

The Polarization of Dielectrics in a Steady Field of Force

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DISCUSSION.

Prof. C. H. LEES expressed his interest in the paper and remarked on the utility of the introduction of the new variable μ . He asked if a simple relation could be given between saturation-pressure and temperature in terms of this variable. The very different results the Author had obtained from van der Waals' and from Clausius' equations might suggest a crucial experiment which would decide in favour of one of them.

The AUTHOR, in reply to Prof. Lees, said he had not been able by means of his special variable to express in simple terms the relation between saturated pressure and absolute temperature.

XIV. *The Polarization of Dielectrics in a Steady Field of Force.* By W. M. THORNTON, D.Sc., D.Eng., Professor of Electrical Engineering in Armstrong College, Newcastle-on-Tyne*.

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1. INTRODUCTION.

THE slow polarization of a dielectric ellipsoid suspended in a steady field of force can be followed by observing from time to time the period of small swings about the line of the field †. In a perfect insulator the polarization reaches its full value in a much shorter time than the period of such a moving system, and a single observation of the latter would suffice to determine the dielectric constant of the ellipsoid. In all solid dielectrics there is, however, slow electrical movement under the influence of the field within the ellipsoid and a consequent accumulation of charge at each end. The restoring couple, and therefore the apparent dielectric constant, increase until the limit to molecular polarization is reached.

* Read January 21, 1910.

† Roy. Soc. Proc. A. vol. lxxxii. p. 422 *et seq.*

The advantage of the method is that the "conduction" current is confined to the separation of charge within the solid symmetrically about the central section.

An account is given below of observations made upon the behaviour of various solid dielectrics, in which the total polarization is expressed in terms of the apparent dielectric constant. From these observations the resistivity of insulators has been found in a new way.

A difference of one part in a thousand in the dielectric constant can be readily measured by the suspended ellipsoid method. On account of this sensitiveness three stages in the polarization were found to be present in all the homogeneous substances examined. First a sudden very rapid yield, then a slow change at a uniform rate, and finally an approach to saturation. The first suggests a normal slackness of charge in the dielectric molecule, the second is probably a continuation of the polarization by the influence of adjacent molecular charges, a slow linear change of the nature of a simple strain. In the third stage the rate of displacement ceases to be uniform, and the polarization reaches a maximum which is shown in the paper to be independent of the intensity of the polarizing field within the specimen.

According to this "three stage" theory, the quantity passing in the instantaneous charge or discharge of a condenser with a solid dielectric, involving as it does the first stage only, should be proportional to the voltage; the total residual *charge* corresponding to the later stages, the apparent dielectric constant of which is independent of voltage, should also be proportional to the voltage, as shown by Hopkinson* to be the case. Dielectric hysteresis loss should decrease with rise of frequency, on account of the smaller range possible in the second stage, which agrees with the experimental results of Threlfall†.

It was found further that there was no permanent residual electrification in the dielectrics examined, showing that the

* Roy. Soc. Phil. Trans. vol. clxvii. part ii. pp. 599-626 (1877).

† R. Threlfall, "On the Conversion of Electric Energy in Dielectrics," part iii. Physical Review, vol. v. p. 65.

polarization, however long continued and slow in action, was quasi-elastic in type.

When testing electric cables the charging current is sometimes measured after one minute's electrification. With the usual insulators this is only in part a true conduction current, the rest being the second stage of polarization. What the latter would be in any condenser can be calculated from the curves of rate of change of apparent dielectric constant given later, and in this way the true conductivity found.

2. EXPERIMENTS ON QUARTZ.

The first systematic examination of the influence of time of charge upon the values obtained for dielectric constants was made by Boltzmann*, and by Romich and Nowak† under his direction. They obtained for quartz, for example, a value greater than 1000 in steady fields. All subsequent observers recognizing these results have specified the duration of charge. The effect was dealt with by J. Hopkinson‡ in an important series of papers, and the recent work of Beaulard§ upon the dielectric constant of water at high frequencies is a good illustration of it. With the exception of Romich and Nowak's experiments, observations of the influence of steady fields have been mostly made on the charge and discharge currents of condensers, and in their interpretation the relative importance of polarization and conduction must be separated. By a conduction current is meant one produced by the passage of free electrons or ions, and this takes place much more freely when the dielectric is in direct contact with the terminal plates between which the pressure is maintained. A very complete *resumé* of work on dielectrics up to 1904 is given by L. Grætz in Band iv. of Winkelmann's *Handbuch der Physik*. A paper by Von Schweidler, in *Annalen der Physik* ||, deals with more recent work and gives a full bibliography ¶.

* *Wien. Ber.* lxvi., lxvii. (1872-3).

† *Wien. Ber.* lxx. (1874).

‡ Original Papers, vol. ii. nos. 18, 19, 27.

§ Science Abstracts, 1905 to 1908.

|| *Ann. der Phys.* xxiv. p. 711 (1907).

¶ See also H. A. Wilson, Roy. Soc. Proc. A. lxxxi. p. 409, "On Electrostatic Induction through Solid Insulators."

In the present experiments the first substance examined was quartz cut parallel to the optic axis and formed into an ellipsoid 2 cm. long and .2 cm. diameter. It was very carefully cleaned, dried, and suspended by a quartz fibre about .001 cm. diameter and 20 cm. long between flat brass plates 6 cm. apart, contained in a vessel dried under vacuum and by phosphoric anhydride for several weeks. The leak between the plates would therefore be exceedingly small, and with a potential-difference of 480 volts between the plates the observed periods were the same in dry air and in vacuo. In order to obtain more than two figure accuracy by this method it is necessary to take the mean of at least five observations of the period. In the first few minutes this was as a rule changing quickly, and it was only in the later stages of the polarization that several readings could be taken.

Particulars of the form and dimensions of the specimens used in this paper are given in that dealing with alternating fields*.

The free period of the quartz ellipsoid was 63.3 seconds. The following table gives the observed periods in fields of various strength for the first 20 minutes of polarization.

TABLE I.

F is the intensity of the external polarizing field in Electrostatic Units.

F.	10 s.	15 s.	30 s.	1 m.	2 m.	3 m.	4 m.	5 m.	6 m.	7 m.	8 m.	10 m.	15 m.	20 m.
.087	...	51.5	46.5	42.7	40.0	38.0	36.6	35.5	34.5	34.0	33.6	33.0	31.8	31.3
.116	...	40.0	36.5	32.7	30.0	28.7	28.0	27.2	26.6	26.0	25.6	25.2	24.0	23.6
.179	...	35.0	30.0	24.5	21.5	20.5	20.0	19.5	19.0	18.7	18.6	18.1	17.0	16.0
.284	32.0	...	21.5	18.0	16.0	15.0	14.2	13.5	13.2	13.0	12.5	11.7	10.5	10.2
.404	21.1	...	15.0	13.0	11.6	10.7	10.5	9.7	9.2	9.0	8.7	8.2	7.5	7.2
.506	15.1	...	13.0	11.3	10.0	9.0	8.5	8.0	7.5	7.2	7.0	6.7	6.2	6.0
.747	11.6	...	10.0	8.75	7.3	6.5	5.75	5.35	5.0	4.75	4.73	4.35	4.05	4.0

* Roy. Soc. Proc. *loc. cit.*

The time at the head of each column is that at which the observation was made; the figures in the column are the measured period in seconds. After each set of readings the ellipsoid was allowed to stand about twelve hours to depolarize. On reversing the polarity of the plates after about one minute's electrification the ellipsoid turned through 180 degrees and followed any subsequent reversal. In five minutes the quartz was sufficiently electrified to pick up pieces of tissue-paper one millimetre square.

Later observations showed that 20 minutes was not long enough to establish full polarization. The ellipsoid was therefore resuspended, having now a free period of 34.73 seconds. After 120 hours in a field of 0.137 electrostatic unit the period was 17 seconds; after 24 hours longer in a field increased to .266 unit, 9.72 seconds.

Values of the dielectric constant calculated from the restoring couple on an ellipsoid making small swings in an alternating field of force are in close agreement with the best previous determinations. The assumption made in calculating the couple is that the polarization is taken up instantaneously in any position, and the agreement shows this to be justified. When, however, the field is unidirectional the components of polarization are not the same along and at right angles to the axis of the ellipsoid. It will be shown subsequently that several days are, in general, required to reach a steady state when the ellipsoid is allowed to stand in line with the field. There is in this position no transverse polarization, but if the ellipsoid is then given small swings there will be one which alternates with the motion and may thus be considered to be proportional to the constant obtained in alternating fields.

The ellipsoid behaves in fact as if it were in effect crystalline, and the restoring couple at unit angular displacement is

$$\left(\frac{\kappa_1}{1 + \kappa_1 N} - \frac{\kappa_2}{1 + \kappa_2 L} \right) V F^2. \quad . \quad . \quad . \quad (1)$$

Where κ_1 is the longitudinal and κ_2 the transverse susceptibility, N and L the longitudinal and transverse reaction coefficients, V the volume of the ellipsoid, and F the intensity of the external field.

This couple is equal to $4\pi^2 I(n^2 - n_0^2)$, where I is the moment of inertia of the suspended system; n , n_0 , the frequency of swing with and without the field.

Hence

$$\left(\frac{\kappa_1}{1 + \kappa_1 N} - \frac{\kappa_2}{1 + \kappa_2 L} \right) V F^2 = 4\pi^2 I (n^2 - n_0^2). \quad (2)$$

Writing

$$\frac{4\pi^2 I (n^2 - n_0^2)}{V F^2} + \frac{\kappa_2}{1 + \kappa_2 L} = a,$$

we have

$$\kappa_1 = a / (1 - N a),$$

and the dielectric constant

$$K_1 = \frac{1 + (4\pi - N)a}{1 - N a}.$$

For a *quartz ellipsoid cut parallel to the optic axis* $L = 6.133$, $N = .3013$, $V = .0534$ c. c., $I = .02912$, $K_0 = 4.60$.

From the later set of observations given above $n^2 = .0106$ in a field .266, $n_0^2 = .00083$. Thus $F^2 / (n^2 - n_0^2) = 7.25$ and $a = 3.069$, giving finally $K = 508$. (Quartz ||).

In the weaker field, $F = .137$, $F^2 / (n^2 - n_0^2) = 7.16$, giving $K = 610$.

An *ellipsoid of quartz cut perpendicular to the axis* had $L = 6.125$, $N = .313$, $V = .056$, $I = .0307$, $K_0 = 4.548$.

Its free period was 33 seconds. After exposure to a field 0.26 for 48 hours the period was 19.3 seconds; after 41 hours longer in a field 0.132, 26.75 seconds.

From these we have the steady values

$$\begin{aligned} F^2 / (n^2 - n_0^2) &= 38.5, & F &= 0.26, \\ ,, &= 36.4, & F &= 0.132. \end{aligned}$$

$a = .6705$, and $K = 11.66$. (Quartz ⊥).

Thus both in alternating and direct fields quartz || has the larger values, but whereas in the former the ratio of the dielectric constants is 1.012, in the latter it is about 45.

For the purpose of section 6 *infra*, it is necessary to know not only the final values but the rate of growth of the polarization. The following observations show the exceedingly slow rate of polarization of quartz ⊥ compared with quartz ||.

The intensity of the field in all the cases given in the paper not otherwise stated was about $\cdot 265$ electrostatic unit.

Quartz I. $K \sim = 4\cdot 548$. Free period $T_0 = 11\cdot 82$ s.

Time	15 s.	35 s.	50 s.	16 m.	120 m.	48 h.
Period	11·2	11·05	11·02	11·0	10·57	—*
K	4·73	5·2	5·69	7·55	10·92	11·66

Quartz II. $K \sim = 4\cdot 60$. $T_0 = 63\cdot 3$ s.

Time	1 m.	2	4	6	10	15 m.	120 h.
Period	17·2	15·8	14·6	13·2	12·0	11·4	—*
K	20	27·3	39	53	78	110	610

* On another suspension.

From the readings of Table I., we have now for the latter ellipsoid after 20 minutes' electrification.

F	·087	·116	·129	·284	·404	·506	·747
$F^2/(n^2 - n_0^2)$	8·8	8·8	8·8	8·26	8·8	9·3	8·92

The mean of $F^2/(n^2 - n_0^2)$ is $8\cdot 81$, and since the derived value of K depends upon this we have the remarkable fact that the polarization approaches the same value irrespective of the intensity of the polarizing field. This suggests that the slow polarization is a consequence of internal molecular attractions started by the initial polarization and maintained to a limit by the continuance of the field, but not in any way proportional to it. This is considered further in section 7.

Fused quartz has been largely employed in the construction of electrosopes for use in measurements of radioactivity. It is conceivable, though not highly probable, that some of the earlier observed feeble radioactive effects may have been

in some measure due to the slow absorption of charge by the quartz support, for the rate of charge or discharge of such an instrument must be influenced by the polarization of the support.

3. EXPERIMENTS ON FLINT GLASS.

Similar measurements to those on quartz were made with flint glass specimens.

Cylinder of density 4.6.—Free period 23.8 seconds. After 5 days in $F = .132$, period 19.5 s. ; after 48 hours longer in $F = .272$, period 13.8. From these $F^2/(n^2 - n_0^2) = 21.86$ and 20.25 respectively, giving $K = 580$.

Ellipsoid of density 4.1.—Free period 41.5 seconds. After 48 hours in $F = .132$, period 23.75 ; after 48 hours longer in $F = .272$, period 12.5. Here $F^2/(n^2 - n_0^2) = 14.1$ in the lower field, 12.4 in the higher. The corresponding mean value of K is 520. On a fresh suspension the following rate of polarization was observed.

$$K \sim = 8.52.$$

Time	30 s.	2.5 m.	4.5 m.	6.5 m.	19 h.
K	27.9	37.7	47.0	50	200

Ellipsoid of density 3.3.—Free period 14.9 seconds. After 22 hours in $F = .271$, period 12.33 ; after 48 hours longer in $F = .136$, period 13.9. For the former $F^2/(n^2 - n_0^2) = 26.85$, and the latter 27.2.

$$K \sim = 6.98.$$

Time	1 m.	15 m.	1 h.	2 h.	4 h.	10 h.	22 h.
K	7.0	8.1	10.5	12.4	16	20.6	22.6

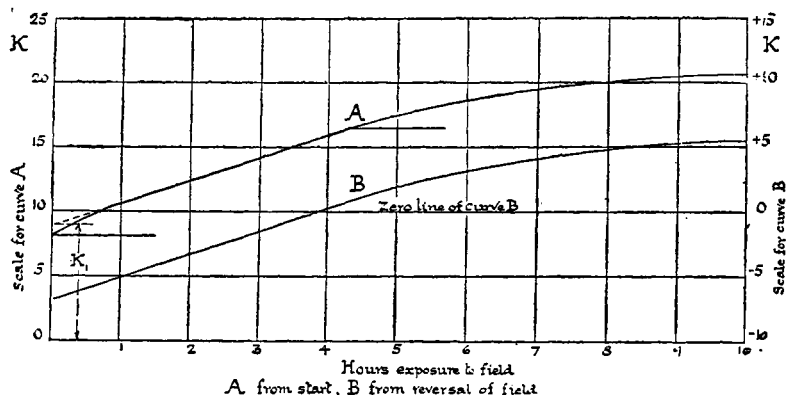
On reversing the field the ellipsoid did not reverse. The rate of fall of K under a reversing field and the early part of its rise after passing through zero are given below.

Field reversed.

Time	12 m.	90 m.	230 m.	5 h.	7 h.	9 h.	11 h.
K	-6.5	-4.0	0	1.6	3.7	4.8	5.6

This shows the *forced depolarization* of a dielectric by a method distinct from discharge through a galvanometer. These rates of change are drawn in fig. 1. Their chief

Fig. 1.



interest lies in the fact that whether the polarization is increasing from zero or being reversed, the rate of change is for a long time the same. It is also noticeable that the time occupied in the linear polarization is nearly the same in both cases. The value of K before the field was reversed was 25, of which 9 was the sudden rise at the start. At reversal there was a rapid change equal to twice that from zero, i. e., of 18, leaving a polarization of $K=7$ in a direction opposite to that of the field. It will be seen that Curve B starts from a value -7 .

The ellipsoid was then exposed to the field for three weeks and acquired a value of $K=6075$.

The following numbers give the *free depolarization* from this high value. The periods from which K was calculated were taken by applying a weak field and measuring the

period after it had been on for a minute in each case, after which it was cut off. There is no doubt a sudden rise of polarization at the moment of applying the field, but since the conditions are the same in each case the figures give an approximation to the rate of relaxation.

Free depolarization of Flint Glass, Δ 3.3.

Time	10 m.	1 h.	2 h.	3 h.	4 h.	5 h.	19.5 h.
K	6075	426	79.7	28.0	12.73	9.0	8.17

4. EQUALITY OF FINAL VALUES.

Before proceeding to examine whether these high constants are true polarization as distinct from the movement of free charge, four typical substances were examined for equality of K in different fields, the periods being taken to be steady when they did not change by a measurable amount in twelve hours. Since the derived value of K is proportional to $F^2/(n^2 - n_0^2)$ equality in observed values of the latter is also true for the dielectric constants.

Paraffin Wax Ellipsoid.—Free period 46.5 seconds. After 7 days in $F = .259$, period 13.63; after 48 hours more in a field .132, 24.0 seconds. From these $F^2/(n^2 - n_0^2) = 13.65$ and 13.69 respectively, giving equality of K .

Sulphur Cylinder.—Free period 23.1. After 16 hours in $F = .131$, period 19.7; after 24 hours longer in $F = .259$, 10.8 seconds. $F^2/(n^2 - n_0^2) = 24.62$ and 25.0 respectively.

Gutta Percha Cylinder.—Free period 49.6 seconds. After 66 hours in a field .26, period 9.01; after 30 hours longer in $F = .132$, 16.7 seconds. $F^2/(n^2 - n_0^2) = 5.66$ and 5.50.

Ebonite Cylinder.—Free period 86.2 seconds. After 48 hours in $F = .26$, period 12.64; after 48 hours longer in $F = .13$, 24.0 seconds. $F^2/(n^2 - n_0^2) = 11.1$ and 10.85.

Thus for different substances and over a wide range of values the effective polarization of an insulated rod approaches the same final value whatever the intensity of the field may be.

5. RATE OF POLARIZATION.

In the foregoing observations of the rate of change of K in steady fields there appear then to be three stages, a sudden yield, followed by a change at a uniform rate for intervals of time differing in the various substances from a few minutes to several hours, and later an approach to saturation.

In order to see how these, especially the second, hold over a wider range of substances the following measurements were made. The details of the observations and their reduction, which are lengthy, are not given. In every case the specimen was dried for several days, in some cases weeks, over phosphoric anhydride and *in vacuo*, until the period tested in an alternating field of force had become steady.

Fused Quartz, $K \sim 3.78$.

Time	1 m.	4 m.	7 m.	16 m.	30 m.	120 m.
K	6.8	8.3	9.7	12.8	14.7	14.7

Paraffin Wax, $K \sim 2.32$.

Time .....	.7 m.	1 m.	2 m.	5 m.	10 m.
K	6.28	6.52	6.77	7.04	7.12

Sulphur, $K \sim 4.03$.

Time	.2 m.	1 m.	2 m.	6 m.	10 m.	50 m.	2.5 h.	19 h.	27 h.
K	4.4	4.51	4.59	4.99	5.43	10.67	20.8	101	141

India Rubber, $K = 3.08$.

Time	1 m.	2 m.	4.5 m.	12.5 m.	32 m.	60 m.
K	5.0	5.78	7.66	11.8	18.6	24.5

Ebonite, $K \sim = 2.79$.

Time	1 m.	2 m.	4 m.	7 m.	10 m.
K	6.25	8.0	11.8	16.9	21.8

Resin, $K \sim = 3.09$.

Time .....	.5 m.	2 m.	4 m.	6 m.	10 m.
K	7.3	7.86	8.19	8.47	8.9

Amber, $K \sim = 2.8$.

Time	1 m.	2 m.	3 m.	5 m.	11 m.	15 m.
K	8.0	13.1	19.1	32	54.2	61

Canada Balsam, $K \sim = 2.72$.

Time .....	.3 m.	1 m.	2 m.	4 m.	6 m.	10 m.
K	20.8	23.5	27.7	34.8	41.7	53

Gutta Percha, $K \sim = 4.43$.

Time .....	.8 m.	1.6 m.	3 m.	7 m.	10 m.
K	32	61.2	107	194	240

Sealing-Wax, $K \sim = 4.56$.

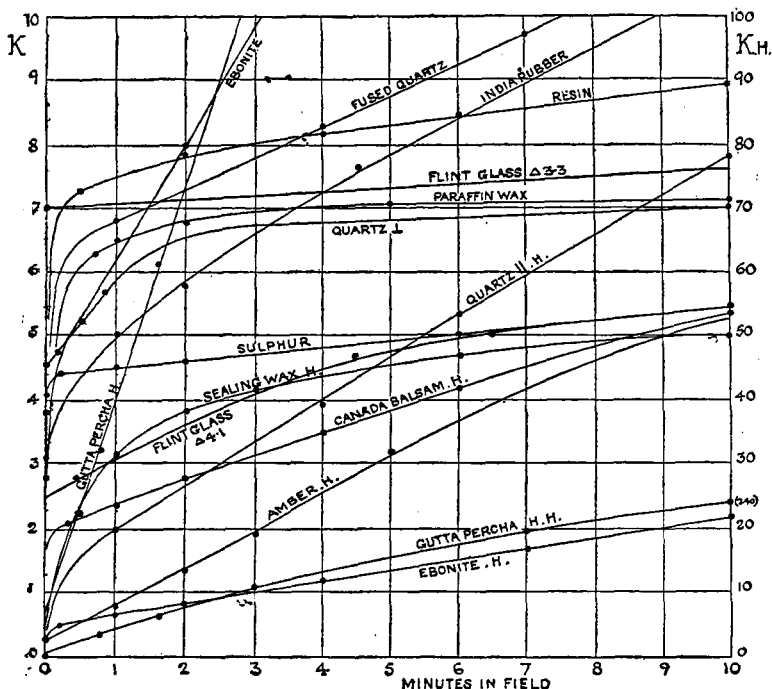
Time .....	.5 m.	1 m.	2 m.	3 m.	6 m.	10 m.
K	22.5	31.2	38.1	41.5	46.8	50

It will be noticed that gutta-percha, upon which so much depends in the working of submarine cables, has the highest values of all the substances examined. It is at least possible that some of the difficulties of cable working arise from this

cause. If by mixing a suitable insulator of lower dielectric constant with it, or by some system of grading, retaining at the same time the impermeability to water, the effective constant could be reduced, the rate of signalling might be accelerated.

Curves of the above rates of change are drawn in fig. 2

Fig. 2.—Rate of Polarization of Dielectrics in Steady Fields.



for the first ten minutes of electrification, and it will be seen that the features of a rapid rise at the start and a straight line change following it are present in all but sealing-wax, a mechanical mixture. The linear change in most cases lasts for several hours. In the case of fused quartz the polarization is steady in half an hour, and no increase was observed after several days in the field. This rapid polarization is possibly the reason for its use as an insulator in electroscopes.

The initial rush is in almost every case over within a minute. This may explain why observations of cable resistance are taken after this interval.

6. MEASUREMENT OF SPECIFIC RESISTANCE.

The fact that the rate of change of the effective dielectric constant is uniform for some time after the field is applied, provides a method of measuring the specific resistance of a dielectric during polarization as distinct from that using the "time of relaxation."

Whatever the nature of the electrical movement during the polarization of an insulated ellipsoid may be it is in effect a current, the density of which is the rate of change of the total polarization in unit volume. The field within the ellipsoid is given by $F_1 = F/(1 + \kappa N)$, where $\kappa = (K - 1)/4\pi$. The polarization is then KF_1 , and writing the apparent specific resistance ρ , we have

$$\frac{d}{dt}(KF_1) = \frac{F_1}{\rho}. \quad . \quad . \quad . \quad . \quad (3)$$

The resistance measured in this way differs, though not to a marked extent, from that found by the passage of a steady current through the dielectric.

It may be said that in view of the facts of slow polarization the measurement of the current after one minute's electrification is meaningless as an indication of the *resistance* of the insulation. A large part of the current is polarization change. The leakage method of measuring the resistance of insulators is also complicated by this slow depolarization of the dielectric and greatly influenced by the time of charge.

We have from the above

$$\frac{\rho}{4\pi} \frac{dK}{dt} = 1 + \left(\frac{K-1}{4\pi} \right) N, \quad . \quad . \quad . \quad . \quad (4)$$

from which ρ may be found at any stage of the polarization*.

Since the measurements are in electrostatic units, ρ is also, and in electromagnetic measure is

$$= v^2 \{ 4\pi + (K-1)N \} / dK/dt \cdot 10^9 \text{ ohms per cm. cube,} \quad . \quad (5)$$

where v is the ratio of the electromagnetic to the electrostatic unit of charge.

* The statement of this section has been modified at the suggestion of Dr. T. H. Havelock, to whom the author is indebted for helpful criticism throughout the work.

The following table gives values of the specific resistance found in this way from the observed rates of change of fig. 2. The indiarubber and gutta-percha were not specially prepared for cable work.

The ratio of Curie's values for quartz \perp and \parallel is 240; those now obtained give 130. It is interesting to note that the velocity of light in quartz is greatest when the wave-front and current are in the direction of least electrical conductivity. In accordance with previous observations the lighter flint-glass has the higher resistivity. Paraffin-wax was the most perfect insulator examined.

TABLE II.
Specific Resistance of Dielectrics at 17° C.

Substance.	$dK/dt.$	ρ ohms per cm. cub.		Temp.
Paraffin-Wax	·00026	4.9×10^{16}	3.4×10^{16} Ayrton and Perry.	46
Quartz \perp	·00064	2.0×10^{16}	$.91 \times 10^{16}$ Curie.	
Flint-Glass Δ 3.3 ...	·00131	9.9×10^{15}		
Sulphur	·00163	8.2×10^{15}	$c. 10 \times 10^{15}$ Threlfall.	
Resin	·00197	7.0×10^{15}		
Fused Quartz	·00805	1.6×10^{15}	3.8×10^{11} Exner.	
Indiarubber	·0089	1.5×10^{15}	1.5×10^{15} Electrician.	
Ebonite	·0316	4.5×10^{14}	2.8×10^{16} Ayrton and Perry.	
Canada Balsam.....	·059	2.8×10^{14}		
Flint-Glass Δ 4.1 ...	·077	2.5×10^{14}		
Amber	·097	1.55×10^{14}		46
Quartz \parallel	·107	1.53×10^{14}	$.38 \times 10^{14}$ Curie.	
Gutta-percha	·35	6.21×10^{13}	4.5×10^{14} Lat. Clark. 2.5×10^{13} F. Jenkin.	

It follows from equation (5) that when the period has reached a steady state the apparent resistance of the dielectric is infinite. This does not mean that no current could pass through it if it were in contact with the poles but that the polarization has reached its limit.

Although the dielectric constant increases at a uniform

rate the apparent resistance increases also, as calculated below, from the curves of fig. 2. This indicates that, as one would expect, the mutual attraction of charges on adjacent molecules increases in intensity as they approach, so that though the resistance to movement increases, the rate, on the whole, is maintained uniform.

Change of Apparent Resistivity with Time.

Light Flint-Glass, Δ 3.3.

Time ...	1 m.	15 m.	1 h.	2 h.	4 h.	10 h.	15 h.	22 h.
ρ	$\cdot 987$ $\times 10^{16}$	1.56	2.0	2.7	2.65	10.28	40.4 $\times 10^{16}$	15.15 $\times 10^{18}$

Sulphur.

Time ...	$\cdot 2$ m.	2 m.	6 m.	10 m.	50 m.	2.5 h.	19 h.	27 h.
ρ	$\cdot 816$ $\times 10^{16}$	$\cdot 818$	$\cdot 83$	84	1.06	1.39	3.03	3.54 $\times 10^{16}$

Indiarubber.

Time ...	$\cdot 5$ m.	1 m.	2 m.	4.5 m.	12.5 m.	32 m.	60 m.
ρ	$\cdot 057$ $\times 10^{16}$	$\cdot 084$	$\cdot 105$	$\cdot 136$	$\cdot 29$	$\cdot 72$	1.66 $\times 10^{16}$

Fused Quartz.

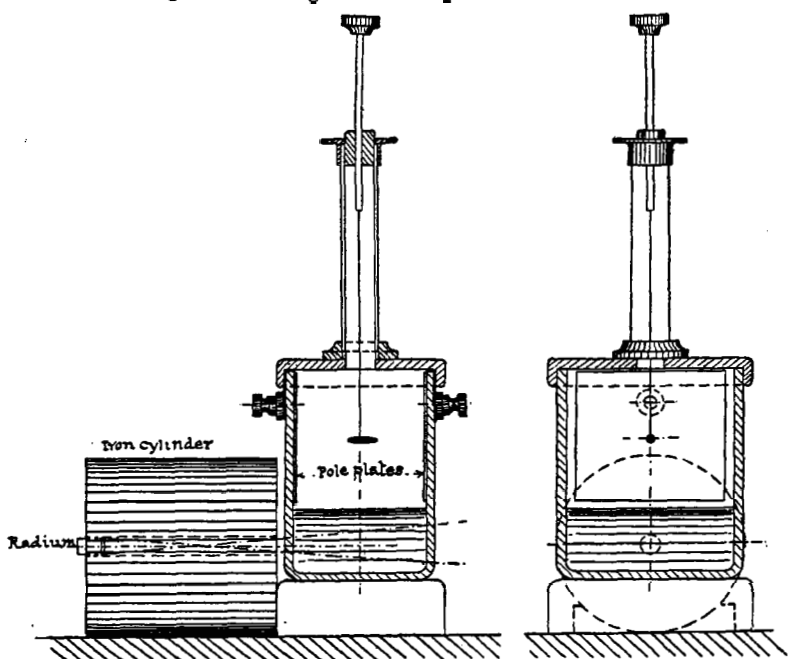
Time ...	$\cdot 5$ m.	1 m.	5 m.	15 m.	20 m.	25 m.
ρ	$\cdot 071$ $\times 10^{16}$	$\cdot 112$	$\cdot 179$	$\cdot 24$	$\cdot 39$	1.15 $\times 10^{16}$

7. NATURE OF CURRENT DURING SLOW POLARIZATION.

The electrical movement within the substance during slow polarization may be a translation of free electrons, as in metallic conduction, a transfer of charge, as in electrolysis, or a separation of the internal charges of the molecule, so that its electrical moment increases.

In order to determine which of these occurs in the present case, a flint-glass ellipsoid was suspended in a glass cell (fig. 3), the upper part having pole plates, so that a field

Fig. 3.—Testing Cell for exposure to Radium.



could be maintained there, and the lower being filled with disulphide of carbon. Outside the cell a massive iron cylinder was placed, having a small central hole pointing towards the line of suspension. The ellipsoid was exposed to the field for several days, and its steady period noted. It was then lowered into the liquid and exposed to the radiation from a strong tube of radium bromide placed in the end of the iron cylinder. After five minutes' exposure the ellipsoid was

raised, allowed to stand in the field for the same time that it had been removed from it, and its period then found to be unchanged. The liquid was used to shield the specimen from any ions which might possibly gather on it from the poles, and to prevent any change in the gradient between the poles by the diffusion of ions from the line of the radium discharge.

If the charge on the ellipsoid had been in any sense free, whether residing on the surface or inside, it would have been rapidly removed and the period lengthened by exposure to the radium. The experiment was repeated with the conditions varied in several ways with always the same result.

It would appear from this that the electrical movement in a dielectric when isolated in the field is entirely confined to the molecule, and is therefore neither metallic nor electrolytic in type, but is the continued displacement of the atomic charges to a greater degree of separation than has been hitherto recognized.

It may be remarked here that the high values of the dielectric constants obtained in the paper are confirmed by measurements on electric cables. Ashton* found that an ozokeritized rubber cable charged at 206.5 volts for 7200 seconds, absorbed 13.8×10^{-5} coulomb. From the given dimensions the dielectric constant corresponding to this is 13.1. In this case also the slow polarization was elastic in type, as shown by the fact that the quantity discharged on short circuit was just twice that absorbed at constant potential.

It was early suggested by Mossotti that the behaviour of a dielectric can be explained on the assumption that it is made up of isolated conducting spheres. On any of the present electronic theories of matter the separation of charge under the influence of the field gives an arrangement similar to this.

It is now suggested that the first stage of polarization produces such a charged system, but that it differs from a system of conductors in that the charges undergo further separation

* A. W. Ashton, Phil. Mag. no. 52, 1901, p. 501, "On the Resistance of Dielectrics."

automatically by reason of the attraction and quasi-elastic approach of opposite charges on adjacent molecules. The limit of the first stage of rapid polarization is that of the re-arrangement of atomic charge within the molecule, that of later stages the establishment of electrical strain throughout the mass under new conditions of internal stress set up by the first polarization.

The range of the dielectric constant in the first stage may be taken as the intercept on the vertical axis in fig. 2. Writing this K_0 , it is of interest to compare it with the values found for the same substances in alternating fields*, as in Table III. The influence of frequency may from this be anticipated. For those substances in which the ratio is nearly unity it will be at low frequencies small, but for the first few in the list a greater change may be expected between zero and 80 alternations a second than from 80 to the frequency of light.

TABLE III.

Ratio of the Initial Values of Dielectric Constants in
Steady Fields to those in Alternating Fields.

	K_{80}	K_0	K_0/K_{80}
Quartz || .....	4.6	13	2.8
Flint-Glass Δ 4.1	8.5	25	2.9
Resin	3.09	7.0	2.3
Canada Balsam	2.72	19.5	6.0
Paraffin-Wax	2.32	5-6	c. 2.4
Gutta-percha	4.43	7.0	1.58
Sulphur	4.03	4.38	1.07
Indiarubber	3.08	3-4	c. 1.1
Ebonite	2.79	4.2	1.5
Quartz \perp	4.54	4.55	1.0
Flint Glass Δ 3.3	6.98	7.0	1.0
Amber	2.8	2.8	1.0
Sealing-Wax	4.56	c. 4.6	1.0

* *Vide* Roy. Soc. Proc. A, vol. lxxxii. p. 422 *et seq.*

ABSTRACT.

The paper contains an account of experiments on the polarization of dielectric ellipsoids and cylinders suspended in a steady electric field. From measurements of the field-intensity, the dimensions of the ellipsoids, and the frequency of torsional swings with and without the field, the dielectric constant can be found from time to time. The method is essentially the same as that using alternating fields described in Roy. Soc. Proc. vol. 82, p. 422. In the present case the longitudinal component of polarization reached a higher value than previously recorded. This was found to be independent of the intensity of the field inside the ellipsoid and to be quasi-elastic in type. The substances examined were quartz, fused and crystalline, flint-glass, amber, sulphur, ebonite, rubber, gutta-percha, paraffin-wax, resin, and sealing-wax. From the rate of increase of the dielectric constant the specific resistance of these was found by considering the change of polarization to be equivalent to a current. The rate of depolarization when the field was reversed was found to be the same as that of polarization and to be uniform for, in most cases, several hours. It is suggested that the cause of this and for the independence of the field-intensity is to be looked for in the continued separation of molecular charge by the attraction of the opposite charges on adjacent molecules induced by the application of the field. From a comparison of the results of the paper and those in alternating fields, the variation of the dielectric constants with frequency can be anticipated.

DISCUSSION.

Mr. JACOB said that some of the Author's curves (fig. 1) showed that he was dealing with dielectric hysteresis. The results for gutta-percha given in the paper could not be applied in telephonic work because of the high frequencies employed in the latter case. He pointed out that the field strengths used in the paper were much smaller than those occurring in actual work on cables.

Mr. RAYNER doubted whether the method described was accurate to one part in a thousand as stated by the Author. The distance between the electrodes was so large compared with their size, that there would be difficulty in determining accurately the strength of the field at the centre. The difficulties in connexion with the determination of the change of period, especially when it was large, would also be great. He drew attention to the necessity of having the surfaces of the insulators perfectly clean and dry.

Prof. C. H. LEE asked if the variation in the period at the start could be ascribed to the motion of the ions in the vessel onto the dielectric.

Mr. G. L. ADDENBROOKE asked what steps had been taken with regard to the *purity* of the materials employed. He asked also what was the shortest time in which it was possible to get an observation. It would be interesting to know if the Author had investigated the effects described at different temperatures.

Dr. RUSSELL stated that he was deeply indebted to Prof. Thornton for his most interesting and instructive paper. The methods of measuring the dielectric coefficient and the insulativity of dielectrics were both novel and valuable. He had a difficulty, however, in understanding why the apparent value of the dielectric coefficient, when the insulating substance was left in an electric field for a long time, did not become infinite. At first sight the experimental results seemed to indicate that it was possible to have a potential difference between points in a dielectric and yet no current. He found it easier to believe that when the steady state was reached there was a minute current flowing across the electrified air to the insulating substance. It was also possible to explain the results by supposing that there was a certain distribution of electric charge inside the dielectric. The subject was one of great practical and theoretical importance, and so he hoped that the Author would continue his researches and clear up the remaining difficulties.

Mr. A. CAMPBELL said that the results, which in themselves were highly interesting, were not directly applicable to telephone cables, since the frequency used with these was of the order of $1000 \sim$ per sec. In connexion with the large polarization shown by gutta-percha, he gave an example of a coil of gutta-percha covered wire which gave an apparent insulation resistance of 200,000 megohms with direct current and 1 minute's electrification, but only a fraction of a megohm when tested at $1000 \sim$ per second.

Prof. THORNTON, in reply, said that the very rapid rise of the polarization at the start made it difficult to measure there. The movement of the ellipsoids would have to be recorded photographically. With regard to the accuracy of the method, it was only at low values that it was sensitive. It was found that with electrodes 15 cm. square and 6 cm. apart the field at the centre was uniform. The swings had an average amplitude of 3 degrees. The influence of moisture or surface impurity was recognized at an early stage. The specimens were carefully wiped before suspension, and dried in a warm room *in vacuo* over phosphorus pentoxide for days or weeks before the field was applied. With regard to the influence of ions, it was found that exposing the specimen to radium greatly reduced its apparent polarization. This effect was a double one: the gradient was lowered at the centre of the field and the ions collected around the ends of the ellipsoid, masking the effective charges there. The polarization recorded in the paper always increased, though in the later stage the rate of falling from the linear increase might be in part due to ions. The purity of the quartz and glass specimens was guaranteed by Messrs. Hilger who made them; the paraffin was also pure, the rest were carefully selected.

It is suggested in the paper that the limit to the polarization is that of the separation of charge in the molecule. If the polarization came from a source external to the ellipsoid it always should increase to infinity, and have the same values for different specimens, such for example as quartz cut parallel and perpendicular to the optic axis, for which in fact it is widely different.
