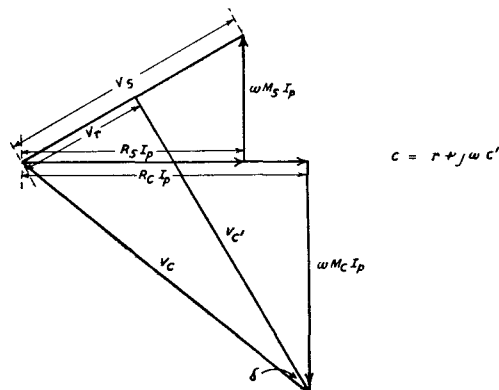
$$c = r + j\omega c'$$

FIG. 8.—A.C. POTENTIOMETER FOR CAPACITY AND LOSS ANGLE OF ELECTROLYTIC CONDENSERS.

the oscillator output is applied *via* a current control and transformer to a potentiometer and the primary winding of a mutual inductometer. If the current in this latter circuit is maintained at a constant value, the magnitude and phase of the potential difference across A and B can be adjusted by varying R and M. The leads A and B are connected first across the resistance S and then across the condenser and R and M are adjusted for each position until no sound is heard in the receiver. Then if R_s, M_s and R_c, M_c are the values of resistance and mutual inductance in the two positions, the equivalent series capacity and resistance of the condenser may be calculated from—

$$C = \frac{R_c{}^2 + \omega^2 M_s{}^2}{\omega^2 S(R_s M_c - R_c M_s)}$$

and

$$r = \frac{S(R_s R_c + \omega^2 M_s M_c)}{R_s{}^2 + \omega^2 M_s{}^2}$$

It is easier, however, and usually sufficiently accurate to draw a vector diagram as in the figure.

The potential across S, (V_s), is the vector sum of $R_s I_p$ and $\omega M_s I_p$, and the potential across the condenser, (V_c), is the vector sum of $R_c I_p$ and $\omega M_c I_p$, due regard being paid to the sign of M. Then V_c must also be the vector sum of V_r, the potential across the equivalent series resistance of the condenser and $V_c{}'$ the potential across the equivalent series capacity. V_r will be in phase with V_s and $V_c{}'$ will lag 90° from V_s as shown.

Then,

$$r = \frac{S V_r}{V_s}$$

and

$$C = \frac{V_s}{\omega S V_c}$$

and the power factor—

$$\frac{V_r}{V_c{}'}$$

The capacities and power factors of ten condensers have been measured by both the bridge and the potentiometer methods described. The capacities ranged from 40 μF. to 250 μF. and the power factors from 0.06 to 0.85. The largest difference in the capacity measurements was about 1% and in the power factor measurements was about 10%.

Measurement of Capacity and Power Factor at Carrier Frequencies.

Recent advances in carrier telephony have necessitated the measurement of the capacity and power factor of specimens of dielectric materials and of condensers at frequencies up to at least 500 kc/s. It has also become necessary to determine the stability of small condensers of the metallized mica and ceramic types, for example, when subjected to variations of temperature. For these purposes the " reactance variation " method is in course of development.

The method has been fully described by Hartshorn and Ward[5] for measurements on specimens up to about 50 $\mu\mu$F. capacity at frequencies between 10 kc/s. and 50 mc/s., and commercial apparatus to their design is available.

The requirements of the Research Branch are rather different, however, in that measurements will be made

(5) See Bibliography.

at comparatively low frequencies, probably not above 500 kc/s., and condensers up to at least 1000 $\mu\mu$F. capacity may require to be tested. The extension of the capacity range has necessitated changes in the type of apparatus employed and the reduction of the frequency range has resulted in greater simplicity and flexibility.

The reactance variation method is based on the fact that the decrement of a tuned circuit is dependent on the total losses in the circuit. A constant E.M.F. at constant frequency is induced into a parallel tuned circuit and the capacity is adjusted until the voltage across the circuit is a maximum. A measurement of the change in capacity necessary to produce a given reduction in voltage across the circuit enables the total shunt conductance of the circuit to be calculated.

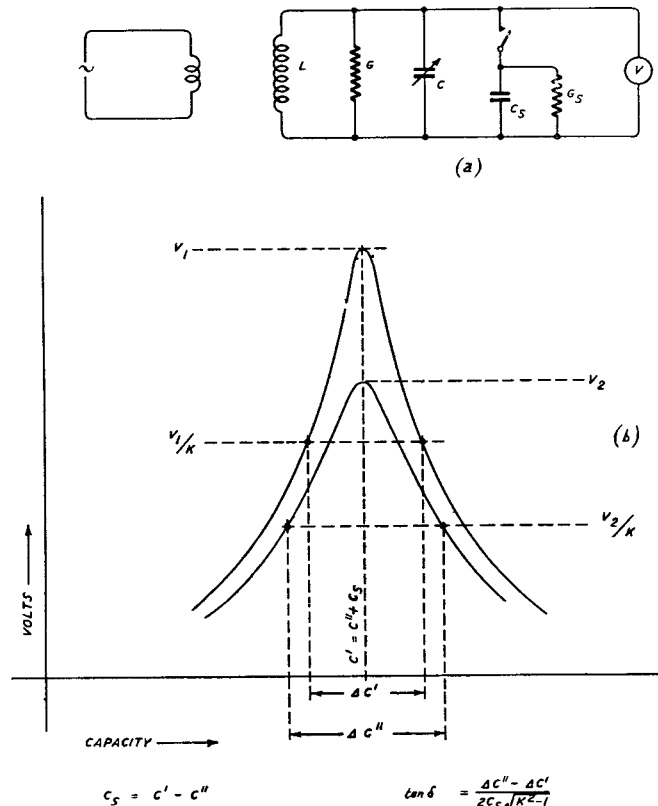The circuit is shown in schematic form in Fig. 9(a),

FIG. 9.—CAPACITY AND POWER FACTOR BY REACTANCE VARIATION METHOD.

where L is the coil, C is an adjustable air condenser and G is the total shunt conductance due to the coil, the condenser, voltmeter and leads, etc. The specimen, represented by a capacity C_s and conductance G_s, may be connected when required. To make a measurement the oscillator is set at the required frequency and the output is adjusted until a convenient maximum voltage reading is obtained with the circuit tuned to resonance by adjustment of C, and with the specimen disconnected. Suppose this maximum voltage across the circuit is now V_1 (Fig. 9(b)) and the capacity of the condenser is C'. Two

9

values of capacity are now found, one less and one greater than C', which reduce the voltage across the circuit to some predetermined value V_1/k. Let the difference between these values be $\Delta C'$. The specimen is then connected and the circuit is tuned to resonance once more. The maximum voltage across the circuit will be smaller because the additional shunt conductance of the specimen has been introduced. Let this value be V_2 and the capacity of the condenser now be C''. A similar process is again followed, the voltage being reduced to V_2/k. Thus a capacity difference $\Delta C''$ is obtained.

Then $C_s = C' - C''$

and the power factor can be obtained from

$$\tan \delta = \frac{\Delta C'' - \Delta C'}{2C_s \sqrt{k^2 - 1}}$$

The use of two points, one on each side of the resonance curve, is desirable since the curve is steeper at these points than near the maximum voltage, and is permissible since it is symmetrical about the point of resonance.

This method is suitable for the measurement of the resistance of inductance coils and for the testing of high resistances at carrier frequencies.

In practice condensers of 1000 $\mu\mu$F. have to be tested and the arrangement shown in Fig. 10 is used. C_1 is an adjustable air condenser of 1500 $\mu\mu$F. maximum capacity. The accuracy of the result depends on a difference of two capacities which may themselves be small, great scale reading accuracy is therefore necessary. Since this cannot be attained with a condenser having such a high maximum capacity a second one C_2, which has a maximum capacity of 100 $\mu\mu$F., is connected in parallel. It is important that the conductances of the condensers should be as low as possible. The power factor of condenser C_1 at a frequency of 50 kc/s. is 0.00001 over most of the range and rises to 0.00003 when its capacity is reduced to about one-tenth of its maximum.

The sensitivity of the method is dependent on the losses existing in the circuit before the specimen condenser is connected. The coils are the principal source of this loss and considerable care is necessary in their design.[6] A number of coils are necessary to cover the frequency range and Fig. 11 shows the variation of
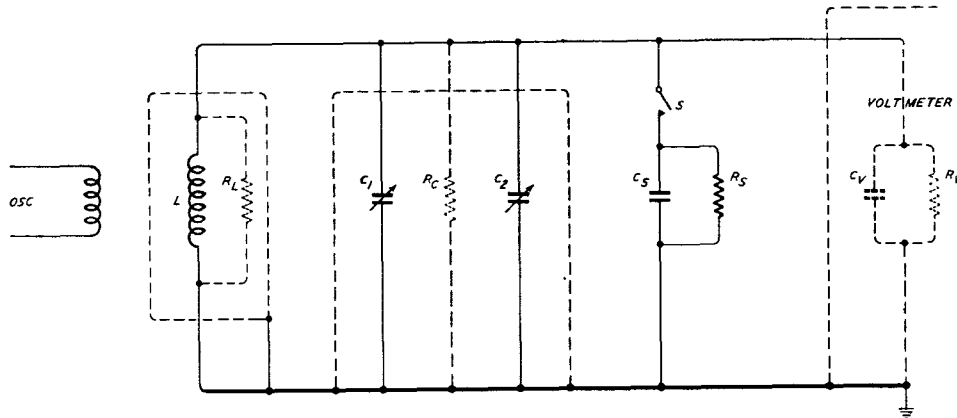
[6] See Bibliography.

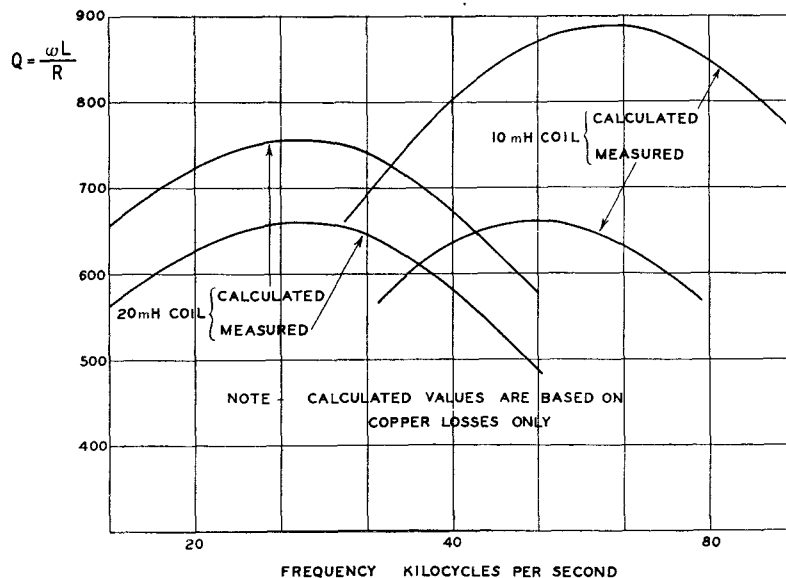FIG. 10.—CIRCUIT OF REACTANCE VARIATION APPARATUS.

FIG. 11.—Q-VALUES OF TYPICAL COILS.

$\dfrac{\omega L}{R}$ with frequency for some of them. Stability is another necessary feature and to assist in this direction without increasing the dielectric loss or unduly augmenting the self capacity they have been impregnated with polystyrene resin. A typical coil is shown in Fig. 12.
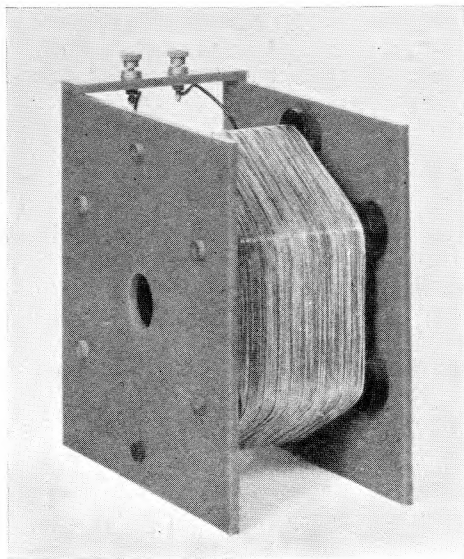
Voltmeter.

The circuit of the voltmeter is shown in Fig. 13. It has been found possible by the adoption of suitable stabilizing means to use the A.C. mains as a source of power. Two indirectly heated valves which are matched under working conditions, form two arms of a bridge, which is unbalanced when an alternating p.d. is applied to the grid of one of them. The unbalance current is measured by the galvanometer. To avoid relying on the calibration of the voltmeter a potentiometer is employed so that when the reduced voltage V_1/k is adjusted, the actual input to the voltmeter bridge is the same as for the measurement of V_1. Since this potentiometer cannot be connected directly across the tuned circuit an amplifier is used. This voltmeter has a flat frequency response and an input impedance greater than 10 megohms up to at least 80 kc/s. It obeys a square law for inputs up to 0.1 volt and full scale deflection, with the galvanometer unshunted, is obtained with an input of 0.03 volt.

The output and frequency of the oscillator must remain constant. A dynatron oscillator is in course of construction, but reproducible results have been obtained with a simple triode oscillator covering the range from 10 to 84 kc/s.

4. PREPARATION OF SPECIMENS— ELECTRODE SYSTEMS.

For the purposes of electrical tests solid dielectric materials are generally obtained in the form of flat sheets, waxes being specially cast in this form. The results of such tests are dependent largely on the type of electrode employed and the choice of suitable electrodes is therefore of vital importance.

Resistance Measurements.

(a) *Surface Resistance.* The resistance to be measured is rarely less than 100 megohms and no appreciable error will result if the electrodes themselves have a resistance amounting to a few thousand ohms. Electrodes of colloidal graphite are used,

FIG. 13.—VALVE VOLTMETER FOR REACTANCE VARIATION METHOD.

backed by several layers of lead foil which are held in place by a suitable clip. A colloidal suspension of graphite in water is available commercially under the trade name of " Aquadag," and may be painted on the surface of the material under test with a camel hair brush.

(b) *Volume Resistance.* In order that the measured resistance may not be too high it is necessary to make contact with the specimen over the whole of the area of the electrode. Either mercury or Aquadag electrodes are suitable. Mercury is recommended by the British Standards Institution and the usual method adopted by the Research Branch is to float the specimen on clean mercury which forms one electrode. The upper electrode consists of mercury contained in a cylinder resting on the surface of the material. If a guard ring is employed it is painted with Aquadag just clear of the upper electrode and contact with it is made by mercury in a small cylinder resting on its surface.

Capacity and Power Factor Measurements.

These present a more difficult problem since errors in capacity will result if there are air films between the specimen and the electrode, while the measured power factor will be inaccurate if the electrodes have appreciable resistance. In the case of power factor measurements the error will increase with frequency.

At power frequencies mercury or Aquadag electrodes appear to be satisfactory.[7] At higher frequencies an Aquadag electrode backed by a flat brass plate may be suitable when the surface of the specimen is flat, but the best results are obtained with Aquadag electrodes backed with mercury. This arrangement is satisfactory at frequencies up to 80 kc/s. Mercury alone is not so good because small bubbles of air may remain on the surface of the material, but when it is used with Aquadag a good contact with the graphite film is obtained. This is necessary because although owing to its extreme thinness the film has a low resistance perpendicular to the surface, its resistance parallel to the surface is considerable.

While the application of Aquadag is generally permissible there are some crystalline waxes which tend to absorb the colloidal graphite. In such cases electrodes of tin foil, applied with a thin film of pure petroleum jelly and backed by brass plates have proved suitable.

5. CONDITIONING CHAMBERS.

The requirements which a conditioning chamber has to meet are severe. It must remain air-tight when differences of temperature of about 30°C or more exist between its interior and its exterior and the former must withstand continuous exposure to very damp or very dry atmospheres without warping or corroding.

The type which appears to meet most requirements satisfactorily, while remaining an economic possibility, consists of an inverted glass tank, about 21 ins. × 14 ins. × 12 ins., resting on a teak base. The edges of the tank rest in a groove filled with mercury which gives an air-tight seal. The testing leads consist of stranded tinned copper conductors with heavy rubber

insulation embedded in paraffin wax where they pass through the base. The outside ends of the leads are located by mounting them in a solid block of paraffin wax resting on the bench. Under the most severe conditions met with in testing the resistance of these leads to earth exceeds 10^6 megohms. The remainder of the base is occupied by heaters, flat dishes containing the solutions used to control humidity and a fan, driven by a small motor mounted underneath the base, which keeps the air in constant circulation. A bi-metallic strip thermostat is used for controlling temperature. The part of the baseboard not occupied by the leads is covered by a wooden platform which carries the specimens under test.

Dry atmospheres are obtained by exposing a large area of phosphorus pentoxide or silica gel in the chamber for some days. Relative humidities up to 95% may be obtained by exposing sulphuric acid solutions of suitable density.[8]

6. PLASTICS.

A large group of dielectric materials are included under the general heading of " plastics." Most of these are of post-war origin and owing to the recent development of a number of new materials of this nature the applications are becoming ever more widespread.

Plastic materials may be divided into two groups according to their behaviour at elevated temperatures. Materials in these groups are described as thermosetting and thermoplastic respectively. When a thermosetting resin is moulded, a non-reversible action takes place giving as the final product an infusible resin. A thermoplastic resin, however, remains permanently susceptible to the softening action of heat. Many thermosetting resins can be used at higher temperatures than the thermoplastic ones.

Thermosetting Plastics.

These are used in large quantities by the Department and are available in various grades according to the purposes for which they are required. For some applications superior electrical properties may be the main consideration, while for others heat resistance or resistance to impact may be of greater importance.

Typical thermosetting moulding powders[9] are made from formaldehyde and

    (1) Phenol or cresol when they are known as phenol plastics.

    (2) Urea or thiourea when they are known as aminoplastics.

In the manufacture of thermosetting resin for electrical purposes, what is known as a " two-stage " process is generally employed. The raw materials are phenol (carbolic acid) and formaldehyde (formalin). An aqueous mixture of these substances is boiled for some hours in the presence of an alkaline catalyst (for example ammonia) and an insoluble resin is produced. This resin is liquid at high temperatures and is separated from the water layer, run into trays, and allowed to cool (Stage I). This transparent, fusible resin is compounded with fillers (wood flour, slate,

(7) (8) (9) See Bibliography.

asbestos, etc.), colouring matter and a further quantity of catalyst, the last generally being hexamine, which is a compound of ammonia and formaldehyde. The ingredients are thoroughly ground together and may be put through hot rolls. The resulting product is ground and screened, and is then ready for moulding. This consists of heating the powder under pressure at a temperature of about 170°C. The fusible resin undergoes further condensation and gives the infusible product so generally familiar. (Stage II). Comparatively minor changes in the method of manufacture may result in large changes in the properties of the product.

Amino-plastic moulding powders have similar properties to phenol-plastic powders, but are available in a variety of colours. Thiourea formaldehyde mouldings have slightly better electrical properties and higher mechanical strength at room temperatures than urea formaldehyde mouldings. The properties fall off more rapidly than those of phenol-plastics, however, with increasing temperature.

It has been stated that the water absorption of phenol-plastics is due almost entirely to the filler, but in the case of amino-plastics it is certainly partly due to the resin itself, so that the total water absorption is greater in the latter case.

Thermosetting plastics are widely used by the Post Office Engineering Department. Thus phenol-plastics which include such materials as Bakelite, Elo, Nestorite, and others are employed in telephone instruments, meter covers, cable distribution heads and so on. Amino-plastics, such as Beetle, Mouldrite and Pollopas have been employed in coloured telephone parts.

It is thus seen that different properties are of first importance in the various applications. For this reason it has been suggested by the Research Branch that moulding powders should be divided into a number of grades suitable for use where: —

1. The highest class of finish and good insulating properties are essential.
2. Impact resistance is of paramount importance.
3. The moulding is to be heat resisting.

The electrical properties only will be considered in detail. Since thermosetting resins have a relatively high power factor they are unsuitable for use where low dielectric loss is required and for this reason only the volume and surface resistivities are normally measured. The surface resistivity is the more important of these properties for the materials under consideration. The specimens are normally conditioned for 48 hours before test at 90% relative humidity and 20-25°C and are tested in this atmosphere.

The volume resistivity is determined, firstly, after conditioning in a dry atmosphere for 24 hours, and then after immersion in distilled water for the same period. In the latter case the surface moisture is removed by pressing with dry blotting paper after which the specimen is tested within five minutes of removal from the water.

The actual resistivities depend, not only on the composition of the moulding powder and on the filler employed, but also on the conditions of moulding.

The specification figures at present in force are: —
Surface Resistivity at 90% relative humidity, 2×10^{10} ohms.
Volume Resistivity.
After drying for 24 hours, 10^{11} ohms cms.
After immersion in water for 24 hours, 3×10^{10} ohms cms.

Thermo-plastic Materials.

These are not at present used to the same extent as thermosetting resins, but this is to some extent due to their more recent development. They may be divided into four groups: —

1. Cellulose type (cellulose acetate, benzyl chloride, etc.).
2. Vinyl resins.[10]
3. Polystyrene resins.[10] & [11]
4. Polyacrylic acid derivatives.

Plastics of the cellulose type are used in the cradles and plungers of hand-microtelephones, but are not otherwise used extensively by the Department.

Most applications of vinyl resins have been non-electrical, but the recent production of polyvinyl chloride under the name of " Mipolam " may lead to electrical applications. The material can be used for cable or wire insulation and can be applied by means of existing rubber extrusion machines with only minor alterations. Important properties are non-inflammability and resistance to temperature up to 150°C without decomposition, although it will of course soften at lower temperatures. It is available in a number of colours which are fast to light. Possible applications are use as the insulating material on jumper wire, and as the outer covering of cables. A number of grades are available, some having superior electrical characteristics, while others have better mechanical properties. The properties of an " electrical " grade which has been tested are given in the table, Fig. 14.

Property.	Thermo setting Resins.	Mipolam Grade K646 (Poly-vinyl Chloride)	Trolitul (Poly-styrene) Resin.	Diakon (Methyl Metha-crylate)
Volume resistivity (ohm cms)	10^{11}—10^{12}	10^{14}	$>10^{17}$	10^{17}
Surface resistivity (90% R H) ohms	10^{10}—10^{11}	—	10^{13}	10^{12}
Permittivity at 800 c.p.s	6	3.5	2.2	3.6
80 kc/s	—	2 9	—	3.2
Power Factor at 800 c.p.s	0 03—0 4	0.07	0.0001	0.035
80 kc/s	—	0 03	—	0.02

Fig. 14 Electrical Properties of Typical Plastic Materials.

Polystyrene Resins.

Although perhaps the oldest known synthetic resin polystyrene has only recently been developed. It is perhaps the most interesting synthetic resin available on account of its exceptional electrical properties and

[10] [11] See Bibliography.

low water absorption. The polystyrene resins are obtained by the polymerization of styrene (that is, by the aggregation of a number of molecules of styrene into one larger molecule having the same percentage composition as the original material, but a larger molecular weight), either by heating with or without catalysts, or it may be heated in an inert solvent. When put in the mould the material is completely polymerized to chains containing several thousands of elementary units. During the moulding process no further polymerization occurs, and the time required for moulding is therefore only that needed for the material to flow into the mould. It is necessary, however, to let the moulded products cool in the mould.

Styrene is a colourless liquid which may be used to impregnate coils, etc. On heating to 120°C for several hours polymerization occurs and the interstices of the coil are filled with solid masses of polystyrene resin.

Polystyrene is colourless and transparent. Above 300°C it breaks down again into the monomer.

The material can be manufactured hard in the form of sheets, rods, etc., or moulded into any required shape. It may be coloured and its use for moulded telephone parts is at once suggested, since although the pure resin is brittle its mechanical properties may be improved by the addition of suitable plasticizers.

The electrical properties are exceptional. The volume and surface resistivities are high even under severe conditions of humidity. Measurements are made with the electrometer method, but otherwise are essentially the same as those made on thermosetting mouldings. The permittivity and power factor are difficult to measure owing to the small magnitude of the latter; the Schering bridge can be employed, using a guard ring at the same potential as the low potential electrode as previously described, but special care is necessary in operation.

Uses of polystyrene have in the past been limited, but will no doubt increase as the properties become better known. It has, however, been used for insulating wire, and in the construction of a coaxial cable in Germany. It is suitable wherever high insulation is required, or where low power loss is desirable. The Radio Branch of the Post Office Engineering Department have used the material for coil formers in view of its low dielectric loss, and small water absorption. Another interesting application is the impregnation of low-loss coils by solution of polystyrene in xylene. The solution may be brushed on to the coils, the xylene evaporating at room temperature. Owing to its low water absorption the use of polystyrene has been suggested for submarine cables. The pure resin is, however, too brittle for this purpose, and the addition of plasticizers would probably produce a deterioration in electrical properties.

Polyacrylic Acid Derivatives.

Originally developed in this country under the name of " resin M," polymerized methyl methacrylate is now marketed under the trade names of " Diakon " and " Perspex." These materials are somewhat similar to polystyrene in that they are prepared from the monomer, and when polymerized contain several thousand elementary units to each molecule. The

moulding is also similar. Either compression or injection moulding may be employed, although the treatment in the former case is somewhat different from that in the preparation of phenol-formaldehyde moulded products in that the material must be cooled in the mould. The electrical properties are not so good as those of polystyrene, the power factor, in particular, being some 100 times greater, but it is superior as regards mechanical properties. It is proposed to use coloured mouldings of " Diakon " for telephone parts. The material " Perspex " has been developed mainly for optical applications and is being tried in notice frames, meter covers, etc.

7. WAXES.

General Classification.

Until comparatively recently the only waxes in general use have been the paraffins, derived either from natural sources or as a distillation product of petroleum oil. During the last few years, however, a number of synthetic compounds of wax-like nature have been developed which may prove of great service in the telecommunications industry.

Paraffin wax consists of saturated hydrocarbons of the series $C_N H_{2N+2}$, and there are many grades which vary according to the source or method of manufacture. It has been used for many years for the impregnation of paper dielectric condensers and for other purposes where high insulation is important.

Ozokerite, known also as Cerasin, Cerite or mineral wax occurs naturally, usually in the neighbourhood of petroleum wells. Its properties vary considerably, depending on its source. The refined product consists essentially of paraffin hydrocarbons and it is therefore similar chemically to the paraffin wax of the petroleum distiller, but, owing to the presence of compounds not found in the latter material, its physical properties are somewhat different. In these it bears some resemblance to beeswax.

" Superlawax," which has a very high volume resistivity, is a purified paraffin hydrocarbon. An example of its use is as a mounting for the earthing switch of the Lindemann electrometer.

There is one animal wax, namely, beeswax, which is used in fairly large quantities in the industry. Its physical properties render it especially suitable for the impregnation of cable forms since it enables the cable to retain some degree of flexibility. Beeswax is unfortunately very expensive and alternatives are being sought.

Besides these well-known waxes certain synthetic materials are now available. One of the most useful of these is perhaps chlorinated naphthalene, of which Halowax and Seekay wax are examples. These are made by direct chlorination of naphthalene which is produced in large quantities by the gas industry. The reaction consists in the replacement of a varying number of the hydrogen atoms in the naphthalene molecule by chlorine in the presence of a catalyst. Many different chemical compounds result according to how many and which of the hydrogen atoms are substituted by chlorine. In the commercial process mixtures are obtained which are assessed on the basis

of the total percentage of combined chlorine. The predominance of any one compound may generally be obtained by control of the conditions. A range of waxes is available and these may easily be distinguished by their melting points, since the melting point rises with increasing percentage of combined chlorine. Chlorinated naphthalene waxes have certain advantages over paraffin wax and beeswax, the most important of which is non-inflammability. They are resistant to insect attack, have a faint characteristic odour and higher permittivity than paraffin wax. Certain grades are suitable for the impregnation of wires and cables, and for the impregnation and filling of paper dielectric condensers.

Electrical Properties.

For the measurement of the electrical properties of waxes the material is cast into the form of thin discs by melting it inside an iron ring which floats on the surface of clean mercury. When the wax has cooled a smaller disc is cut by means of a special tool from the large disc so prepared. The surface of the wax is carefully scraped flat and smoothed.

The electrical properties of a few of the waxes previously mentioned are given below: —

Wax	Vol. Resistivity (ohm—cms)	Permittivity (800 c.p.s.)	Power factor (800 c.p.s)
Beeswax ...	5×10^{14}	3.0	0.02^5
Paraffin wax	8×10^{14}	2.2	$\angle 0.001$
Chlorinated naphthalene	10^{14} to 10^{16}	4 to 6	$\angle 0.001$
Superlawax...	2×10^{18}	2.6	$\angle 0.001$

Physical Properties.

Waxes used for impregnation should be tenacious without being sticky. The relative tenacity of various waxes may be determined by measuring the force required to pull apart two flat brass discs which have been sealed together with a thin film of the material. The stickiness is determined by weighing the amount of silver sand which is picked up during one minute on lowering a disc of standard weight and 2 in. in diameter, the underside of which is coated with wax, on to a tray of clean silver sand.

The specific gravity, melting point, pouring temperature and contraction on cooling are other properties which have to be determined.

Chemical Properties.

Since waxes used by the Department are frequently in contact with copper, tin or aluminium, tests are generally carried out on new waxes to ascertain whether they have any corrosive action on these metals. In the absence of obviously harmful constituents exposure of strips of metals to the wax at an elevated temperature accelerates any corrosive action which may occur. This method has certain disadvantages, but is the only one of general applicability.

8. CERAMICS.

Ceramic materials were originally regarded as clay products which had been specially heat treated or fired, but it is now necessary to employ a broader description. A ceramic material is perhaps best defined as an inorganic compound which can be fired to form a vitreous product. The electrical uses of these materials are many, and will be considered in relation to their properties.

Porcelains.

The art of making porcelain was introduced by the Chinese more than 2,000 years ago, but it is only comparatively recently that the need has arisen for a high grade electrical porcelain. The use of porcelain as an insulator for external applications may be attributed to its resistance to weathering, durability, low cost and high dielectric strength.

Electrical porcelain consists of a suitable mixture of clay, flux and filler vitrified by firing. China clay (aluminium silicate) and ball clay are used, together with felsper to act as flux, and quartz to toughen the product.

The main application by the Department is for line insulators for which high insulation resistances are required. Under adverse weather conditions the leakage is largely due to low surface resistance which is, however, increased by glazing. The capacity and power losses should also be low, and porcelain fulfils these requirements better than other materials employed.

Steatite.

The use of steatite is comparatively modern, its first applications being for heat-resisting fittings such as gas burners. Steatite occurs naturally as talc or soapstone and consists of magnesium silicate. Ordinary talc is widely distributed, but the material mainly used for electrical purposes is obtained in large masses in the Fichtel Mountains in Germany where it is known as " Speckstein."

Steatite is fabricated into the required shape before firing, and allowance must be made for shrinkage. Articles of simple configuration can afterwards be ground and polished to an exact specified size. Tapped holes, however, cannot be ground to size after firing, and must be shrunk to the required size by careful design and control of conditions during the firing process. In spite of such limitations, however, steatite finds considerable application due to the facts that it is the strongest mechanically of ceramic materials and has useful electrical properties.

On account of its low dielectric loss, especially at high frequencies, steatite is used in the construction of components in radio receiving sets. Dielectrics with a steatite base such as Calit and Frequentite,[12] have a power factor of 4×10^{-4} at 1 megacycle per sec. and 3×10^{-4} at 50 megacycles per sec. and their permittivity is about 6. (Fig. 15.)

Rutile.

Rutile occurs in nature in gneiss and schist particularly in the Grave Mountain in America and in Norway. It is a crystalline form of titanium dioxide and is characterised in that it has an exceptionally high permittivity, which, in single crystals of the material varies with the direction. The permittivity of a mass of pulverized crystals is about 110.

Powdered rutile may be mixed with a binder and

---

(12) See Bibliography.

Trade Name.	Composition.	Permittivity.	Temperature Coefficient of Permittivity parts in 10^4 per $1°$ C.	Power factor at $20°$ C $\times 10^4$		
				at 800 c.p.s.	at 10^6 c p.s.	at 5×10^7 c.p.s.
Calit	Steatite (Magnesium Silicate)	6.5	$+1.2$ to $+1.6$	10	4	3
Frequenta	Steatite	6	$+1.0$	—	4	3
Condensa "C"	Rutile (Titanium Dioxide)	80	-7.0 to -7.4	HIGH	5.5	—
Kerafar (New)	Rutile + Zirconium Dioxide	55	-5	—	—	—
Diacond	Magnesium Titanate	16	—	5	1	—
Tempa "S"	Magnesium Titanate	14	$+0.3$ to $+0.5$	5	0.8	—

FIG. 15. ELECTRICAL PROPERTIES OF TYPICAL CERAMIC MATERIALS.

then fired to form a ceramic material which has good mechanical properties. Although this material has a high permittivity, it has also a large power factor especially at audio frequencies.

Other Ceramic Materials.

Various attempts have been made to produce a ceramic material having a low power loss and a high permittivity. For example, zirconium dioxide has been added to rutile to produce a material known as Kerafar.

Rutile has a large negative temperature coefficient of permittivity, but this may be reduced by using a material with a high positive temperature coefficient as a binder. Since, however, these materials have a low permittivity that of the resulting ceramic will be lowered. Reduction of the temperature coefficient to zero has been attained by Soyck,[13] but only by a reduction of permittivity to between 10 and 12. As far as is known, no material has yet been produced having a very high permittivity and a low temperature coefficient of permittivity.

The use of synthetic magnesium titanate as a base in materials such as "Diacond" and "Tempa" results in a power factor of 5×10^{-4} at 800 c/s. and a permittivity of 15. These materials have also a smaller temperature coefficient of permittivity than have materials prepared from rutile.

Ceramic materials, usually with a steatite or rutile base, have been applied during the last few years to the manufacture of small capacity condensers. These have found considerable application in radio apparatus on account of their low power factors at radio-frequencies and small size. The most satisfactory condensers of this kind have been produced by a German firm which is associated with the Kahla porcelain factories. A few British firms also are now producing ceramic dielectric condensers.

Investigations are now being carried out to determine the suitability of ceramic condensers for use by

(13) (14) (15) See Bibliography.

the Post Office at audio and carrier frequencies. The requirements to be met are small size, low power losses, and stability of capacity under changing conditions of temperature and humidity.

9. TEXTILE MATERIALS.

Textiles are widely employed as wire coverings to provide mechanical protection and electrical separation of the conductors. The ideal textile should have a high insulation resistance and be sufficiently strong in tension to meet the requirements of manufacturing processes. Moisture resistance, flame resistance, and freedom from attack by insects and fungi are also desirable. The material should be chemically stable and free from impurities which would tend to cause corrosion under adverse conditions. It will be seen that the requirements are varied and severe.

Insulation Resistance.

The relative insulating properties of textile materials are not easy to assess. One of the chief difficulties is the preparation of a specimen in suitable form. Early measurements were made on compressed masses of yarn either unsupported or contained in glass tubes. Owing probably to air spaces and also in some cases to leakage along the supporting tubes, when they were used, the results were so variable as to be of very little value.

A more reliable method is described in an early investigation by the E.R.A.[11] The yarn was wound on a flat highly polished stainless steel electrode about four inches square and half an inch thick. The second electrode consisted of a similar plate resting on the first and loaded with weights. Tests showed that the resistance measured decreased as the pressure between the electrodes was increased until a limiting pressure was reached after which no appreciable change in resistance occurred. Measurements were made always at this pressure. Results of tests made with numbers of layers up to ten, successive layers being wound at right angles showed that with more than two layers the results were difficult to interpret. One layer was therefore adopted as the standard arrangement, but even then the results of successive tests on different samples of the same material were found to vary by as much as twenty times and a large number of observations were required in order to assess the insulating properties of a single material.

The measurement of the longitudinal resistance of yarns is also difficult, but much more consistent results are obtainable. Fortunately, the longitudinal resistance gives a reasonably good idea of the relative insulating properties of various materials under practical conditions although it might appear that the transverse resistance is more relevant.

Murphy and Walker[15] wound from thirty to one hundred turns of yarn round two brass pillars mounted, with 1.3 cms. between centres, on ebonite coated with ozokerite wax. Several sets of electrodes were mounted on one panel and connected to give 2000 threads in parallel.

A similar but rather more convenient method is in use at the Post Office Engineering Department Research Branch. The yarn is wound on two parallel

stainless steel rods mounted on two blocks of high grade insulating material. Reconstructed amber was formerly used, but recently Trolitul, which has a considerably higher surface resistivity and negligible water absorption, has been tried. Both these materials are rather difficult to work. Measurements of the leakage current due to these formers showed that in some cases, even after the insulating material had been carefully cleaned, the insulation resistance was comparable with that obtained with the best yarns. Guard rings, which consist of narrow bands of Aquadag painted round the end pieces, are therefore employed. Connection is made to these rings by Staybrite steel clips. Figs. **16** and **17** show the arrangement of the formers and the guard rings.
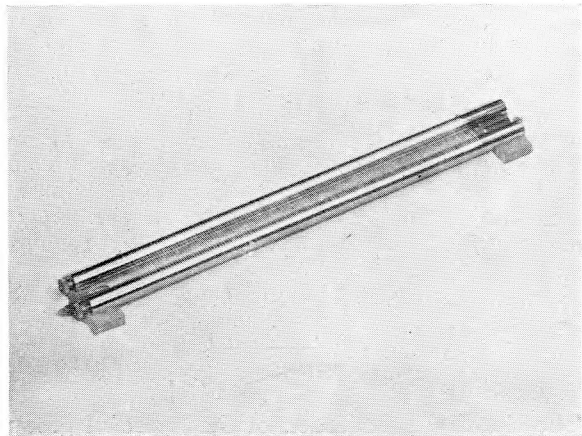
The insulation resistance measured under any given conditions depends on the number of turns and the weight per unit length of the yarn. In order to enable comparisons to be made between different samples and kinds of yarn, results are expressed in ohms per centimetre related to a rayon (artificial silk) count of
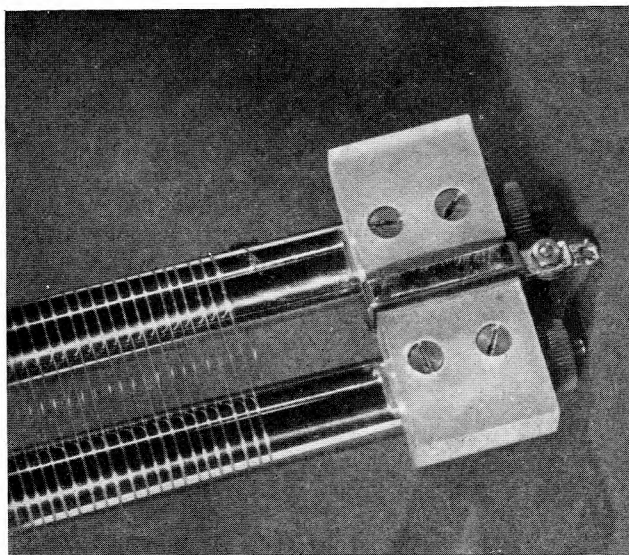
Fig. **17**.

1000 deniers. The count of a yarn in deniers is defined as the weight in grams of 9000 metres. Thus if—

r = observed insulation resistance in ohms,
T = number of turns wound on the former,
l = distance between centres of the rods,
and D = count in deniers,

then the insulation resistance (R) in ohms per centimetre for a count of 1000 deniers is given by—

$$R = \frac{2TDr}{1000l}$$

The above method has been found to give very consistent results. Tests made on samples of rayon at an interval of approximately nine months showed that the logarithm of the insulation resistance can be determined to within about 2%.

Anomalous Effects—Polarization.

The resistance of a moisture absorbing dielectric is altered by the passage of a current.[16] In the case of most cellulose materials the resistance is increased.

If a current is passed through a yarn in equilibrium with an atmosphere of relative humidity exceeding 30% a back E.M.F. is developed. This back E.M.F. is of the order of 2 volts and may be ascribed to electrolysis of the aqueous solutions present. If a short thread of cotton yarn, which has been " polarized " in this way when exposed to a high relative humidity, is connected to a galvanometer after removal of the polarizing voltage, a current (of the order of 10^{-8} amps) will flow for some minutes.

At lower relative humidities the residual E.M.F. becomes a function of the polarizing voltage and reaches a value of 100v when the polarizing voltage is 400v. It appears, therefore, that at low relative humidities yarns behave as dielectrics in which anomalous charging and discharging current phenomena are pronounced, a conclusion which is borne out by the results of capacity and power factor measurements.[17]

It will be seen from the above that the measurement of the true resistance of a yarn, that is, the resistance at the instant of application of the testing voltage, before polarization has occurred, is very difficult. Fortunately, for comparing the insulating properties of different yarns measurement of what may be called the " polarized resistance " is satisfactory, and the usual procedure is to measure the resistance after the testing voltage has been applied for one minute.

Insulation Resistance as a Function of Moisture Content.

The insulation resistance of a textile varies rapidly with the relative humidity of the atmosphere surrounding it, and it is therefore necessary to make measurements under carefully controlled conditions. The humidity chambers already described are used to condition the samples which are maintained in an atmosphere of given humidity for 48 hours before a measurement is made. Tests are made first in a dry atmosphere and then at various humidities up to 95% relative humidity. Typical results are given in curve A of Fig. **18**.

(16) (17) See Bibliography.
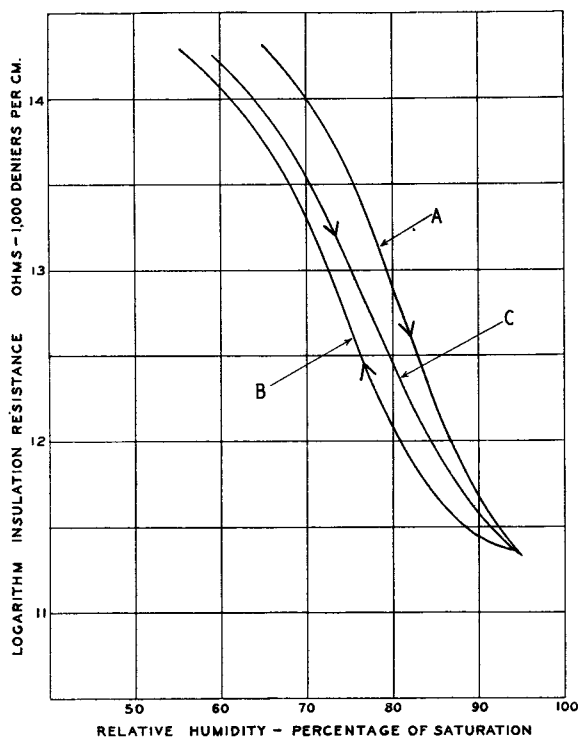
FIG. 18.—Effect of Humidity Cycle upon Insulation
Resistance.

If a second series of measurements are made on the same sample but with decreasing humidities curve B is obtained. A further series of tests with increasing humidities gives curve C. It will be seen that a hysteresis effect occurs, but that exposure of the yarn to high relative humidities reduces the area of the loop. It has been found that after the third cycle little reduction in the area of the loop occurs.

If moisture content of a yarn is plotted against relative humidity a similar hysteresis effect occurs and it appears probable that the insulation resistance is more closely related to the moisture content than to the relative humidity. Only over certain portions of the moisture content range, however, can the insulation resistance be simply related to the moisture content and there is therefore little advantage in not using the comparatively easily determined relative humidity.

If insulation resistance is plotted against moisture content it is found that over a wide range the slope of the curve is the same for cotton and other textiles composed of cellulose or derivatives of cellulose. Similarly wools and silks give curves with characteristic slopes. Another interesting point in this connection is that after exposure to the same relative humidity the moisture content of silk and wool will be greater than that of cotton, but the insulation resistance will also be higher.

Conduction in Textiles.

The mechanism of conduction in textiles is not yet fully understood, but much valuable work has been done in the Bell Telephone Laboratories. It has been suggested that the structure of a textile results in the water paths forming a regular space pattern. The

paths may be regarded as filaments of water with alternate expanded and contracted portions, the conductivity depending mainly on the cross-sectional area of the constricted portions. Whether this hypothesis is acceptable or not, it appears that absorption of moisture causes a change in the structure of the textile which affects the conductivity. If this change is only reversible with difficulty the hysteresis effect is easy to understand.

Classification of Textile Materials.

Textiles used as wire coverings may be divided into three main groups as follows:—
    (1) Of vegetable origin, consisting mainly of cellulose, such as cotton.
    (2) Of animal origin, consisting mainly of proteins. Silk and wool are examples.
    (3) Synthetic textiles, consisting generally of cellulose or chemical derivatives of cellulose, such as rayon (artificial silk).

Cotton.

The main constituent of cotton is cellulose, a compound of carbon, hydrogen and oxygen with an empirical formula $C_6H_{10}O_5$. Three of the oxygen atoms are present in hydroxyl groups so that cellulose may be represented by

$$(C_6H_7O_2) \diagdown\diagup \begin{matrix} OH \\ OH \\ OH \end{matrix}$$
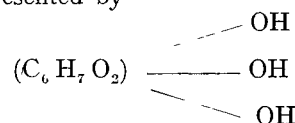
The chemical substitution of the hydroxyl groups by acetyl groups is accompanied by a reduction in the moisture absorption and by an increase in the insulation resistance.

Washed Cotton.

Raw cotton always contains small quantities of natural salts which are deposited during growth, water soluble salts contributing some 70% to the ash weight. The conductivity of yarn is increased by the presence of these electrolytic impurities, which may, however, be removed by washing. Cases have been recorded[18] in which boiling cotton repeatedly in distilled water increased the resistance 40-fold, while similar treatment with a saturated solution of calcium sulphate increased it by 90-fold. Subsequent washing in distilled water in the latter case caused a total increase in the insulation resistance of 130-fold. The main electrolytic constituents are sodium and potassium salts and these are more completely removed by treatment with calcium sulphate solution than with distilled water.

The presence of electrolytic impurities not only increases the conductivity, but also increases the tendency for corrosion by the small currents which flow. The use of washed cotton is for this reason to be preferred to that of ordinary cotton. Washed cotton is used extensively by the Bell Telephone Company where silk was previously employed.

Acetylated Cotton.

By treating cotton with acetic acid, one or more of the hydroxyl groups may be replaced by acetyl

[18] See Bibliography.

groups. The insulation resistance of the resulting yarn is increased to an extent depending on the proportion of combined acetic acid present. In the manufacture of acetylated cotton, known commercially as "Cotopa," the process is stopped when the proportion of combined acetic acid reaches 26-29 per cent. This corresponds approximately to the replacement of one hydroxyl group. The structure and mechanical strength of the original cotton thread are preserved.

The increase in insulation resistance for ordinary Cotopa (26.9% combined acetic acid) and for Super-Cotopa (56% combined acetic acid) is shown in Fig. **19**.
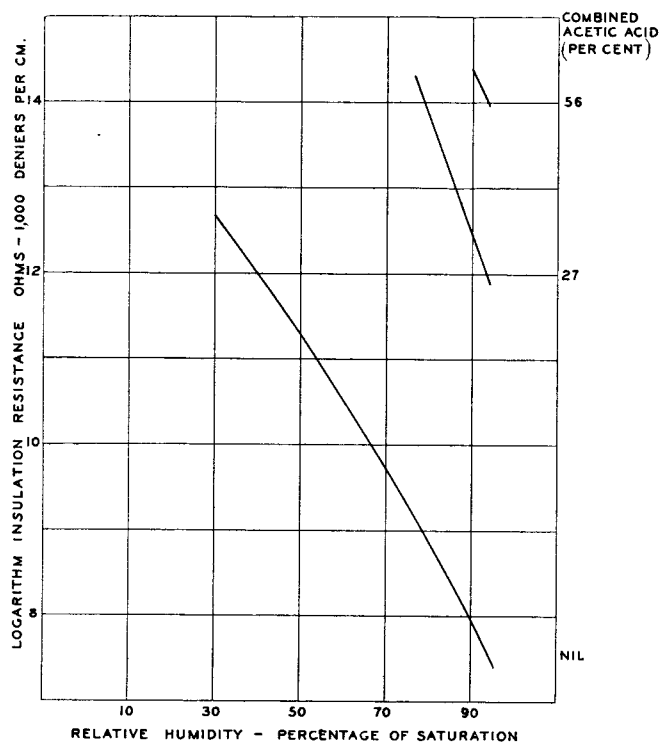
FIG. **19**.—EFFECT OF ACETYLATION UPON INSULATION RESISTANCE OF COTTON.

Cotton or Cotopa may be treated or " mercerized " to give the surface a glossy appearance similar to that of rayon (artificial silk). The process may be mechanical, but, in the case of ordinary cotton or Cotopa yarns, it consists of passing the yarn through a solvent which destroys the cellular structure of the surface.

Acetylated cotton can also be produced in various colours by dying either before or after acetylation. The former method is more common. Many dyed acetylated cotton yarns have good insulating properties and results of tests made on samples obtained in 1934 are given in Fig. **20**. The insulation resistances are lower than those of similar yarns now available. The gold dyed yarn gave particularly low results.

Cotopa is being used by the Post Office as an alternative to rayon, but applications are at present restricted to coarser counts.

Silk.

Natural silks may be divided into two groups:—
1. Wild silks, generally known as Tussah silk. These always have a brownish colour which is difficult to remove.
2. Mulberry silks, obtained by rearing a certain species of silkworm artificially. The diameter of the fibres is considerably less than that of wild silk.

The silk thread consists of two parts, an inner tube composed of fibroin and an outer portion of sericin or silk gum. Both these materials are proteins of complex chemical composition.
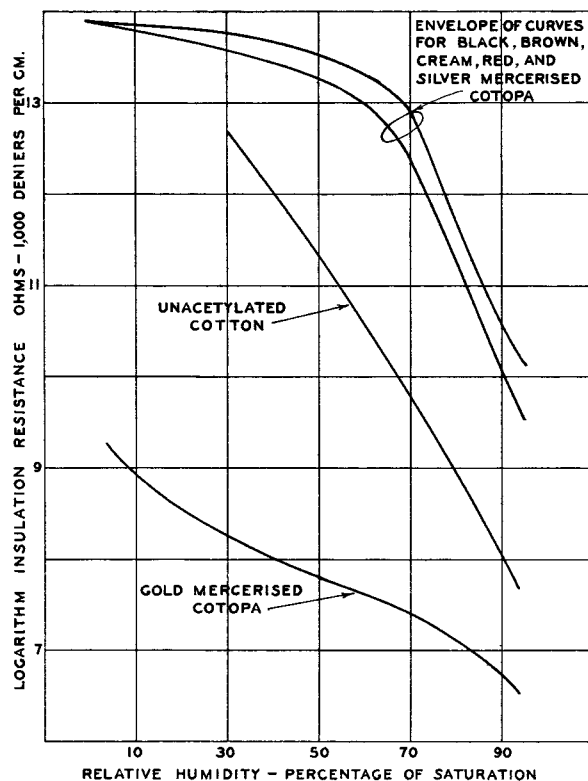
FIG. **20**.—INSULATION RESISTANCE OF COLOURED COTOPA YARNS.

Silks have insulation resistances which are greater than those of cotton. Typical values are shown in Fig. **21**. Natural silk is used for the insulation of fine wires, especially where space is limited, but in view of the existence of suitable synthetic yarns, natural silk is little used on thicker wires.

Isoelectric Silk.

Silk is an amphoteric substance, that is, it can behave as an acid or as a base. If immersed in acid solutions it can combine with acid radicals, and if immersed in an alkaline solution it can combine with basic radicals. It might therefore be expected that the combining capacity of the silk would vanish or have a minimum value if the solution in which it is placed is neutral.

Actually it is found that silk does exhibit a minimum
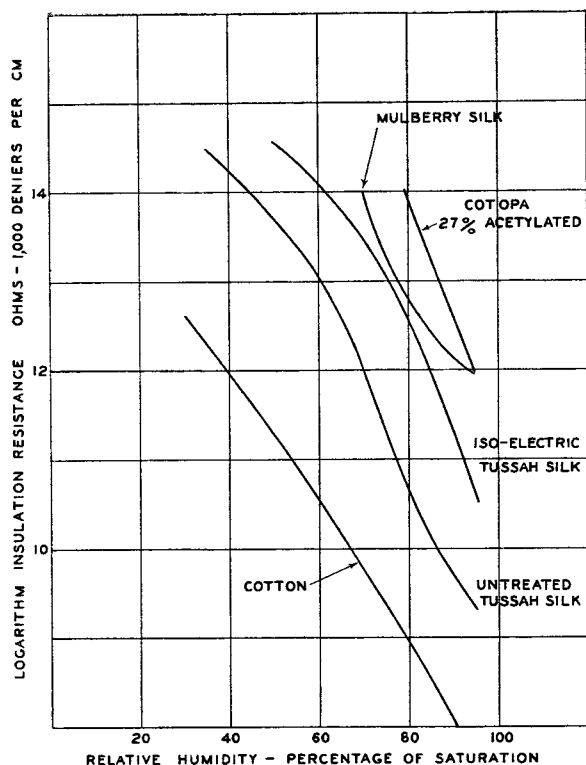
FIG. 21.—INSULATION RESISTANCE OF SILKS.

combining capacity, but in solutions which are not neutral but very slightly acid, corresponding to a PH value of 3.8. Silk treated in this way is said to be "isoelectric." The PH value of the solution in which a silk must be washed to become isoelectric is the same both for mulberry and tussah silk.

The increase in insulation resistance which results from washing a silk in an isoelectric solution is indicated in Fig. 21. Even though the improvement is considerable the insulation resistance of isoelectric tussah silk is not so high as that of Cotopa or of certain synthetic yarns which have yet to be considered.

Rayon.

Many materials used as substitutes for silk are derived from cellulose. The use of the terms "artificial silk" and "synthetic silk" is therefore undesirable. The term "rayon" is considered to be more suitable.

Rayon is the name given to filaments made by pressing or drawing various solutions derived from cellulose through an orifice, and solidifying by means of some precipitating medium. Rayon yarn comprises the assembled filaments. There are four types of rayon, but of these only cellulose acetate rayon is suitable for use in the electrical industry. The insulation resistance of ordinary cellulose acetate rayon is compared with that of ordinary Cotopa and with cotton in Fig. 22.

One disadvantage of cellulose acetate rayon is that it melts at temperatures lower than that of a soldering iron.

The flame resisting properties of ordinary cellulose acetate rayon are not good. A recent attempt has been made to produce a cellulose acetate yarn with better flame resisting properties; the yarn contains a fairly high proportion of tricresyl phosphate (30-60%) and does not support combustion.[19] The insulation resistance was also found to be abnormally high.

Insuwools and Insusilks.

Various methods have been suggested to improve the insulation resistance of natural silk and wool.[20] The composition of silk has already been given. Wool consists of another protein called keratin.

Three types of insusilks and insuwools have been developed with high insulating properties:—
   A. The yarn is treated with tannic acid.
   B. The tannic acid derivative obtained in A is acetylated.
   C. The yarn is acetylated only.
Results of insulation resistance measurements are given in Fig. 23 and show that the yarns have good insulating properties; in sample B the insulation resistance is of the same order as that of ordinary Cotopa.

10. INSULATION OF WIRES AND CABLES.

Enamel Coverings.

Electrical insulation and mechanical protection are usually the chief functions of a wire covering. Where space is limited enamel has much to recommend it, since thin uniform coatings can be applied which have good electrical properties. Enamel, however, lacks
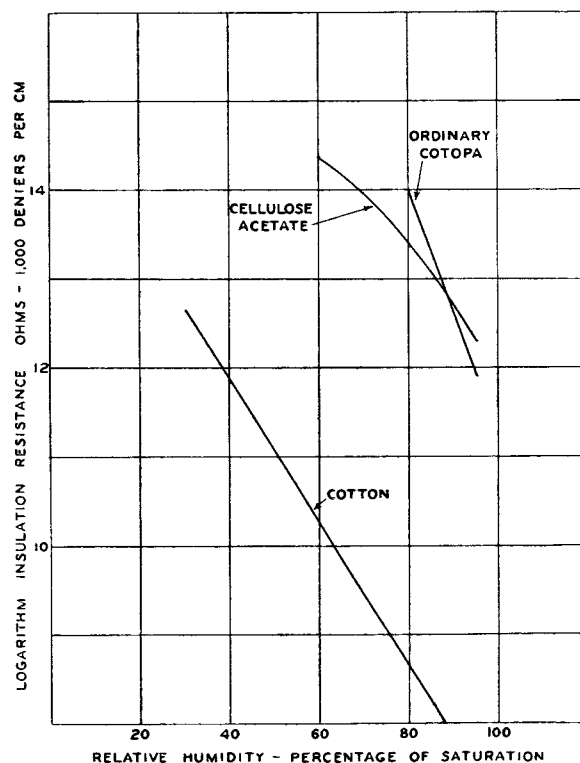
FIG. 22.—INSULATION RESISTANCE OF COTTON, COTOPA AND CELLULOSE ACETATE RAYON.

[19] [20] See Bibliography.
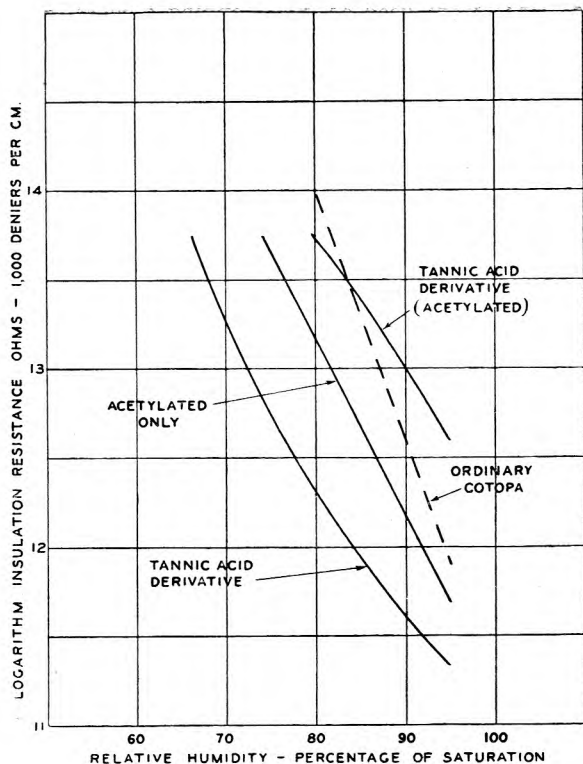
FIG. 23.—INSULATION RESISTANCE OF INSUWOOLS.

the cushioning effect obtained with textiles, and is liable to pinholes and cracks which may lead to corrosion and eventually, particularly in the case of fine wires, to disconnection.

Textile Coverings.

The range of textiles from which the designer can choose his covering for a particular purpose has already been discussed. Where the covering is to be impregnated cotton is usually employed, since it is very absorbent and if thoroughly dried before impregnation high insulation values are obtainable. Cotton, however, has a relatively poor space factor.

The choice between braiding and lapping the textile will depend on the amount of stretching and abrasion that the wire will suffer in practice.

Natural silk is used only on the finer wires, especially where space is limited. Silk does not withstand high temperatures so well as cotton and is now used less than formerly owing to the considerable improvement in enamelled wires during the last few years.

Cellulose acetate rayon or Cotopa is employed where high insulation resistance is important and where damp conditions are likely to be experienced.

Measurement of Electrical Properties of Wire Coverings.

In addition to the tests carried out on individual yarns tests are also made on completed coverings, the properties of which will be dependent on the method of applying the textiles and on the impregnation.

In testing single wires, a length is wound on a ribbed ebonite former and suspended above mercury, as shown in Fig. **24**.
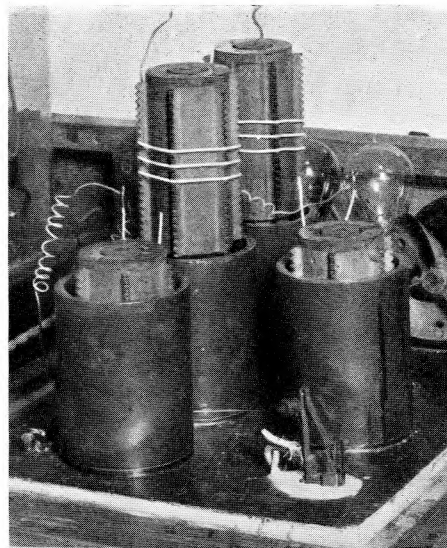
FIG. **24**.

The wires are conditioned for two days in an atmosphere of given relative humidity and then lowered into the mercury. Insulation resistance and capacity measurements are made between the conductor and the mercury.

The conditions in this test are much more severe than those encountered in practice, but useful comparative figures are obtained.

To obtain data as to the performance of the coverings in practice two wires are twinned and tests are made on 220 or 440 yard coils of the twinned pair.

Naked Flame Test.

In order to assess fire risks it is necessary to have available a test which gives a quantitative measure of the degree to which wire coverings will support combustion.

It has been established[21] that a methylated spirit flame gives a reproducible temperature. A Barthel type, " Onix," 20 mm. spirit burner, in which the spirit is vapourized and heated before ignition, is most suitable.

For comparative flame tests, specimens are conditioned for 18 hours at 75% relative humidity and 22°C. They are then held in the flame for a given period (usually 4 secs.) and the time for which they continue to burn after removal from the flame is observed.

Submarine Cable Dielectrics.

Early submarine cables of the type in which the actual dielectric is used to prevent water reaching the conductors were insulated with gutta percha or balata. Gutta percha consists essentially of a substance similar in its chemistry to rubber, together with certain resins and some dirt. It has a permittivity of 3.1 and a

(21) See Bibliography.

power factor of 0.02 at 800 c/s. The high loss is largely due to the resins and dirt for when these are removed the power losses fall to about one twentieth of the normal value. The deresinated material is unsuitable for submarine cables since it is not sufficiently plastic at safe working temperatures and very expensive.

A material with similar mechanical properties to gutta percha was developed about 1927 under the name Paragutta. It consists of deresinated and purified gutta percha, deproteinized rubber and certain waxes which improve the mechanical properties. The permittivity of Paragutta is about 2.7 and its power factor about 0.002.

A still lower power factor is obtained with K-gutta which consists of deresinated gutta percha and petroleum jelly.

Fig. 25 gives a comparison between the d.c. resistance of a 7/.032″ stranded conductor and the added
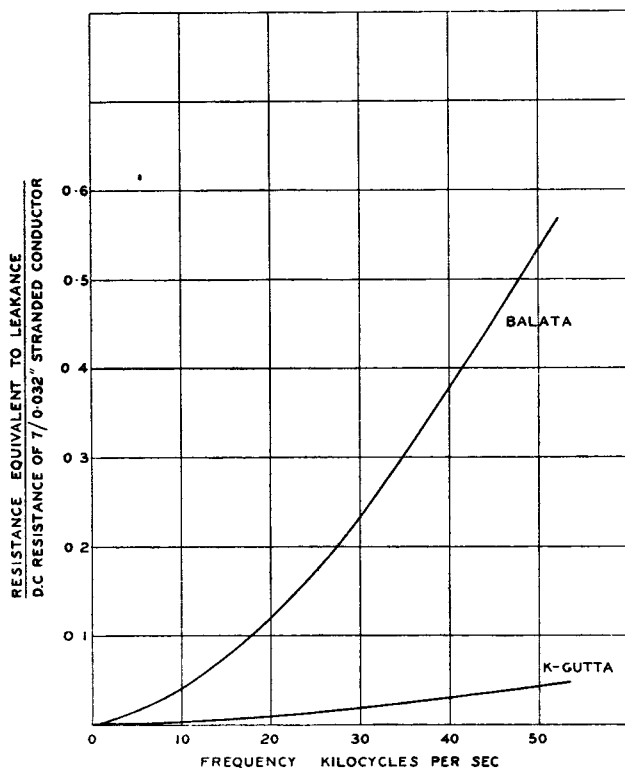
FIG. 25.—EFFECT OF LEAKANCE ON EQUIVALENT RESISTANCE FOR BALATA AND K-GUTTA.

effective resistance due to power loss in the dielectric when Balata, which is similar to gutta percha, and K-gutta are used as coverings.

The stability of the electrical properties of these newer materials under deep sea conditions is good.

II. PAPER DIELECTRIC CONDENSERS.

General.

A large number of paper dielectric condensers are used by the Post Office for a variety of purposes, and a few remarks regarding their general properties, therefore, will not be out of place. Many of these condensers are used as d.c. stopping devices so that the insulation resistance is the most important property concerned, it only being necessary that the impedance shall be sufficiently low to pass the required alternating current. In other cases, however, it is necessary that the capacity shall be within specified limits and that the power losses shall be low. Condensers with paper dielectrics generally have lower insulation resistances and higher power factors than the condensers with mica dielectric, but are considerably cheaper.

In order that the insulation resistances of condensers of different capacities may be readily compared it is convenient to quote the product of insulation resistance in ohms and capacity in farads, since this product is less dependent on the actual capacity of the condenser than is the insulation resistance alone. It is important to realize that this quantity (which may conveniently be designated the " K-R value " of the condenser) is not necessarily independent of the capacity. This is because the measured insulation resistance depends, not only on leakage in the dielectric material, but also on the leakage between the connecting leads and terminals.

In measuring the insulation resistance the testing voltage is generally 300v and the deflection is observed after 1 min. The deflection is frequently observed also at the end of a second minute. The percentage decrease during the second minute is known as the " electrification."

The Significance and Desirability of the Electrification Test.

The electrification test is linked up with absorption phenomena in the dielectric of the condenser, mentioned in Section 1. The anomalous charging current $i(t)$ is given by

$$ i(t) = \beta \times C_0 \times \mathrm{E} \times \phi(t) $$

where C_0 is the geometric capacity and β and $\phi(t)$ depend upon the material.[22]

The form of the function $\phi(t)$ is somewhat uncertain, but for many materials $\phi(t) = Bt^{-a}$ holds, where B and a are constants depending on the material. This applies for small values of t, to varnished cloth[23], mica[24] and cellulose acetate.[25]

The anomalous charging current gradually decreases in value, and ultimately only the normal conduction current will flow. The decrease in current during the second minute of testing a condenser is a measure of the decrease in the anomalous charging current during that period. The significance of the property defined as " electrification," however, is less definite, since the current flowing at the one minute period will include a component due to leakage across the tag strip. Experience indicates, however, that in the case of a paraffin-wax impregnated paper condenser a low or unsteady electrification indicates a faulty condition in the dielectric. Originally it was specified that the galvanometer deflection should steadily decrease during the second minute and the difference between the readings at the beginning and end of the second minute should not be less than 20% of the first minute reading. While the value of 20% can be easily obtained in a paper dielectric condenser impregnated

[22] [23] [24] [25] See Bibliography.

with paraffin wax, it is quite possible that for other impregnating materials such a value may not be attainable although the insulation resistance may be high, and the condenser quite satisfactory. The present specification for Post Office paper dielectric condensers stipulates merely that the deflection shall decrease steadily after the test voltage has been applied for one minute.

Impregnating Materials.

In determining the suitability of a material for the impregnation of a condenser a number of properties must be considered. The permittivity should be as high as possible in order that the completed condenser may be of small dimensions. The power factor should be low, but the permissible value will depend upon the proposed use of the completed condenser. The insulation resistance should be as high as possible.

Apart from tests on the actual material it is desirable that condensers impregnated with the material under test should be examined. In view of variations in manufacturing processes and in sources of supply of the materials it is also necessary to test samples submitted by each contractor who is to supply the final product. Variations in the power factors of condensers impregnated with petroleum jelly and submitted by various contractors are indicated in Fig. **26**.
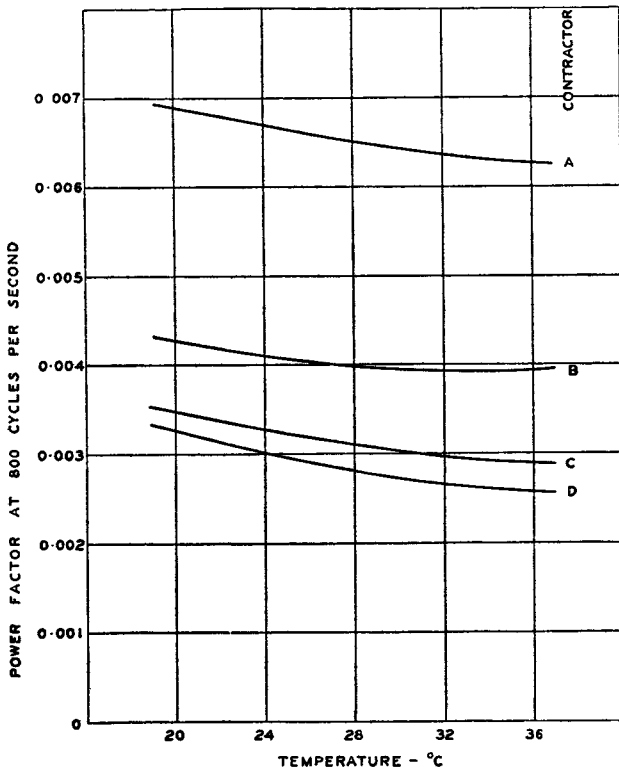
FIG. 26.—POWER FACTOR OF PAPER CONDENSERS SUPPLIED BY VARIOUS CONTRACTORS.

Although paraffin wax is a suitable material for the impregnation of condensers, the use of petroleum jelly has recently been urged, chiefly since it is non-hygroscopic. The material has similar electrical properties to paraffin wax, and no objection has yet

been found to its use. The condenser cases should, however, be hermetically sealed. Another material which has been found suitable is chlorinated naphthalene wax which has the advantage of a permittivity of from 5 to 6 as compared with 2.2 of paraffin wax and petroleum jelly. A much smaller condenser of given capacity can, therefore, be produced.

Variation of Electrical Properties with Frequency and Temperature.

The capacity of paper-wound condensers impregnated with any of the materials mentioned above decreases as the frequency is increased. The decrease is not greater than 0.5% between 200 and 3200 cycles per second. The power factors generally increase as the frequency is raised; the actual power factor at a given frequency is greater than would be accounted for by power losses in the dielectric owing to the series resistance of the foils and connecting leads.

The temperature stability of paper condensers varies considerably, and either an increase or decrease in the capacity with increasing temperature may be observed according to the method of construction. The variation of capacity does not generally exceed 0.5% between 20° and 35°C. Certain paper dielectric condensers intended for use in filters have been tested, and have very small temperature coefficients of capacity.

The d.c. properties deteriorate as the temperature is increased and for this reason condensers should always be located where the temperature is as low as possible. Otherwise premature failures may occur.

Life Tests on Paper Dielectric Condensers.

Examination of condensers which had been in service for 10 to 15 years indicated that the life of a paraffin wax impregnated condenser depended mainly upon the prevention of the ingress of moisture; that is, upon the efficiency of sealing. To accelerate failure, therefore, it is necessary to increase the ingress of moisture due to any defect in the seal. For this purpose condensers are enclosed in an airtight chamber in which a free surface of water is exposed, and the temperature varied each day between room temperature and 30 to 35°C. Opportunity is thus given for the condensers to draw in moisture saturated air if the seal is defective. A suitable potential difference is maintained between the terminals of each condenser. Periodical measurements of insulation resistance under room conditions after the condensers have been at room temperature for at least 18 hours are taken, and a condenser is deemed to fail if its K-R value falls below 300. A considerable speeding up of failure is thus obtained, but as a result of observations on condensers over a period of seven years it has been concluded that a batch of condensers would have to survive a minimum of three years under such adverse conditions before it was safe to say that they were essentially permanent under normal conditions. From a works or specification point of view such a test is obviously without value on account of the time involved.

The above test represents an extreme case of actual conditions, since in practice the condenser is subject merely to temperature fluctuations and to a damp

atmosphere. It has been suggested that the ingress of moisture might be accelerated by submitting the condensers to reduced pressure, of the order of half atmospheric pressure, followed by the admission of moisture saturated air. It should be pointed out, however, that such a test would in no way simulate actual conditions, and that while reliable results might be obtained, it would be necessary to undertake tests on a large number of condensers probably over a long period to verify this point.

The development of a rapid test which will indicate whether a given type of condenser will be reliable in service is a difficult problem, but since failure is frequently due to the ingress of moisture a method of determining the penetration of moisture through the seal of a metal cased, paper dielectric condenser will give some idea of the probable life of the unit. Such a method has been developed as a result of tests on some two hundred paraffin wax impregnated paper condensers. It consists briefly of heating the condenser to 100°F. and immersing it in cold water for one hour. The condenser is then wiped dry, and the subsequent behaviour of the insulation resistance under normal room conditions during the next seven days is investigated. In general, the seal is considered satisfactory if the insulation resistance has recovered to a specified value within two days, provided that it does not then decrease during the next five days.

This test would appear particularly suitable for testing hermetically sealed condensers. A test has, however, been suggested in which the condenser is merely immersed in hot water and deemed satisfactory if no air bubbles appear. It would appear likely, however, that a small quantity of water might penetrate the seal without the appearance of bubbles, and for this reason it is considered that insulation resistance measurements after immersion are desirable.

12. ELECTROLYTIC CONDENSERS.

Fundamental Phenomena.

If two aluminium plates are immersed in a solution containing, for example, a suitable salt of boric acid, the application of a direct voltage between the electrodes will cause a current to flow. This will drop very rapidly during the first few seconds and will finally almost disappear, due to the formation of an extremely thin insulating film, consisting essentially of aluminium oxide. The film will act as a rectifier, since, if the applied e.m.f. is reversed a large current will flow at first, but will soon diminish owing to the formation of an insulating film on the second electrode.[26]

The film has a permittivity of approximately 8, and the value of the film commercially arises from its extreme thinness and high dielectric strength. The thickness varies between 0.01 and 0.05 micron so that a very high capacity per unit area is obtained.

Insulating films may be " formed " for withstanding voltages from 500 to 700v either at a constant voltage or in steps at gradually increasing voltages. Contact with the film on the side remote from the aluminium electrode is always made by means of an electrolyte in order that any perforations which may

occur shall be reformed. Condensers to withstand high voltages must have insulating films with a high breakdown voltage, and since this is nearly proportional to the thickness, they will have a relatively low capacity per unit area. The size of such condensers is therefore greater than those of similar capacity for use at lower voltages, so that it is at the lower voltages that the greatest economy in space is realized. For this reason it is not usual to manufacture electrolytic condensers with working voltages greater than about 550v. For higher voltages two condensers may be connected in series. In this connection it is important to note that, even if the voltage distribution between two substantially equal electrolytic condensers connected in series is unequal at voltages lower than the rated working voltages, it will become approximately equal when the rated voltage is approached.

The breakdown voltage of a condenser depends on the concentration of the electrolyte ; the higher the concentration the lower is the breakdown voltage, and also therefore, the working voltage of the condenser. On the other hand a concentrated solution has a lower resistance, and the power losses of a condenser containing such a solution will be relatively low. The capacity, however, is unaffected by the concentration of the electrolyte, depending only on the formation voltage—that is, in effect, on the thickness of the insulating film.

Types Available.

Three types of electrolytic condensers are available, the chief differences being in the manner in which the plates are separated and in the nature of the electrolyte.

The Wet-type Condenser.

In this type of condenser the anode is supported in the centre of a cylindrical container, which forms the cathode, and is immersed in a liquid electrolyte. Various forms are given to the anode in order to increase the capacity of the completed condenser. Wet electrolytic condensers have two advantages over other types ; they recover perfectly from over-voltage owing to film forming properties of the liquid electrolyte, and may be given higher values of A.C. loading.

The Semi-dry Type Condenser.

The anode takes the form of a long strip of foil (usually aluminium) on which the dielectric film is formed. The cathode is of the same form and the two foils are rolled up together with spacers which provide mechanical separation between the electrodes and hold the electrolyte between them. The spacers frequently consist of cotton gauze and are impregnated with the electrolyte while hot by a dipping or vacuum process. The completed roll is mounted in a cylindrical aluminium, or bakelite container.

Semi-dry type condensers are manufactured mainly in Holland.

The Dry Type Condenser.

The general construction is similar to that of the semi-dry type. A material is added to the electrolyte to make it solid at normal temperatures. The dry type condenser is the most used in this country.

[26] See Bibliography.

Characteristics.

An electrolytic condenser does not possess an "insulation resistance," but passes a steady current of a few amperes per farad when a d.c. voltage is applied. The leakage current depends on the past history of the condenser and to obtain a value characteristic of a condenser it should be measured after the application of the test voltage for a period such as 24 hours. The variation of leakage current with applied voltage is shown in Fig. **27**. It would appear that some advantage would be gained by using condensers at a working voltage of about 70% of their present rated working voltage. The considerable reduction in leakage current flowing under these conditions would probably reduce electrolysis and corrosion, with the result that the condenser would have a longer life. Measurements of capacity over a period of two years during life tests indicate that the films in modern electrolytic condensers do not decrease in thickness appreciably when a voltage as low as one half the rated voltage is applied.

The actual capacity of commercial condensers may vary from 90% to 130% of the nominal capacity. If a closer tolerance were required the cost of the article would be increased. Electrolytic condensers may be used in situations where low temperatures may be encountered, but some falling off in capacity occurs as indicated in Fig. **28**.

Electrolytic condensers have a higher power factor than other types chiefly owing to the resistance of the electrolyte. The equivalent series resistance is, however, extremely low; for a 100 μF. condenser with a power factor of 0.1 at 800 cycles per sec. the equivalent series resistance is 0.2 ohm, so that precautions are necessary in testing. Since the power loss is due largely to series resistance the power factor increases rapidly with increasing frequency as shown in Fig. **29**. As a result of their large power factors at higher audio frequencies, electrolytic condensers (especially of small capacity) have impedances considerably greater than the simple reactances due to the capacities of the condensers alone. The efficiency of electrolytic condensers as by-passes at the higher frequencies is therefore reduced, and the use of a paper dielectric condenser may be found more satisfactory.

Electrolytic condensers are used most where large capacities are required, or where a moderate capacity
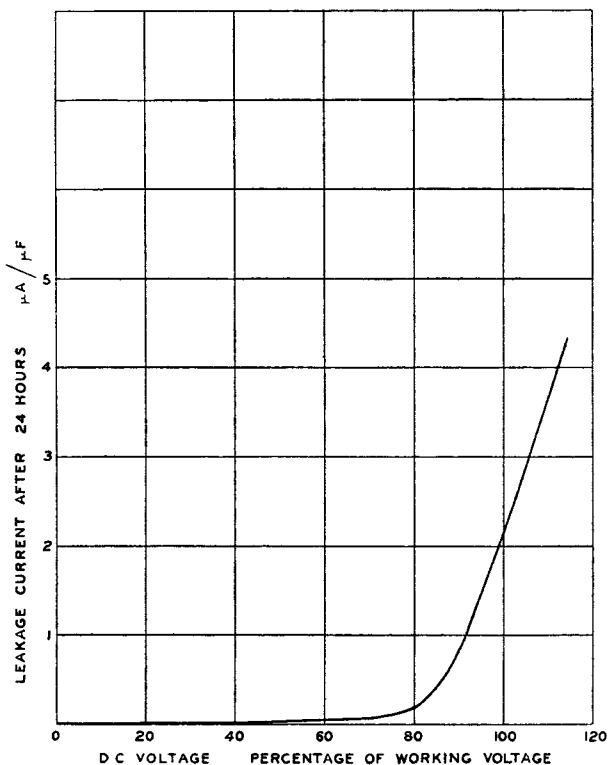
Fig. **27**.—Variation of Leakage Current of 250v. Electrolytic Condenser with Applied Voltage.
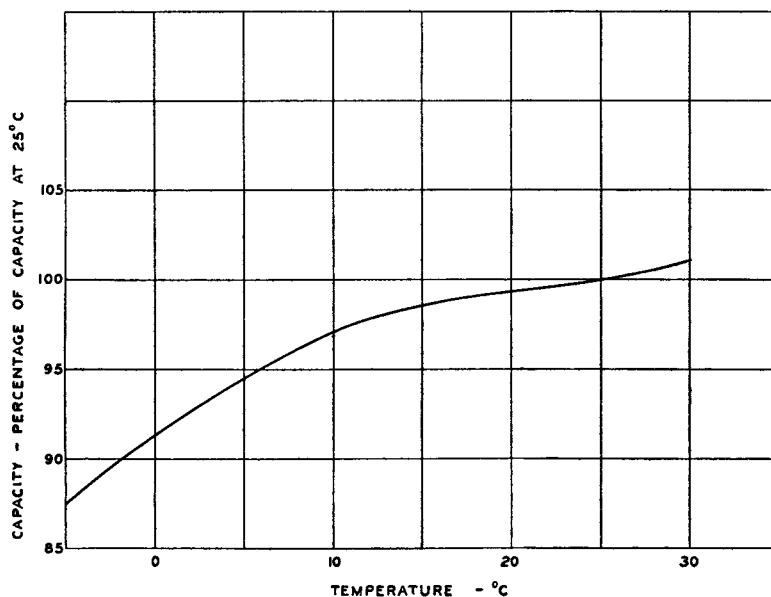
Fig. **28**.—Variation of Capacity of 250v. Electrolytic Condenser with Temperature.
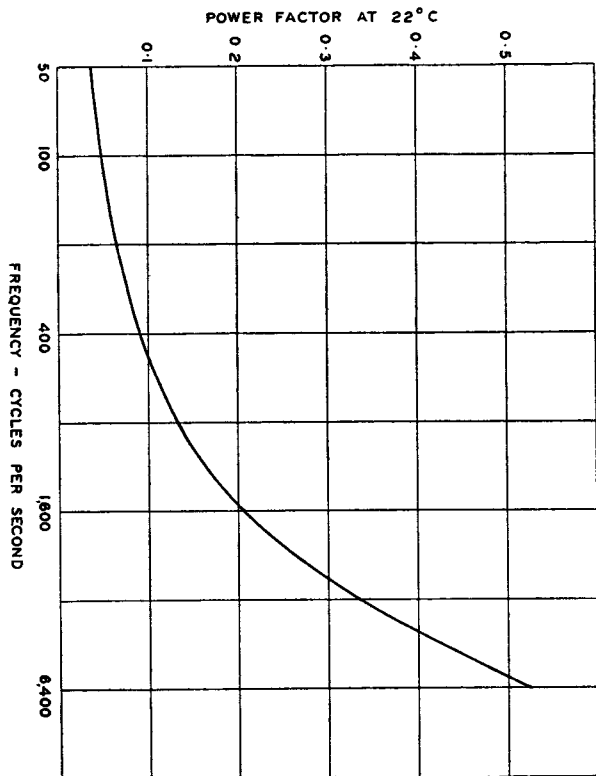
FIG. 29.—VARIATION OF POWER FACTOR OF 250V. ELECTROLYTIC CONDENSER WITH FREQUENCY.

is desirable in as small a space as possible. They find their greatest application in radio receiving apparatus, being especially used in the smoothing filters for the power supplies. They are also employed for the smoothing of power supplies to repeater stations and telephone exchanges, in V.F. telegraph equipment, and for other miscellaneous uses.[27]

The more general application of electrolytic condensers by the Post Office has been delayed owing to the lack of reliability of the products which have been available in the past. Considerable advances have, however, been made by certain firms during the last few years, and there is every indication that a reliable electrolytic condenser of long life may be available in the near future.

Conclusion.

The Authors wish to thank the members of the Research Branch of the Post Office Engineering Department who have helped in the compilation of this paper. It is hoped that the brief review of the properties and testing of dielectrics which has been given will be of assistance to those who have to use these materials.

[27] See Bibliography.

BIBLIOGRAPHY.

1. Clerk Maxwell, " Electricity and Magnetism," Vol. 1, p. 48.
2. See, however, " Dielectric Phenomena," Vol. 3. S. Whitehead.
3. F. A. Lindeman, A. F. Lindeman and T. C. Keeley. Phil. Mag. 47, March, 1924.
4. Schering, Zeits. f. Instrumentenk 40, 124, 1920. B.E.A.I.R.A., Tech. Rep. L/T 24.
5. L. Hartshorn and W. H. Ward, I.E.E., J. 79, 597, 1936.
6. S. Butterworth, Wireless Engineer 3 ; 203, 309, 417 and 483, 1926.
7. " Contact Phenomena in Dielectrics," B.E.A. I.R.A. Tech. Rep. L/T 45.
8. Wilson, Indust. and Engin. Chem. 13, 326, 1921.
9. Dunton and Caress, I.E.E., J. 79, 463, 1936.
10. Indust. and Engin. Chem. 29 (News Edition, V. 15, p. 499), 1937.
11. Chem. and Metallurgical Engin. 41, 589, 1934. Revue des Telephones Telegraphes No. 156, 234, 1937.
12. W. Jackson, I.E.E., J. 79, 565, 1936.
13. W. Soyck. Säcks Ingenieur Zeitschrift 30, 10, 1935.
14. B.E.A.I.R.A., Tech. Rep. A/T 53.
15. Murphy and Walker, J. Phys. Chem. 32, 1761, 1928.
16. Murphy, J. Phys. Chem. 33, 509, 1929.
17. Murphy, J. Phys. Chem. 33, 200, 1929.
18. British Cotton Industry Research Association Bulletin, 1933.
19. British Patent No. 448,307.
20. A. A. New, Elect. Communication 14, 213, 1936.
21. H. L. D. Wyman, B.E.A.I.R.A., Tech. Rep. L/T 75
22. J. Hopkinson, Roy. Soc., Proc. 41, 453, 1886.
23. L. Hartshorn, I.E.E., J. 70, 417, 1932.
24. L. Hartshorn and E. Rushton, B.E.A.I.R.A. Tech. Rep. L/T 60.
25. L. Hartshorn and E. Rushton, B.E.A.I.R.A. Tech. Rep. L/T 49.
26. R. E. W. Maddison, Phil. Mag. 8, 29, 1929.
27. See also " Electrolytic Condensers," P. R. Coursay, 1937.

APPENDIX.

The Trend of Dielectric Research.

While measurements of the properties of dielectrics give useful data to the telecommunication engineer, the variations of these properties with frequency and temperature give valuable information regarding the basic molecular structure of the materials concerned.

The properties of a number of materials[1] have been found to vary with frequency in accordance with equations first given by Hopkinson[2] and based on his Superposition Principle which states that the effects of successively applied voltage increments are similar and additive. Two theories which help to give an understanding of the processes involved in conduction have been developed. They are Murphy and Lowry's theory[3] of absorbed ions and Debye's[4] theory of polar molecules.

Debye's theory was originally developed to explain the temperature variation of the dielectric constants of alcohols. Debye assumes the molecules to possess equal positive and negative bound charges which are, however, unsymmetrically distributed so that the whole molecule possesses a definite electrical moment. On this theory the power factor increases as the frequency is increased up to a certain frequency and then decreases. The variations of the dielectric properties of chlorinated diphenyl (Permitol)[5] and of an ester of paraffin wax[6] are in accordance with the theory which has also received considerable confirmation in other fields.

The application of the quantum theory to the problem of metallic conduction[7] cleared up many difficulties present in the free electron theory of Drude and Lorentz. It has been applied by A. H. Wilson[8] to insulators, and the results of his deductions have been confirmed as, for example, in the variation of conductivity of insulating varnish films with temperature.[9]

At low voltage gradients the conductance and permittivity of most dielectrics are independent of the voltage. Above a certain critical voltage, however, these properties increase as the voltage is further increased. Zener[10] has attempted to explain this increase. From his theory the lattice constant of the molecular structure of the crystal may be calculated. The theory is partially confirmed experimentally.

Zener's theory cannot account for breakdown since it leads to a stable increase of conductivity with field strength. The position a few years ago was discussed by S. Whitehead[11], but considerable work has since been carried out.[12]

While modern theories in combination with experimentally observed facts contribute largely to advance in the knowledge of the structure of the materials to which they relate, they sometimes also point to directions in which dielectric materials for special purposes may be selected and controlled.

Bibliography to Appendix.

1. See ref. 23, 24, 25 of main bibliography. Also L. Hartshorn and E. Rushton, B.E.A. I.R.A. Tech. Rep. L/T 80.
2. J. Hopkinson, Roy. Soc., Proc. A. 41, 453, 1886.
3. Murphy and Lowry, J. Phys. Chem. 34, 598, 1930.
4. Debye. Phys. Zeits., 23, 97, 1912.
5. W. Jackson, Roy. Soc., Proc. A. 153, 158, 1935.
6. W. Jackson, Roy. Soc., Proc. A. 150, 197, 1935.
7. F. Block, Zeits. f. Physik. 47, 1, 1928.
8. A. H. Wilson, Roy. Soc., Proc. A. 133, 458, 1931.
9. B.E.A.I.R.A. Tech. Rep. L/T 95.
10. Zener, Roy. Soc., Proc. A. 145, 523, 1934.
11. " Dielectric Phenomena," S. Whitehead.
12. Fröhlich, Roy. Soc., Proc. A. 160, 230, 1937.

THE INSTITUTION OF POST OFFICE ELECTRICAL ENGINEERS.

PRINTED PAPERS.

The following papers contributed to the proceedings of the Institution have been printed by authority of the Council and may be obtained, if still in print, from

"THE LIBRARIAN,
The Institution of Post Office Electrical Engineers,
G.P.O. (ALDER HOUSE), LONDON, E.C.1."

The prices do *not* include postage, and in every case, Members, Associate Members, and Associates have the privilege of purchasing copies at two-thirds the stated price.

* For Officers of the Department only.
† The Council have awarded Institution Medals for these papers.
O Signifies out of print.

PRINTED PAPERS (*continued*).

* For Officers of the Department only
† The Council have awarded Institution Medals for these papers.
O Signifies out of print.