STUDIES IN DIELECTRICS.

PART II. THE EFFECT OF SUPERIMPOSED MAGNETIC FIELDS ON THE PERMITTIVITY AND POWER FACTOR OF DIELECTRICS.

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The effect of superimposed magnetic fields on the permittivity and power factor of insulating materials is important from both physical and practical standpoints. An increase in the power factor would lead to greater dielectric losses and heating and this would, in the long run, result in a lower breakdown voltage of dielectrics, due to their consequent deterioration. On the other hand, a reduction of the power factor, and consequently the losses, would result in a more satisfactory functioning of the insulation and lead to longer life.

The literature relating to work in this direction is very meagre. Monkhouse (*Proc. Phys. Soc.*, 1928-29, **41,** 83) has conducted tests on pressboard under a "highest maintained A-C stress" in accordance with E.R.A. report A/S_2 (*Journal I.E.E.*, 1922, **60,** 794) and from the measurement of the temperature rise of the specimen and the time of breakdown, he concludes that the power factor and losses are considerably increased by a superimposed magnetic field. Measurements of dielectric losses in bakelised paper and glass by A. Smurrow (*Archiv. f. Elektrot.*, 1929, **22,** 31) showed that these are considerably affected by a unidirectional magnetic field. Fujikawa and Kitasato (*Bull. I.P.C.R.*, 1931, **10,** 153) have measured the power factor of pressboard, empire cloth, oil paper and mica under the action of unidirectional magnetic fields up to 8 000 gauss by more accurate bridge methods and observed that in brown pressboard, the power factor was increased by a small amount (2 to 4 per cent.). The change was slightly greater with stronger fields, and the magnitude of the electric stress had practically no effect. In black pressboard the corresponding changes were greater (from 2 to 17 per cent.). In empire cloth, the magnetic field produced an increase in the power factor at low values of electric stress, but a decrease at higher values of stress. The same result was observed with oil paper and mica. In general, the change in power factor was determined by the magnitude of the electric stress and the magnetic field intensity. Further work has been carried out by the same authors (*Sc. Papers, I.P.C.R.*, 1932, **19,** 148) on the influence of alternating magnetic fields on the power factor of pressboard, empire cloth and mica. With alternating fields up to 25 000 gauss, they have observed, in general, an increase in the power factor of the materials, the increase being greater with increasing magnetic fields. It was also observed that with the same magnetic field, the ratio of power factor with the magnetic field to that without the field decreased with increasing values of the electric stress. Further, with a given strength of the electric and magnetic fields, the ratio decreased as the angle of time phase difference between the two fields increased from 0 to 90°.

The investigations of R. Schmid (*Ann. der Physic*, 1932, **14**, 809) on the effect of unidirectional magnetic fields up to 14 000 gauss on the loss angle of micanite paper, bakelised paper, paraffined paper, excelsior linen and mica give contrary results. He has observed that the loss angle in these dielectrics at 500 cycles remained unchanged under the action of both longitudinal and transverse magnetic fields. Very recently the loss angle and insulation resistance of transformer oil, paraffin oil, glass, paper and linen under longitudinal unidirectional magnetic fields up to 12 000 gauss have been measured by Konried (*Archiv. f. Elektrot.*, 1934, **28**, 154) at frequencies from 50 to 200 cycles and it was observed that the magnetic field had no effect on these for all values of electric stress up to the breakdown value.

The results of these few workers are conflicting and lead to no definite conclusion. In connection with the study of the various dielectric properties of insulating materials undertaken in these laboratories, it was decided to investigate the effect of magnetic fields on their permittivity and power factor. The following measurements were made with unidirectional magnetic fields up to a maximum of 18 000 gauss with the help of the electromagnet described in Part I.

EXPERIMENTAL.

Schering Bridge.—For the measurement of the capacity and power factor of the dielectrics, the high voltage Schering Bridge was employed. A full description of a similar bridge is given by Churcher and Dannatt (*World Power*, 1926, **5**, 238). The standard, loss-free, 100 $\mu\mu$F condenser was of the concentric cylinder type with air as dielectric. It was completely enclosed in a wooden box lined with earthed metallic lining. The diagram of connections of the bridge is shown in Fig. 1. A vibration galvanometer with a sensitivity of 30 mm. deflection per micro-ampere at one metre distance was used as detector. The bridge and galvanometer were separated from the high voltage apparatus by an earthed metal screen to avoid stray capacity effects.

At maximum values of R_3 (1 000 ohms) and C_4 (1 μF) the vibration galvanometer was responsive to a change of 1 in 1 000 or 0·1 per cent. in both R_3 and C_4. Consequently at these values the capacity and power factor could be measured to an accuracy of 0·1 per cent. This represents only the highest accuracy obtainable; in other cases where the bridge impedances were different, the accuracy was lower but never fell below 0·5 per cent.

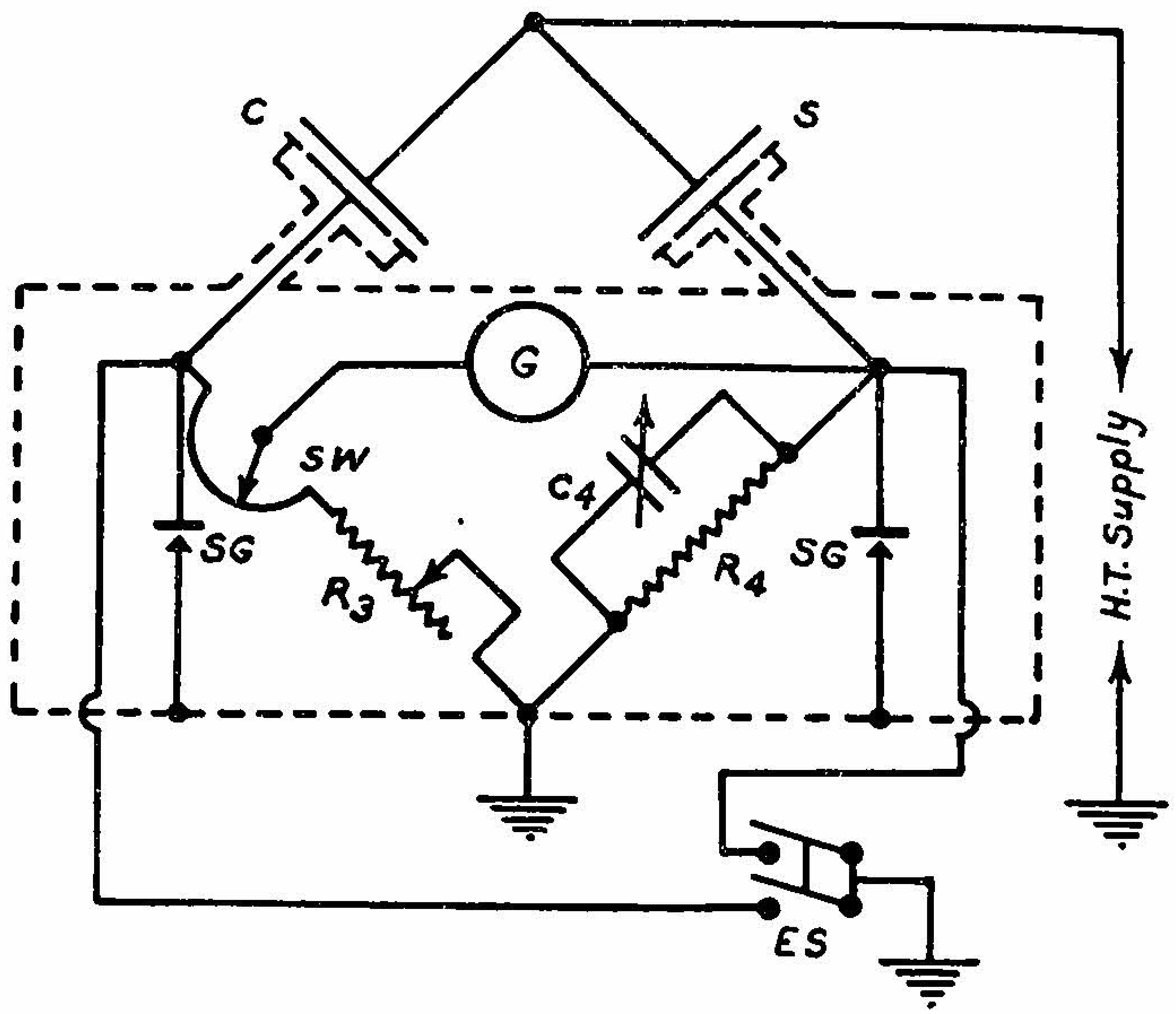

Fig. 1.

Schering Bridge.

C—Test condenser with guard-ring.
S—100$\mu\mu$F. Standard condenser.
R_3—Variable Resistance.
R_4—Fixed Resistance $= \frac{1000}{\pi}$ ohms.
C_4—Variable condenser.
G—Vibration galvanometer.
SW—Slide wire resistance.
- - - —Earthed screens.
SG—Safety gaps.
ES—Earthing switch.

Expressions for C, Cos ϕ and loss :—

$C = S.\frac{R_4}{R_3}\sin^2\phi$; $\cos\phi = \omega.C_4.R_4$.

Dielectric loss $W = \omega.C.E.^2 \cos\phi$, where,

E = applied voltage.

ϕ = phase angle of test condenser.

Correction for slide wire in series with C is negligible.

High Voltage Supply.—The test voltage was of 50 cycles and obtained from a 10 kVA, 220/115 000 V testing transformer supplied from a sine-wave alternator. The voltage and frequency of supply were completely under control.

Materials.—The following materials of which the dielectric strength under the action of unidirectional magnetic fields had been previously investigated (see Part I), were chosen for the tests; namely, Air, Transformer oil, Switch oil, Manilla paper, Presspahn, Press-board, Kraft paper, and Glass. Mica was also tested. The materials were properly conditioned before the tests (see Part I, page 24).

Test Condensers.—The condenser used for the measurement of the permittivity and power factor of air and oil with longitudinal magnetic fields is shown in Fig. 2. It consisted of two 2″ diameter circular copper electrodes $\frac{1}{64}$″ thick pasted on two glass plates which formed the

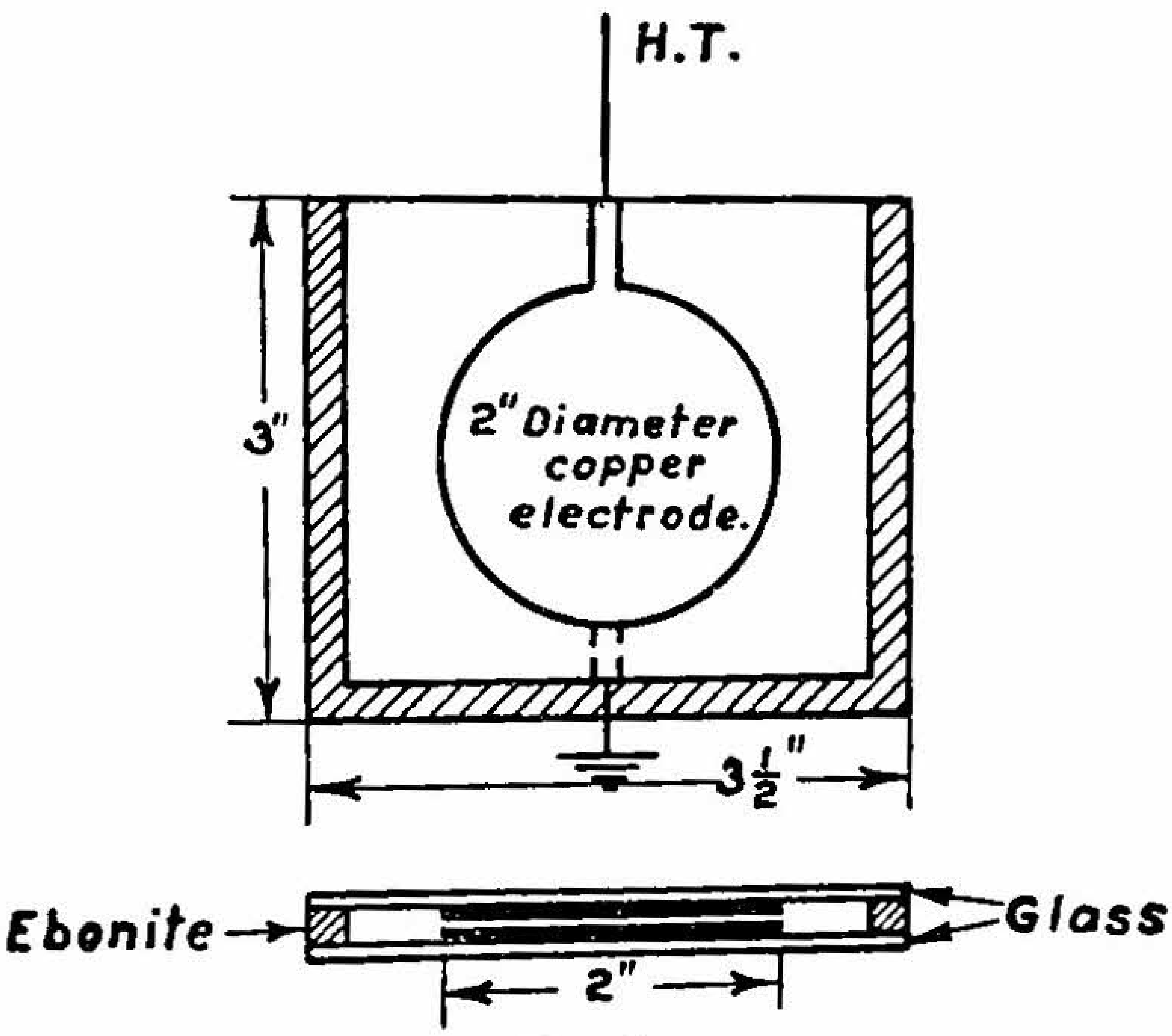

Fig. 2.

Condenser for the Measurement of Power Factor of Air and Oil with Longitudinal Magnetic Fields.

two sides of a small rectangular cell with an ebonite spacer between the glass plates. The distance between the electrodes was about $\frac{1}{16}$″. The capacity between the electrodes with air as dielectric was measured with the help of the Schering Bridge and found to be about 12 $\mu\mu$F. With the cell filled with oil, the capacity was about twice this value. For measurements with transverse magnetic field, a suitable condenser with large enough electrodes and capable of being accommodated in a short air gap was not available. Observations under this condition were therefore not possible.

The test condenser for use with solid dielectrics under longitudinal magnetic fields consisted of two 1″ diameter brass discs, about $\frac{1}{64}$″ thick pasted on mica sheets (see Part I, Fig. 5). The dielectric under test was cut into 2″ square samples and held between the electrodes by means of four screws at the corners of the mica plates.

Fig. 3 represents the condenser used for measurements on solids with transverse magnetic field. The electrodes were 5 cms. × 4 mm. rectangular pieces cut out of $\frac{1}{16}$″ thick brass sheet and fixed to two ebonite pieces of the shape shown in the figure. The test samples cut

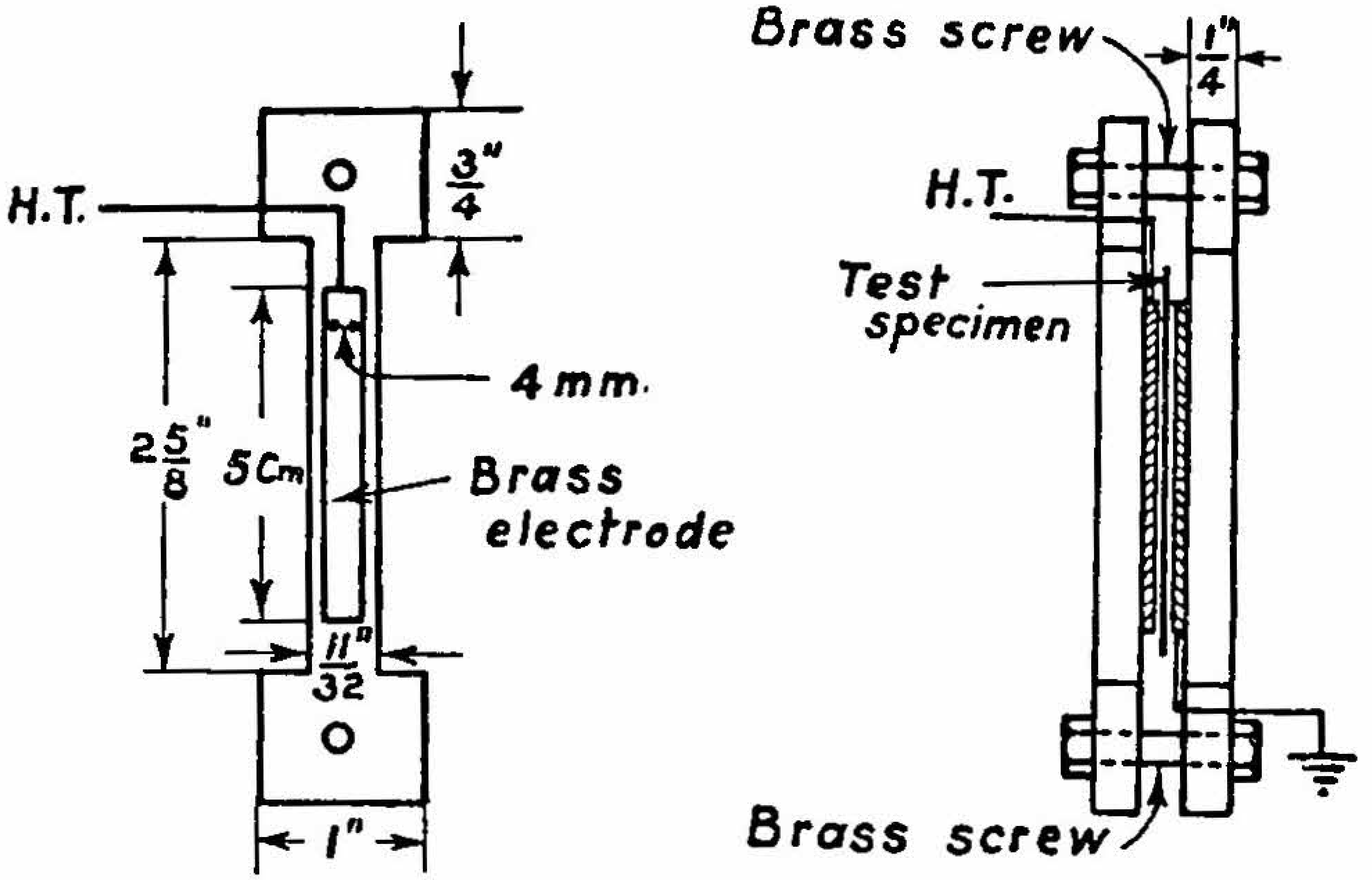

Fig. 3.

Condenser for the Measurement of Power Factor of Solids with Transverse Magnetic Fields.

to 6 cm. × 8 mm. rectangular pieces were held between the electrodes by two clamping screws at the top and bottom of the ebonite pieces. This condenser had a capacity accurately measurable on the bridge, and proved quite satisfactory.

Method of Testing.—The test condenser was placed in the air gap of the magnet and the electrodes connected to the transformer and bridge respectively. With the magnetic field off, measurements of capacity and power factor were made for both ascending and descending values of the electric stress; these were found to agree closely. The same measurements were repeated with the magnetic field. Beyond a certain value of the electric stress, the bridge became very unsteady and the measurements could not be continued. A large number of sets of readings were obtained for each material and the results reproduced here represent the mean values.

RESULTS.

All the results are given in Tables I to VII; some of them are also shown graphically in Figs. 4 to 7. C_e and $P.F_e$. refer to values of capacity and power factor respectively without the magnetic field and C_{me} and $P.F_{me}$. to those with the magnetic field.

TABLE I.

Air and Mineral Oils.

Longitudinal Magnetic Field: 15 000 Gauss.

Stress in kV per cm.		1·58	3·16	4·74	6·32	7·90	9·48	11·06	12·64
Air	C_{me}/C_e	1·000	1·000	1·000	1·000	1·000	1·000	—	1·000
	$P.F_{me}./P.F_e.$	1·000	1·000	1·000	1·000	1·000	1·000	—	1·000
Trans-former Oil	C_{me}/C_e	1·000	1·000	1·000	1·000	1·000	1·000	1·000	1·000
	$P.F_{me}./P.F_e.$	1·000	1·000	1·000	1·000	1·000	1·000	0·990	1·000
Switch Oil	C_{me}/C_e	1·000	1·000	1·000	1·000	1·000	1·000	—	1·000
	$P.F_{me}./P.F_e.$	1·000	1·000	1·000	1·008	1·000	1·000	—	1·010

Table I shows that the permittivity and power factor of air and oil are unaffected by longitudinal magnetic fields up to 15 000 gauss. The slight changes at one or two points are probably due to experimental error. This result is in conformity with the observations of Konried (*loc. cit.*) who has detected no change in the loss angle of Transformer oil and glass with longitudinal unidirectional magnetic fields up to 12 000 gauss.

In the case of the solids, the measurements were made with both longitudinal and transverse magnetic fields. Tables II and III show that the permittivity and power factor of mica and glass are unaffected by both longitudinal and transverse magnetic fields, the few small discrepancies being probably due to experimental errors. These substances therefore resemble air and oil in this respect. The result agrees with that obtained by R. Schmid (*loc. cit.*) on mica and that by Konried (*loc. cit.*) on glass but differs from that of Fujikawa and Kitasato (*loc. cit.*).

TABLE II.

Glass.—Thickness, 50 mils.

Stress in kV per cm.		1·968	3·936	5·904	7·872	9·84	11·81	13·78	15·74
Longitudinal field 18 000 gauss	C_{me}/C_e	1·000	1·000	1·000	1·000	1·000	1·000	1·000	1·000
	$P.F_{me}/P.F_e$	1·000	1·000	1·000	1·000	1·000	1·000	1·000	1·000
Transverse field 12 500 gauss	C_{me}/C_e	1·000	1·000	1·000	1·000	1·000	1·010	1·010	1·000
	$P.F_{me}/P.F_e$	1·000	1·000	1·000	1·000	1·000	1·000	1·000	1·000

TABLE III.

Mica.—Thickness, 3 mils.

Stress in kV per cm.		32·75	65·50	98·25	131·00	163·75	196·5	229·25	262·00
Longitudinal field 18 000 gauss	C_{me}/C_e	1·000	1·000	1·000	1·000	1·004	1·000	1·000	1·000
	$P.F_{me}/P.F_e$	1·000	1·000	0·995	1·000	1·000	0·996	1·004	1·004
Transverse field 12 500 gauss	C_{me}/C_e	1·000	1·000	1·000	1·000	1·000	1·000	1·000	1·000
	$P.F_{me}/P.F_e$	1·000	1·000	1·010	1·000	1·000	1·000	1·004	1·000

The other solid dielectrics, however, show distinct changes in power factor and slight changes in permittivity. The permittivity of manilla paper (Table IV, Fig. 4) is unaffected by the transverse field but is increased by about 1 per cent. by the longitudinal field. With

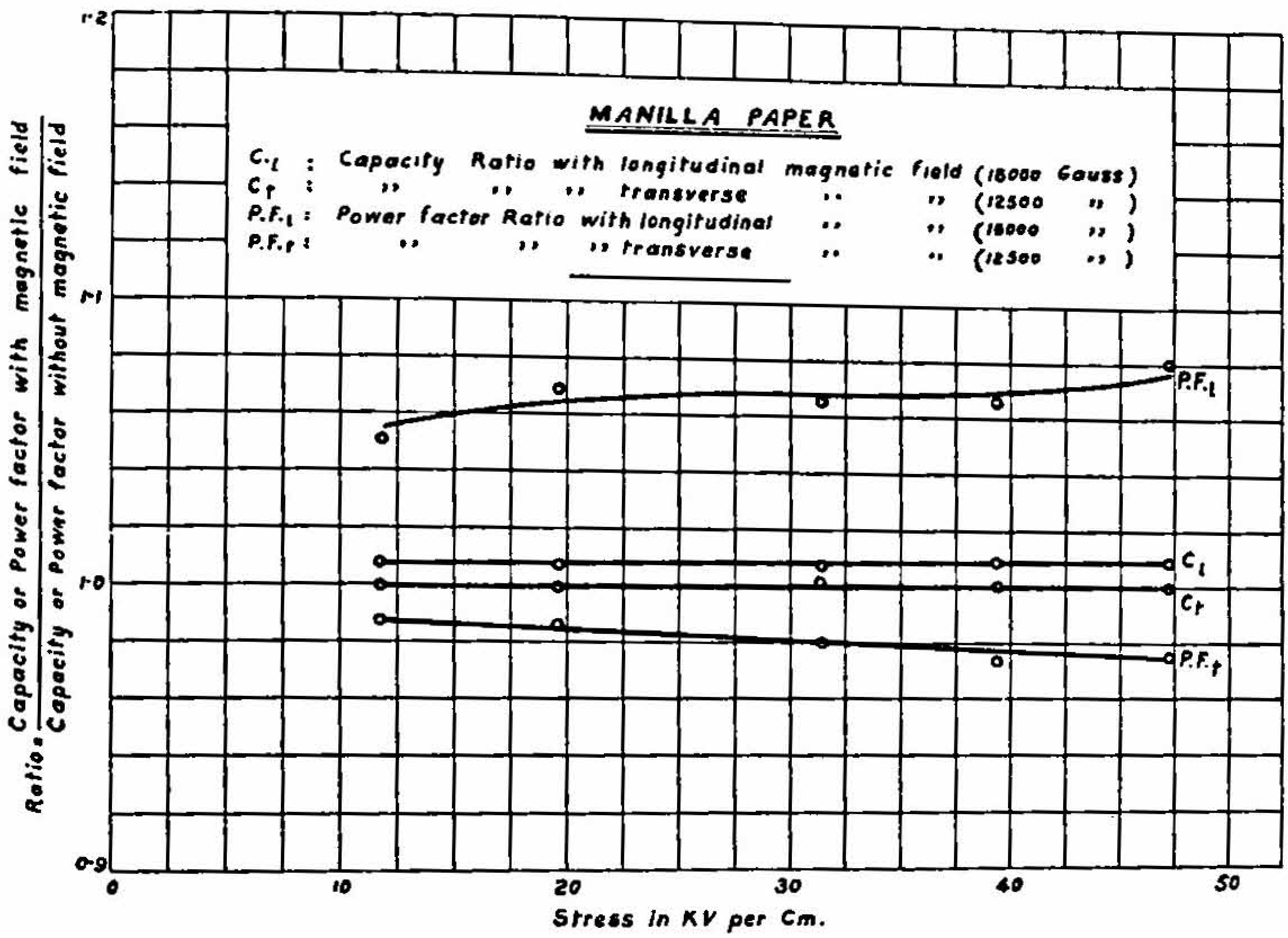

Fig. 4.

Variation of the Permittivity and Power Factor of Manilla Paper with Magnetic Field at Different Electrical Stresses.

(*Refer Table IV.*)

the longitudinal field, its power factor increases by about 5 to 8 per cent. while with the transverse field, it decreases by about 1 to 2·5 per cent. The value of the electric stress also determines the magnitude of the change; the higher the electric stress, the greater is the observed effect of the magnetic field.

In presspahn (Table V, Fig. 5) the permittivity seems to be unaffected by the magnetic field but the power factor increases by about 10 per cent. with the transverse field and decreases by a similar amount with the longitudinal field. The curves indicate a maximum change at a particular value of the electric stress which is about 35 kV per cm. with the transverse field and 48 kV per cm. with the longitudinal field.

TABLE IV.

Manilla Paper.—Thickness, 5 mils.

Stress in kV per cm.		11·8	19·68	31·4	39·36	47·2
Longitudinal field 18 000 gauss	C_{me}/C_e	1·008	1·007	1·007	1·009	1·010
	$P.F_{me}./P.F_e.$	1·051	1·070	1·066	1·066	1·080
Transverse field 12 500 gauss	C_{me}/C_e	1·000	1·000	1·000	1·000	1·000
	$P.F_{me}./P.F_e.$	0·988	0·986	0·980	0·974	0·975

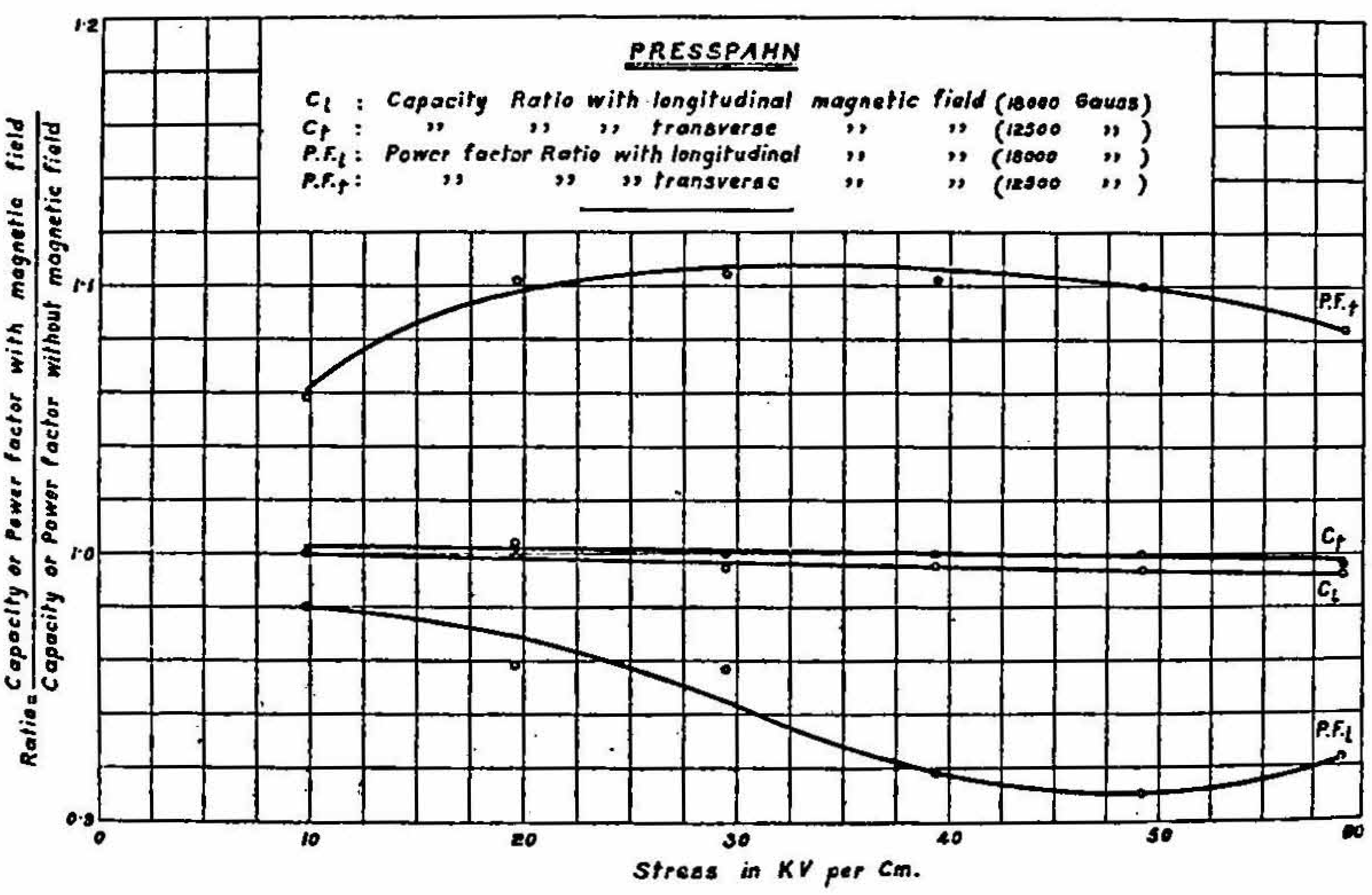

Fig. 5.

Variation of the Permittivity and Power Factor of Presspahn with Magnetic Field at Different Electrical Stresses.

(*Refer Table V.*)

TABLE V.

Presspahn.—Thickness, 10 mils.

Stress in kV per cm.		9·84	19·68	29·52	39·36	49·2	59·04
Longitudinal field, 18 000 gauss	C_{me}/C_e	1·000	0·999	0·994	0·996	0·994	0·992
	$P.F_{me}/P.F_e$	0·980	0·958	0·957	0·918	0·910	0·923
Transverse field, 12 500 gauss	C_{me}/C_e	1·000	1·004	1·000	1·000	1·000	0·995
	$P.F_{me}/P.F_e$	1·058	1·102	1.104	1·102	1·100	1·084

Pressboard (Table VI, Fig. 6) resembles presspahn in this that its permittivity is unaffected by magnetic fields. The behaviour of these two substances with regard to changes in power factor is, however, different. The longitudinal magnetic field produces an increase in the

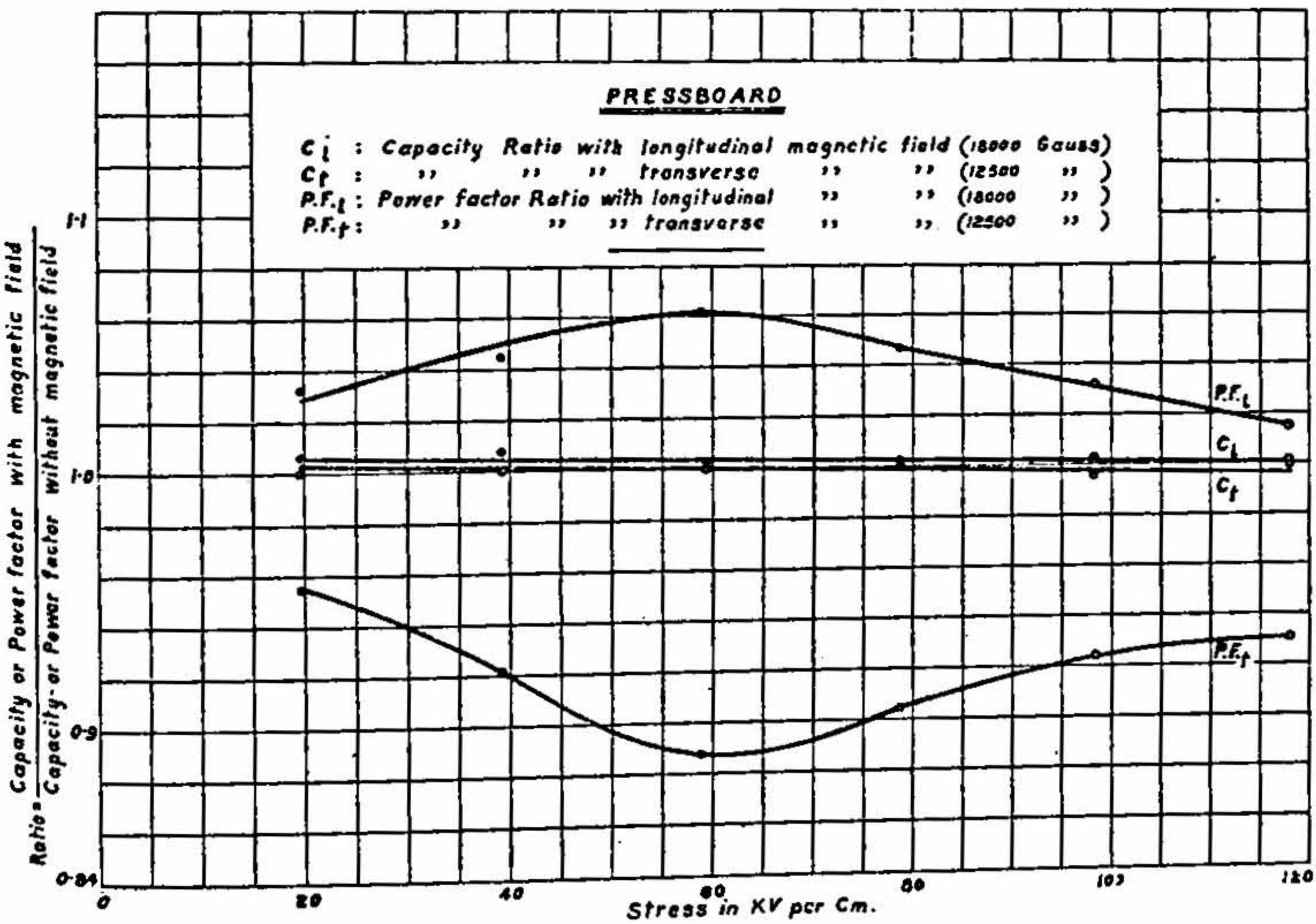

Fig. 6.

Variation of the Permittivity and Power Factor of Pressboard with Magnetic Field at Different Electrical Stresses.

(*Refer Table VI.*)

power factor of pressboard of up to 6 per cent. while the transverse field produces a decrease of up to 9 per cent. The points of maximum change are more conspicuous and occur at a stress of about 60 kV per cm. In comparing these results with those published by Fujikawa and Kitasato (*loc. cit.*) it must be remembered that their tests were conducted at lower values of the electric stress (up to 35 kV per cm.) and magnetic field strength (up to 8 000 gauss). With the longitudinal magnetic field, an increase in the power factor of about 2 to 4 per cent. in brown pressboard and of about 2 to 17 per cent in black pressboard was observed by them. Though the changes observed by them are in the same direction as those observed here, it is difficult to compare the results without a knowledge of the composition of the materials.

The change in the permittivity of Kraft paper (Table VII, Fig. 7) is as high as about 2 per cent.; the transverse field increases it and the longitudinal field decreases it. On the other hand, both longitudinal and transverse fields decrease the power factor; the effect of the

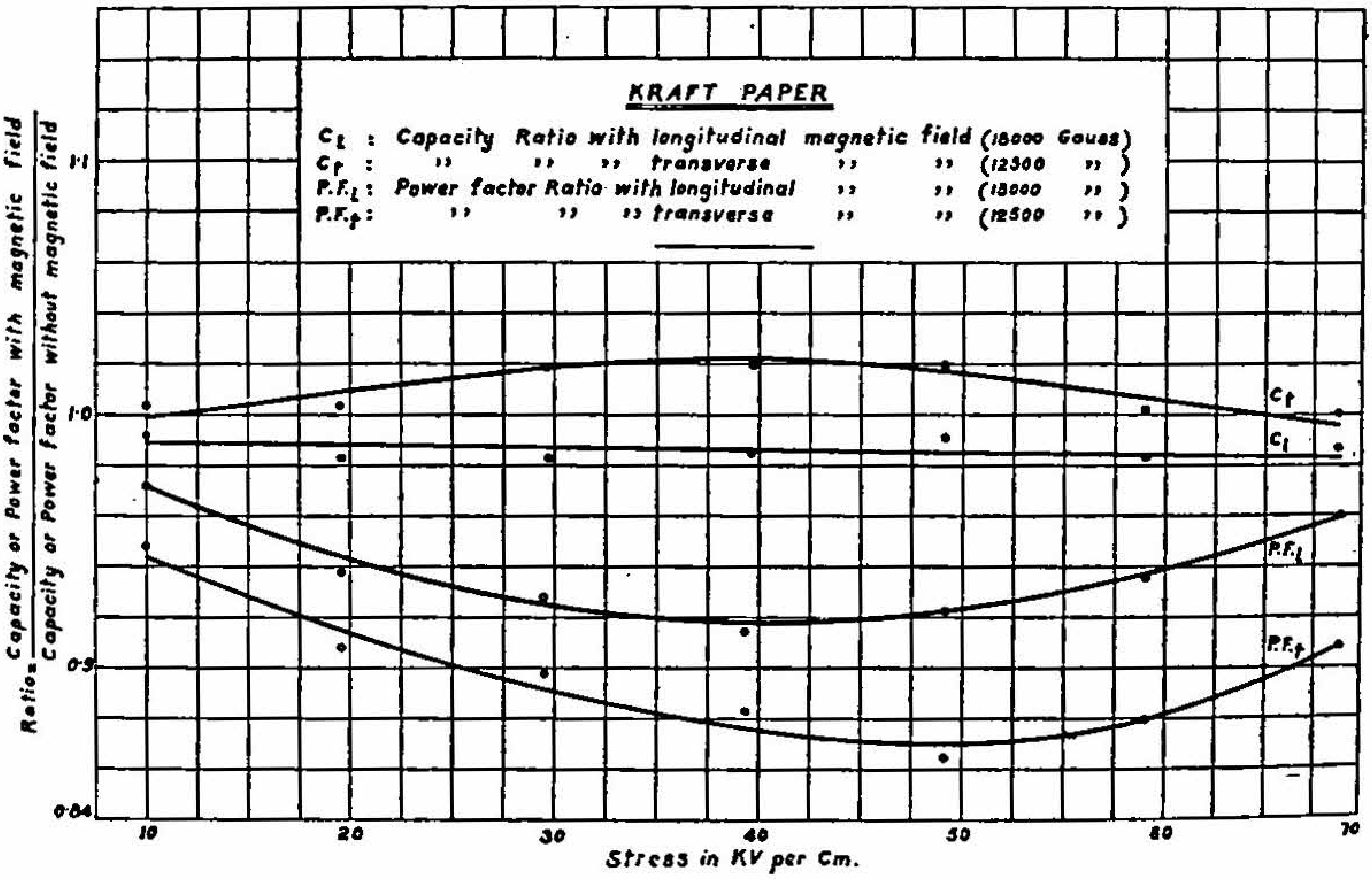

Fig. 7.

Variation of the Permittivity and Power Factor of Kraft Paper with Magnetic Field at Different Electrical Stresses.

(*Refer Table VII.*)

latter is greater and amounts to as much as 13 per cent. with an electric stress of 50 kV per cm. The curves again exhibit points of maximum change which are, however, not quite coincident.

TABLE VI.

Pressboard.—Thickness, 5 mils.

Stress in kV per cm.		19·68	39·36	59·04	78·72	98·4	118·08	137·76
Longitudinal field 18 000 gauss	C_{me}/C_e	1·006	1·000	1·003	1·003	1·003	1·001	..
	$P.F_{me}/P.F_e$	1·032	1·045	1·062	1·047	1·032	1·015	..
Transverse field 12 500 gauss	C_{me}/C_e	1·000	1·008	1·000	1·000	0·996	1·000	1·000
	$P.F_{me}/P.F_e$	0·955	0·922	0·888	0·905	0·924	0·930	0·944

TABLE VII.

Kraft Paper.—Thickness, 10 mils.

Stress in kV per cm.		9·84	19·68	29·52	39·36	49·20	59·04	68·88
Longitudinal field 18 000 gauss	C_{me}/C_e	0·992	0·983	0·983	0·985	0·991	0·983	0·987
	$P.F_{me}/P.F_e$	0·972	0·938	0·928	0·915	0·923	0·936	0·960
Transverse field 12 500 gauss	C_{me}/C_e	1·003	1·003	1·019	1·020	1·020	1·002	1·000
	$P.F_{me}/P.F_e$	0·948	0·908	0·898	0·883	0·865	0·880	0·908

Comparing these changes with those produced by unidirectional magnetic fields in the B. D. V. of the same dielectrics (see Part I), it will be seen that in the case of manilla paper, pressboard and kraft paper, the change in power factor is of opposite sign to the change in B. D. V. In other words, a magnetic field, which increases the power factor and consequently the dielectric loss, reduces the B. D. V. of the material. If the final breakdown is due to temperature, this is what might be expected, because any factor increasing the dielectric loss would also increase the temperature rise and cause a breakdown at a lower value of dielectric stress. Similarly, a lowering of the power factor and the losses would tend to an increase in B. D. V. It must, however, be noted that presspahn behaves differently and consequently no general conclusion could be drawn from this result.

SUMMARY.

The effect of a superimposed unidirectional magnetic field on the permittivity and power factor of air, mineral oils and solid dielectrics has been studied and the following conclusions are drawn:—

(1) The permittivity and power factor of air and mineral oils are unaffected by longitudinal fields up to 15 000 gauss.

(2) The permittivity and power factor of glass and mica are not affected by longitudinal fields up to 18 000 gauss and transverse fields up to 12 500 gauss.

(3) The permittivity of manilla paper, presspahn, pressboard and kraft paper are very little affected by magnetic fields.

(4) Magnetic fields have an appreciable effect on the power factor of manilla paper, presspahn, pressboard and kraft paper, the nature and magnitude of the change depending on the relative directions of the magnetic and electric fields and the magnitude of the electric stress.

(5) The effect of the magnetic field appears to be maximum, in some materials, at a certain value of the electric stress.

(6) The change of power factor in manilla paper, pressboard and kraft paper is opposite to the change in their B. D. V. under similar conditions. In presspahn, however, the changes are in the same sense.

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