STUDIES IN DIELECTRICS.

PART I. THE EFFECT OF SUPERIMPOSED MAGNETIC FIELDS ON THE BREAKDOWN VOLTAGE OF DIELECTRICS.

By N. V. Narayanaswami and F. N. Mowdawalla.

The problem of the effect of superimposed magnetic fields on the dielectric properties of insulating materials has hitherto received very little attention. Considerable work has been done by physicists on the effect of magnetic fields on electrical discharges in gases, and indicates that a magnetic field exercises considerable influence on the sparking potential of, as well as the discharge current in, gases. The effect of unidirectional magnetic fields on the dielectric constant of some gases has also been investigated and found to be negligible. Recently some interesting observations relating to the effect of magnetic fields on breakdown voltage and power loss have been made. Monkhouse (*Proc. Phys. Soc.*, 1928-29, **41**, 83) observed that the spark-over voltage of air was altered when it was subjected to a magnetic field, the magnitude and sign of the change depending on the direction and nature (whether unidirectional or alternating) of the field and the shape of the electrodes. R. Schmid (*Ann. der Physik*, 1932, **14**, 809) has studied the impulse breakdown of air and observed that a unidirectional longitudinal magnetic field of 14 000 gauss lowered the puncture voltage by as much as 25 per cent. while a transverse field increased it by about the same amount. His results show that the magnitude of the change is greatest with an impulse voltage, smaller with a 500-cycle A-C voltage and negligible with a D-C voltage. According to these investigators, the nature of the electrodes and the length of the spark gap greatly influence the change produced by the magnetic field.

A study of the literature on the subject indicates that the influence of magnetic fields on the dielectric properties of solid and liquid insulating materials used by engineers is just beginning to be investigated and sufficient data are not yet available. A. Smurrow (*Archiv. f. Elektrot*, 1929, **22**, 31) has concluded from theoretical considerations that a magnetic field should affect the dielectric properties of insulating materials, and has experimentally observed a reduction in the B. D. V. of transformer oil and air with both longitudinal and transverse alternating magnetic fields. A number of anomalous phenomena relating to insulation failures and corona discharges which were observed in connection with the operation of high voltage networks led Monkhouse (*loc. cit.*) to investigate the effect of magnetic fields on the B. D. V. of some solids and liquids with a view to determine if the abnormal behaviour could be explained thereby. Working with magnetic fields of intensities up to about 6 500 gauss, he observed that an alternating field, whether longitudinal or transverse, increased the B. D. V. of insulating oil by about 9 per cent. while an unidirectional field decreased it by the same amount. The B. D. V. of pressboard was decreased to the extent of 25 per cent. by a magnetic field, whether alternating or unidirectional, when it was longitudinal or parallel to the electric field. On the other hand, no effect was observed when it was transverse or at right angles to the electric field. A. Smurrow (*E.T.Z.*, 1930, **51**, 1459) has observed that the B. D. V. of mica was increased by as much as 50 per cent. with a transverse field while no effect was observed with a longitudinal field. These results indicate that, in some cases, even low magnetic fields have considerable influence on the B. D. V. of insulating materials. As such a change in the dielectric strength of insulating materials would affect the design of insulation of electrical machinery and apparatus and as the observations of Monkhouse and Smurrow were not supported by the work of other investigators, it was decided to carry on further investigation of the matter using stronger magnetic fields and a wider range of materials. The materials tested were Air, Transformer and Switch oils and some solid dielectrics, *e.g.*, Manilla paper, Presspahn, Pressboard, Kraft paper and Glass. Detailed specifications relating to these materials are given in the Appendix.

EXPERIMENTAL.

Electromagnet.—For the production of magnetic fields of high intensity, the electromagnet shown in Fig. 1 was used. The core was formed of stalloy stampings but tapered solid pole pieces, as shown in the figure, were used for unidirectional fields used in the present experiments. The air-gap between the poles was adjustable and depended upon the position in which the pole-pieces were clamped. The normal current carrying capacity of the coils was 12 amperes but for short periods the current could be pushed up to 20 amperes with artificial ventilation by means of an electric fan. A curve connecting field strength with gap length is shown in Fig. 2, which shows that with 20 amperes excitation and 5 mm. air-gap, a gap flux density of 18 000 gauss could be obtained. This was the maximum value of the flux density used in the experiments.

Test Electrodes.—The electrodes used in the experiments are shown in Figs. 3 to 6. Fig. 3 shows the arrangement adopted for the measurement of the B. D. V. of air and oil with longitudinal magnetic fields. The electrodes consisted of two 1″ diameter copper discs about $\frac{1}{64}$″ thick, which were pasted to two 3″×2″×$\frac{1}{32}$″ glass plates by a mixture of rosin and beeswax. This rosin compound showed no tendency to dissolve in oil. An ebonite piece cut as shown in the diagram and having

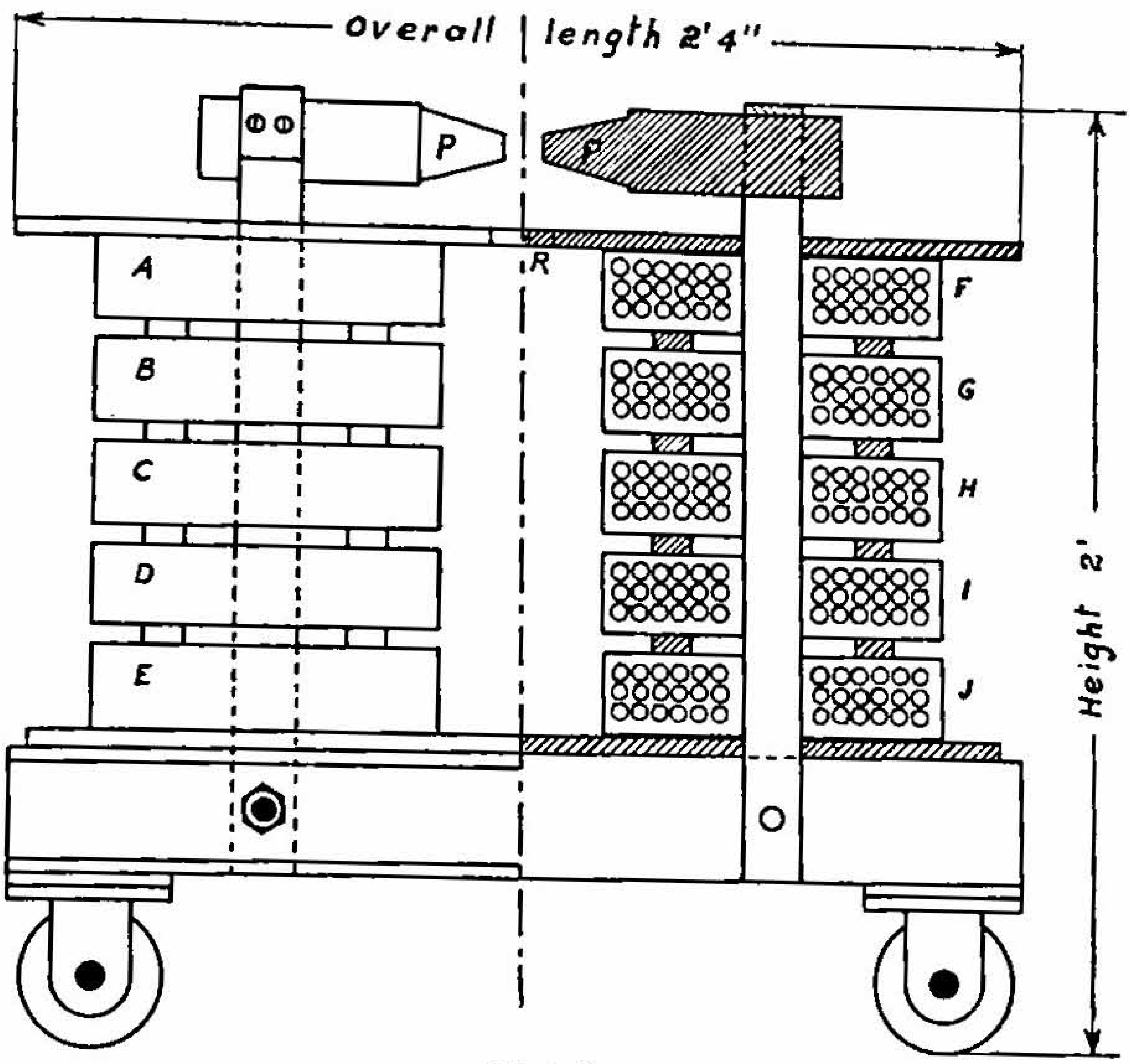

Fig. 1.

General Appearance of Electromagnet.

PP—Solid Poles.

A, B, C, D, E, F, G, H, I & J—Coils 600 turns each of No. 11 D.C.C. Copper wire.

R—Receptacle in insulating board for test cell.

the same external dimensions as the glass plates was used as spacer between them and was fixed to them with the same rosin compound so as to form a rectangular cell with glass sides and ebonite edges. The electrical connection from one of the electrodes was taken to the top by means of a thin copper wire soldered to it; from the other, the connection was taken to the bottom by means of a similar copper wire passing through the ebonite base of the cell. The wire at the top was connected to the high voltage terminal of the transformer and that at the bottom to earth. When the cell was introduced between the poles of the magnet the electric field was longitudinal or parallel to the magnetic field. The over-all thickness of the cell used for the B. D. V. of air was 9 mm. and a flux density of 12 500 gauss in the dielectric was obtainable with an exciting current of 20 amperes. The cell used for the B. D. V. of oil had an over-all thickness of 7 mm. and a field strength of 14 000 gauss was obtainable. For tests with oil the cell was carefully cleaned prior to each experiment so as to exclude dirt, fibres and other impurities, and a small ebonite cover was provided.

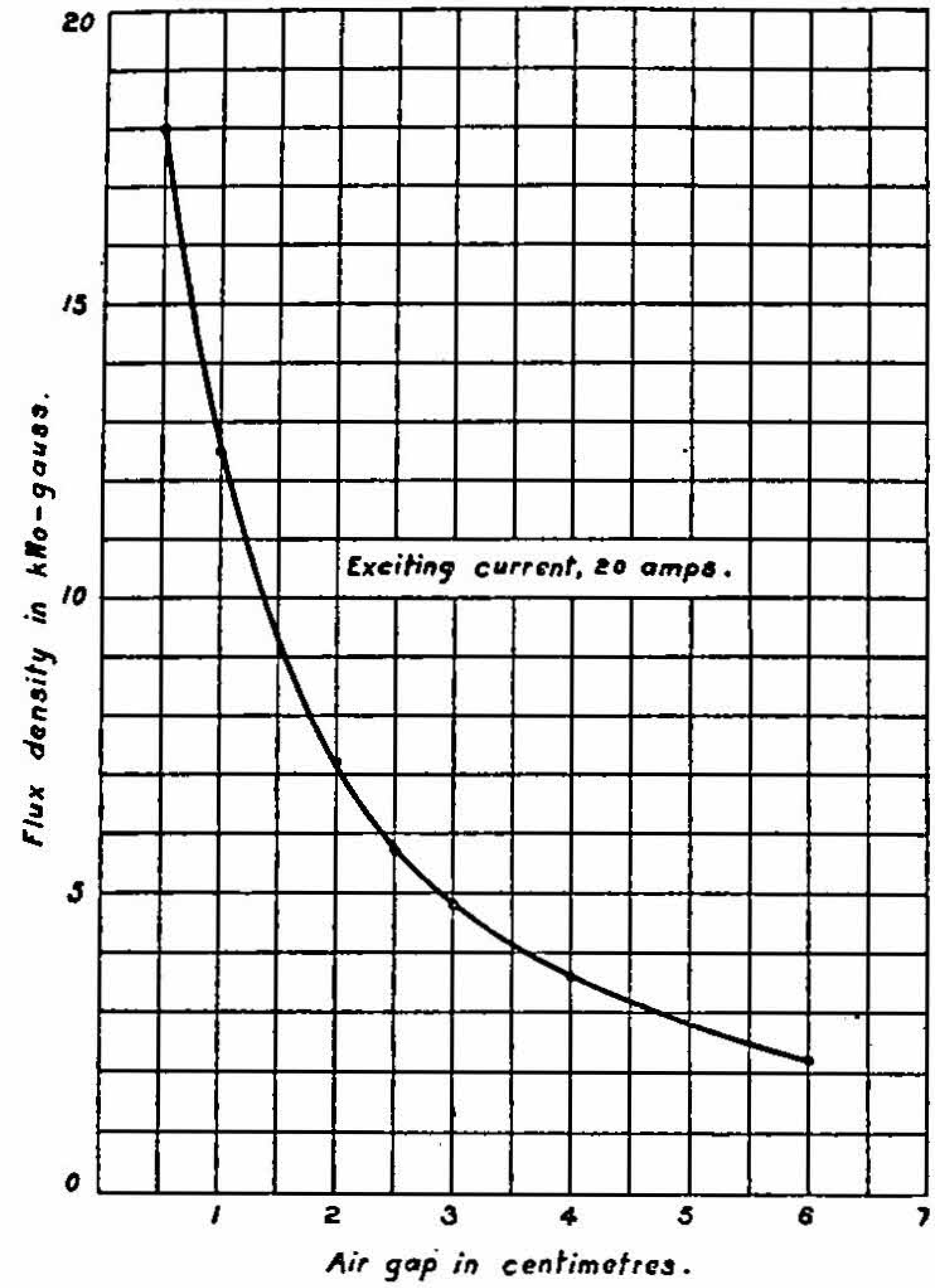

Fig. 2.

Air Gap Flux Density for Different Gaps in Electromagnet.

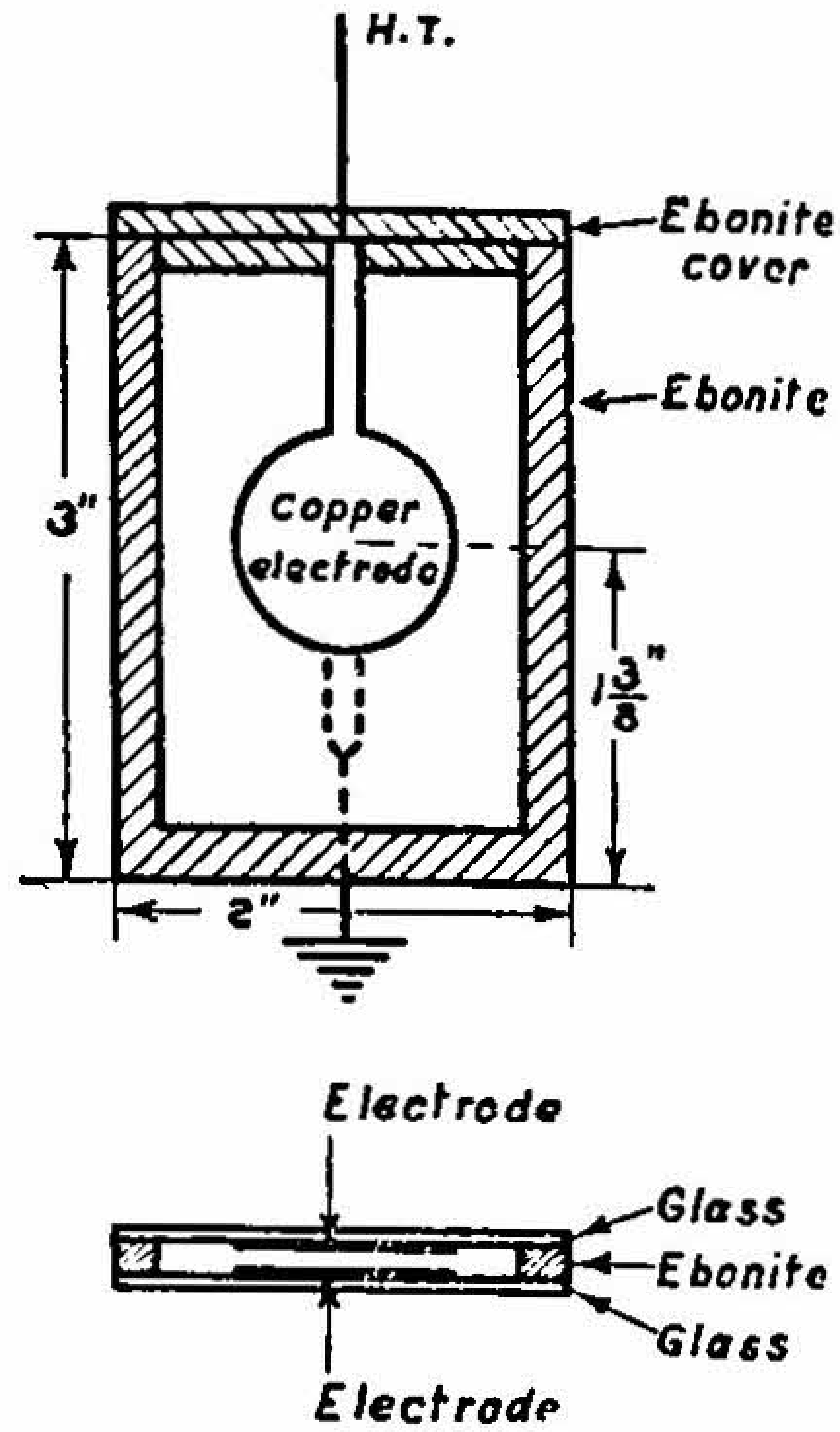

Fig. 3.

Electrodes for B. D. V. Measurements on Air and Oil with Longitudinal Magnetic Fields.

The measurement of the B. D. V. of air and oil with transverse magnetic fields was carried out with a similar cell with glass sides and ebonite edges as shown in Fig. 4. In this case, however, the electrodes were $\frac{1}{8}$″ diameter brass spheres turned at one end of two brass rods about 2″ long. The rods were threaded at the other end for screwing into threaded holes in the ebonite sides of the cell. Lock nuts were provided for preventing the movement of the rods after the gap had been adjusted. When the cell was introduced between the magnet poles the electric field was transverse or perpendicular to the magnetic field. The cell had an over-all thickness of 1 cm. and when inserted in an air gap of 1·1 cm. a field intensity of 11 500 gauss was obtained.

The electrodes used for the measurement of the B. D. V. of solids with longitudinal magnetic fields are shown in Fig. 5 and consisted of 1″ diameter brass discs cut out of $\frac{1}{64}$″ brass sheet and pasted on 4″ × $3\frac{1}{2}$″ mica plates 1 mm. thick. The test sample cut to 2″ square was held

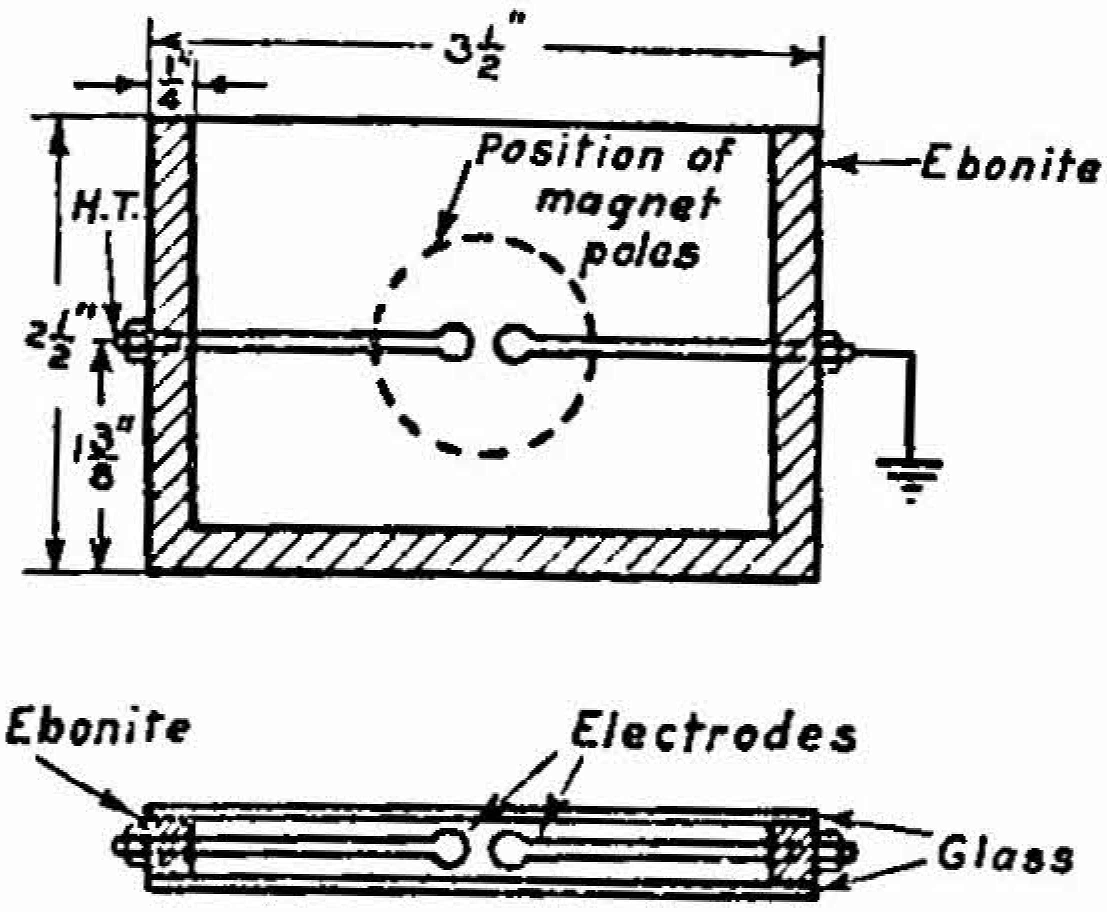

Fig. 4.

Electrodes for B. D. V. Measurements on Air and Oil with Transverse Magnetic Fields.

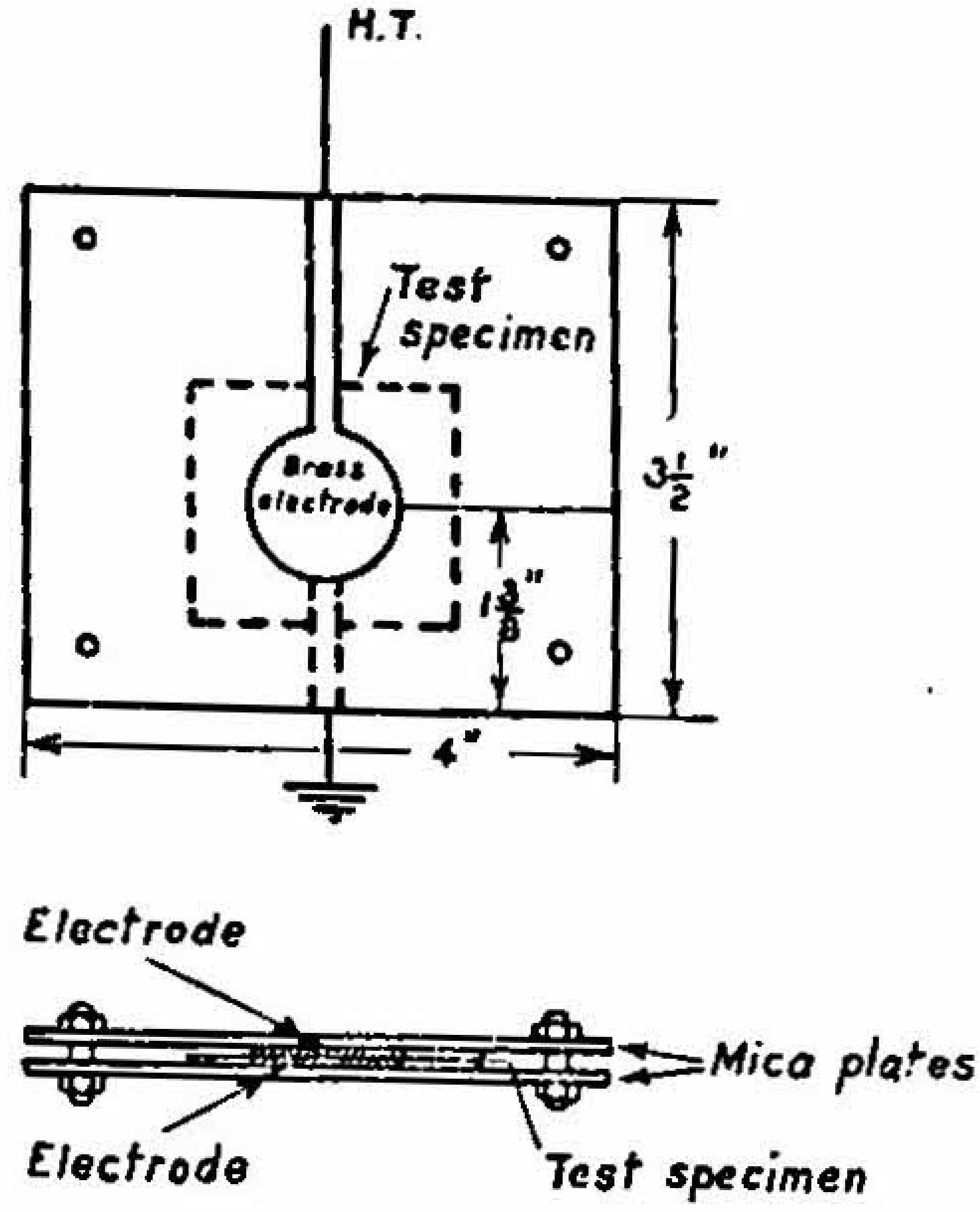

Fig. 5.

Electrodes for B. D. V. Measurements on Solids with Longitudinal Magnetic Fields.

between the electrodes by means of brass screws at the corners of the mica plates. The over-all thickness of the cell did not exceed 4 mm. so that it could be introduced in a 5 mm. air gap and a field intensity of 18 000 gauss obtained. This cell was found to be suitable for the measurement of the B. D. V. of all materials except glass. For glass of which the samples were 1·2" square, the diameter of the electrodes had to be reduced from 1" to ⅛" in order to provide sufficient flash-over distance between them over the surface of the test specimen.

Fig. 6 represents the arrangement used for the B. D. V. of the insulating papers with transverse magnetic fields. The electrodes had necessarily to be of small diameter in order that they could be introduced in a small air gap, and consequently $\frac{1}{16}$" diameter brass pins were used. These were passed through two ebonite pieces cut into the shape shown in the figure. The test samples cut into small rectangular pieces 2·5 cms. × 4 mm. were held in position between the electrodes by means of screws at the top and bottom of the ebonite pieces. In some cases, wider specimens were required as they had to be folded over on the sides of the ebonite in order to prevent flash-over from the high tension electrode to the magnet poles.

High Tension Supply.—All the B. D. V. measurements were conducted with 25-cycle alternating current. The general scheme of connections is shown in Fig. 7. The testing transformer was rated at

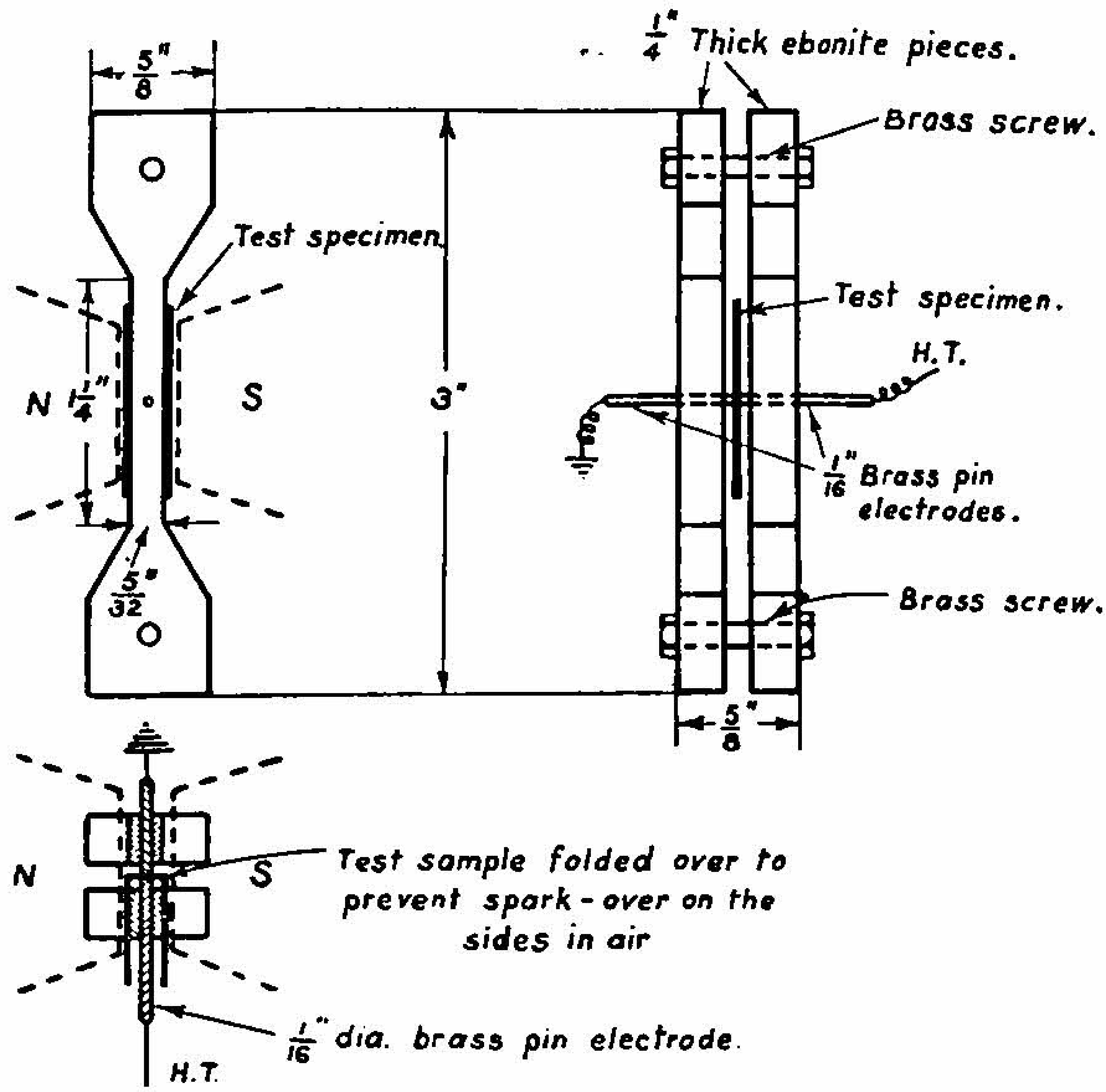

Fig. 6.

Electrodes for B. D. V. Measurements on Solids with Transverse Magnetic Fields.

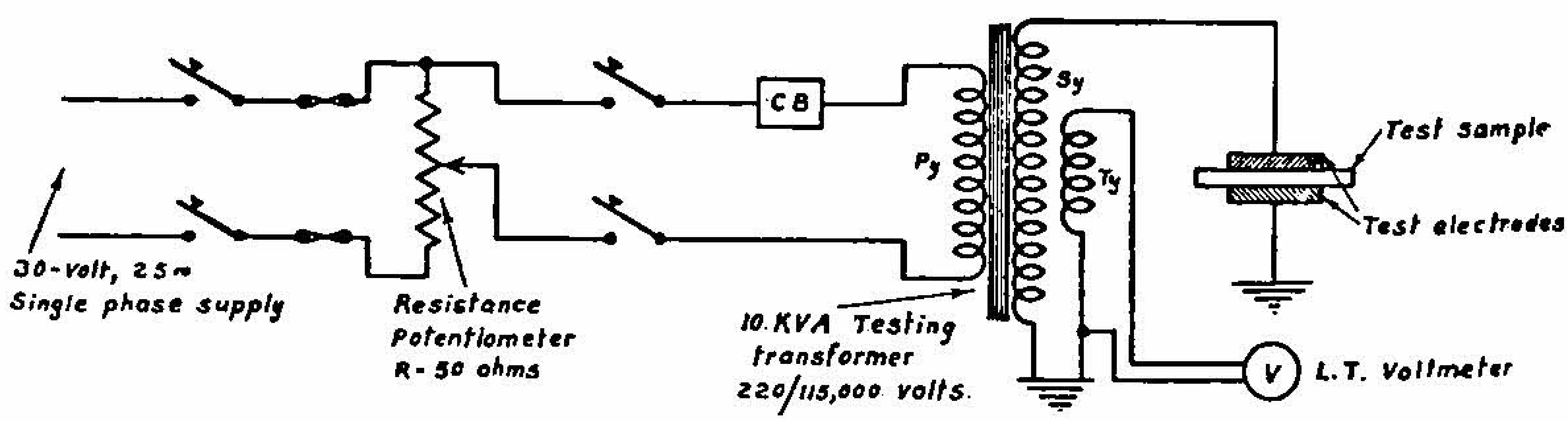

Fig. 7.

General Scheme of Connections.

10 kVA, 220/115 000 volts, and provided with a tertiary winding for voltage measurement.

Method of Testing.—In order to obtain satisfactory results it was necessary to prepare the samples very carefully before the tests. The oil was thoroughly dried by heating and passing through a filter press two or three times, after which it was stored in glass-stoppered bottles. The samples of insulating paper were dried in a closed oven. In the case of air, the temperature, pressure and humidity were not under control but it was assumed that they remained constant during each set of tests which lasted for about an hour. With the test cell in position, the B. D. V. of air was measured alternately with and without the magnetic field. The test voltage in each case was rapidly raised (about 1 kV per second) from zero to the disruptive value consistently with its value being read accurately on the voltmeter. The mean of a large number of readings was taken as the true B. D. V. of air. This method was also adopted in the case of all the other dielectrics.

In the case of oil, each shot produced a small amount of carbon and also removed a small amount of moisture. After each shot, the oil was stirred with a clean glass rod in order to distribute the carbon particles. As the tests with and without the magnetic field alternated, the very small changes in the oil produced at each shot may be regarded as affecting both sets of readings equally.

With solids, the specimen had to be renewed after each test and therefore a large number of test samples was required. A certain amount of error was therefore introduced due to the non-uniformity of the material but, as the average of a large number of readings was taken as the true B. D. V. and as the measured thickness of the various samples was found to be remarkably uniform, this error may be regarded as being negligible.

RESULTS.

Air.—The readings for the B. D. V. of air under two different sets of conditions are given in Tables I and II, the values representing the average of the number of readings in each set. The ratio of B. D. V. with magnetic field to that without the field is also given.

TABLE I.

Air.—
- Barometric Pressure .. .. 68·6 cms.
- Temperature .. .. 24·5°C.
- Relative Humidity .. .. 70·2 per cent

Magnetic Field Strength	Mutual direction of electric and magnetic fields	No. of B. D. V. readings taken in each set	B. D. V. with magnetic field	B. D. V. without magnetic field	Ratio*
Gauss			kV	kV	
10 500	Longitudinal	50	6·25	6·25	1·00
12 500	,,	,,	6·00	6·00	1·00

* Ratio refers to the ratio of the B. D. V. with magnetic field to that without the field.

TABLE II.

Air.—{ Barometric Pressure .. .. 68·65 cms.
Temperature .. .. 24·5°C.
Relative Humidity .. .. 66·7 per cent. }

Magnetic Field Strength	Mutual direction of electric and magnetic fields	No. of B. D. V. readings taken in each set	B. D. V. with magnetic field	B. D. V. without magnetic field	Ratio*
Gauss			kV	kV	
10 000	Transverse	50	7·90	7·90	1·00
11 500	,,	,,	6·95	6·90	1·01

* Ratio refers to the ratio of the B. D. V. with magnetic field to that without the field.

In all cases this ratio is unity, indicating that the magnetic field has no effect on the 25 cycle B. D. V. of air. This result is not in agreement with that of Monkhouse (*loc. cit.*) and Smurrow (*loc. cit.*) but seems to agree with that of R. Schmid (*loc. cit*). As the main object of the investigation was to study liquid and solid dielectrics further work on air at different pressures and temperatures was not continued.

The variation of successive breakdown readings is shown in Fig. 8. The maximum variation from the mean value is not more than 4 per cent.

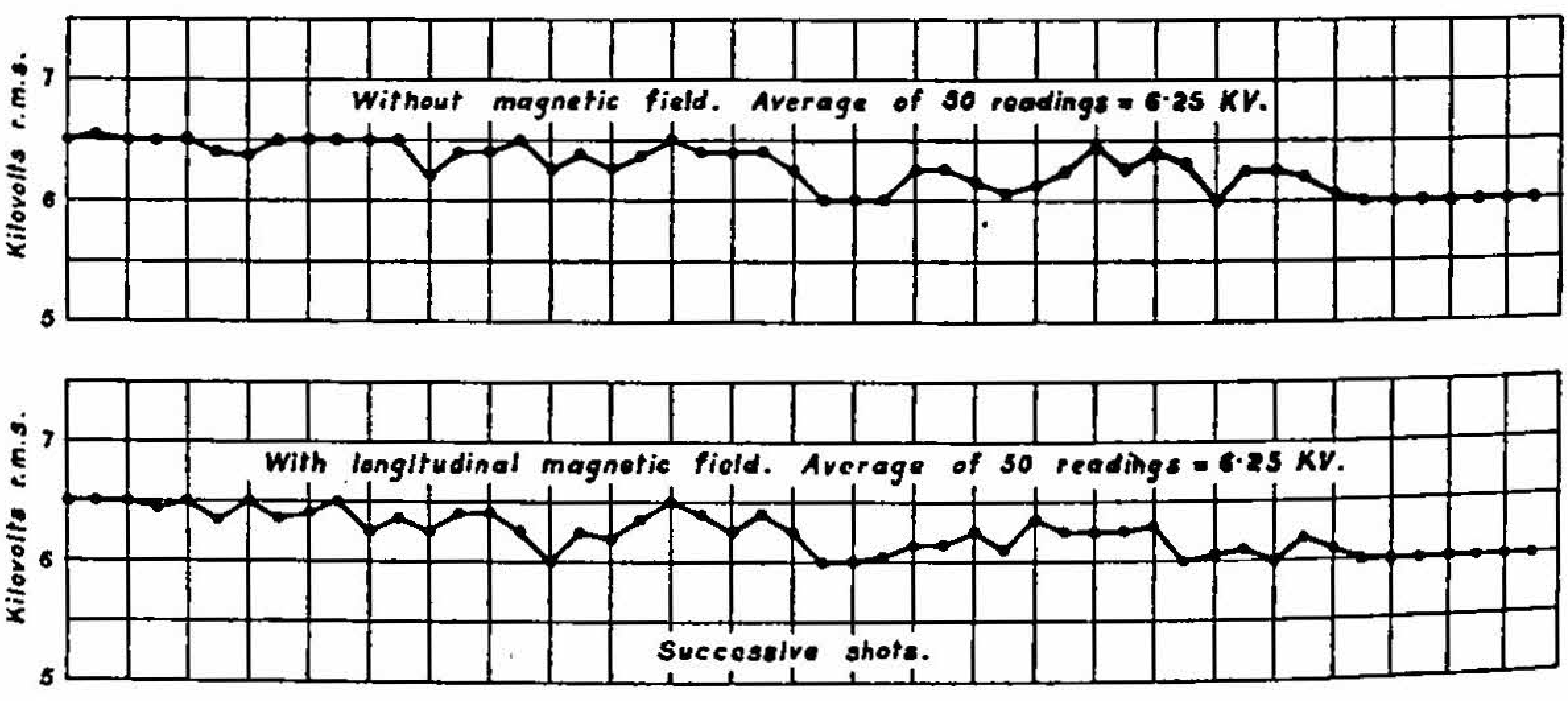

Fig. 8.

Variation of B. D. V. of Air with Successive Shots.

Oils.—The results for transformer and switch oils are given in Tables III and IV.

TABLE III.

Transformer Oil.

Magnetic Field Strength	Mutual direction of electric and magnetic fields	No. of B. D. V. readings taken in each set	B. D. V. with magnetic field	B. D. V. without magnetic field	Ratio*	Average Ratio
Gauss			kV	kV		
14 000	Longitudinal	60	15·70	15·80	0·99	
,,	,,	100	16·70	17·00	0·98	0·99
,,	,,	100	18·00	18·10	0·99	
11 500	Transverse	60	8·95	8·65	1·03	
,,	,,	100	6·00	5·95	1·01	1·02
,,	,,	100	8·30	8·10	1·02	

TABLE IV.

Switch Oil.

Magnetic Field Strength	Mutual direction of electric and magnetic fields	No. of B. D. V. readings taken in each set	B. D. V. with magnetic field	B. D. V. without magnetic field	Ratio*
Gauss			kV	kV	
14 000	Longitudinal	100	14·80	14·80	1·00
11 500	Transverse	100	7·80	8·00	0·98

* Ratio refers to the ratio of the B.D.V. with magnetic field to that without the field.

The ratio of the B. D. V. with and without the magnetic field is given for the several cases and differs but little from unity in all cases. It is therefore concluded that the magnetic field has an inappreciable, if any, effect on the B. D: V. of mineral oils. R. Schmid's (*loc. cit.*) conclusion that a unidirectional magnetic field has no effect on the dielectric current in certain liquid dielectrics appears to confirm this result. On the other hand, Monkhouse and Smurrow (*loc. cit.*) have reported appreciable changes in the B. D. V. of transformer oil with lower magnetic fields.

Individual readings shown in Fig. 9 indicate an initial rise in the B. D. V. of the sample due probably to the effect of successive shots.

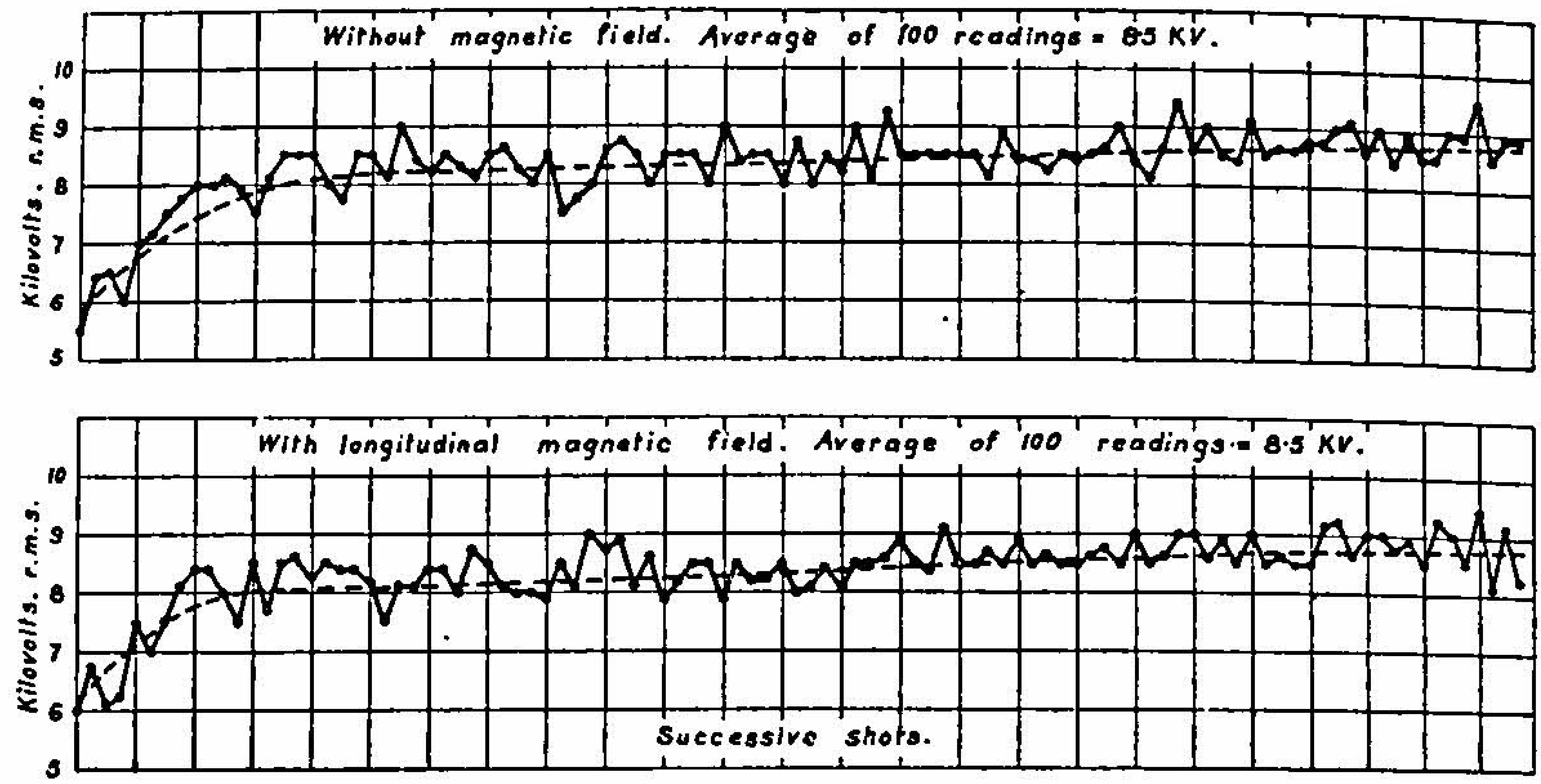

Fig. 9.

Variation of B. D. V. of Transformer Oil with Successive Shots.

As this affects both the sets of readings equally no error is introduced thereby. The dotted curve shows the mean value of the B. D. V. at each point and the maximum variation therefrom is small.

Solids :—Results relating to solids are given in Tables V to IX.

TABLE V.

Manilla Paper.—No. of layers, 2 ; thickness of each layer, 5 mils.

Magnetic Field Strength	Mutual direction of electric and magnetic fields	No. of B. D. V. readings taken in each set	B. D. V. with magnetic field	B. D. V. without magnetic field	Ratio*	Average Ratio
Gauss			kV	kV		
18 000	Longitudinal	30	1·75	1·75	1·00	0·98
,,	,,	30	1·53	1·58	0·97	
,,	,,	30	1·55	1·63	0·95	
,,	,,	30	1·70	1·70	1·00	
,,	Transverse	30	1·95	1·93	1·01	1·01
,,	,,	30	1·93	1·93	1·00	
,,	,,	30	1·83	1·80	1·01	
,,	,,	30	1·80	1·78	1·01	

* Ratio refers to the ratio of the B.D.V. with magnetic field to that without the field.

TABLE VI.

Presspahn.—No. of layers, 1; thickness of each layer, 10 mils.

Magnetic Field Strength	Mutual direction of electric and magnetic fields	No. of B. D. V. readings taken in each set	B. D. V. with magnetic field	B. D. V. without magnetic field	Ratio*	Average Ratio
Gauss			kV	kV		
18 000	Longitudinal	30	1·75	1·85	0·95	0·96
,,	,,	25	1·68	1·75	0·96	
,,	,,	15	1·98	2·00	0·99	
,,	,,	25	1·83	1·90	0·96	
,,	Transverse	20	2·20	2·00	1·10	1·06
,,	,,	20	2·40	2·25	1·07	
,,	,,	20	2·38	2·30	1·03	
,,	,,	20	2·30	2·20	1·05	
,,	,,	20	2·10	2·00	1·05	

*Ratio refers to the ratio of the B.D.V. with magnetic field to that without the field.

TABLE VII.

Pressboard.—No. of layers, 1; thickness of each layer, 5 mils.

Magnetic Field Strength	Mutual direction of electric and magnetic fields	No. of B. D. V. readings taken in each set	B. D. V. with magnetic field	B. D. V. without magnetic field	Ratio*	Average Ratio
Gauss			kV	kV		
18 000	Longitudinal	25	2·23	2·33	0·96	0·96
,,	,,	25	2·08	2·20	0·94	
,,	,,	25	2·10	2·13	0·99	
,,	,,	25	2·08	2·18	0·95	
,,	,,	25	2·13	2·20	0·97	
,,	,,	25	2·30	2·38	0·97	
,,	Transverse	25	3·50	3·40	1·03	1·04
,,	,,	25	3·55	3·45	1·03	
,,	,,	25	3·35	3·20	1·05	
,,	,,	25	3·25	3·15	1·03	
,,	,,	25	3·33	3·23	1·03	
,,	,,	25	3·40	3·28	1·04	

* Ratio refers to the ratio of the B.D.V. with magnetic field to that without the field.

TABLE VIII.

Kraft Paper.—No. of layers, 1; thickness of each layer, 10 mils.

Magnetic Field Strength	Mutual direction of electric and magnetic fields	No. of B. D. V. readings taken in each set	B. D. V. with magnetic field	B. D. V. without magnetic field	Ratio*	Average Ratio
Gauss			kV	kV		
18 000	Longitudinal	25	2·23	2·18	1·02	
,,	,,	25	2·18	2·13	1·02	
,,	,,	25	2·40	2·38	1·01	1·02
,,	,,	25	2·38	2·35	1·01	
,,	,,	25	2·45	2·40	1·02	
,,	,,	25	2·40	2·30	1·04	
,,	Transverse	25	3·13	3·00	1·04	
,,	,,	25	3·10	3·00	1·03	
,,	,,	25	3·05	2·90	1·05	1·04
,,	,,	25	3·00	2·90	1·04	
,,	,,	25	3·00	2·88	1·04	
,,	,,	25	3·00	2·88	1·04	

*Ratio refers to the ratio of the B. D. V. with magnetic field to that without the field.

TABLE IX.

Glass.—No. of layers, 1; thickness of each layer, 4 mils.

Magnetic Field Strength	Mutual direction of electric and magnetic fields	No. of B. D. V. readings taken in each set	B. D. V. with magnetic field	B. D. V. without magnetic field	Ratio*	Average Ratio
Gauss			kV	kV		
18 000	Longitudinal	25	7·25	7·00	1·04	
,,	,,	25	7·25	7·15	1·02	1·03
,,	,,	25	7·25	7·05	1·03	
,,	,,	25	7·40	7·20	1·03	

*Ratio refers to the ratio of the B.D.V. with magnetic field to that without the field.

There seems to be a small but definite effect of the magnetic field in all cases. Longitudinal fields seem to lower the B. D. V. of manilla paper, presspahn and pressboard but to increase that of kraft paper and glass. The effect of transverse fields seems to be to increase the B. D. V. in all cases, the maximum increase being about 6 per cent. in the case of presspahn. These results do not agree with those of Monkhouse (*loc. cit.*) who reports a considerably greater effect with smaller magnetic fields. It would appear from these results that the influence of even very intense magnetic fields is not so great as to affect the insulation of machinery and apparatus and it therefore does not seem to be necessary to take this factor into consideration in the design of insulation for electrical machinery and apparatus.

Fig. 10 represents the variation of B. D. V. of a number of test samples of pressboard and indicates larger variations than in air and oil. Similar variations were also noticed in the case of the other materials.

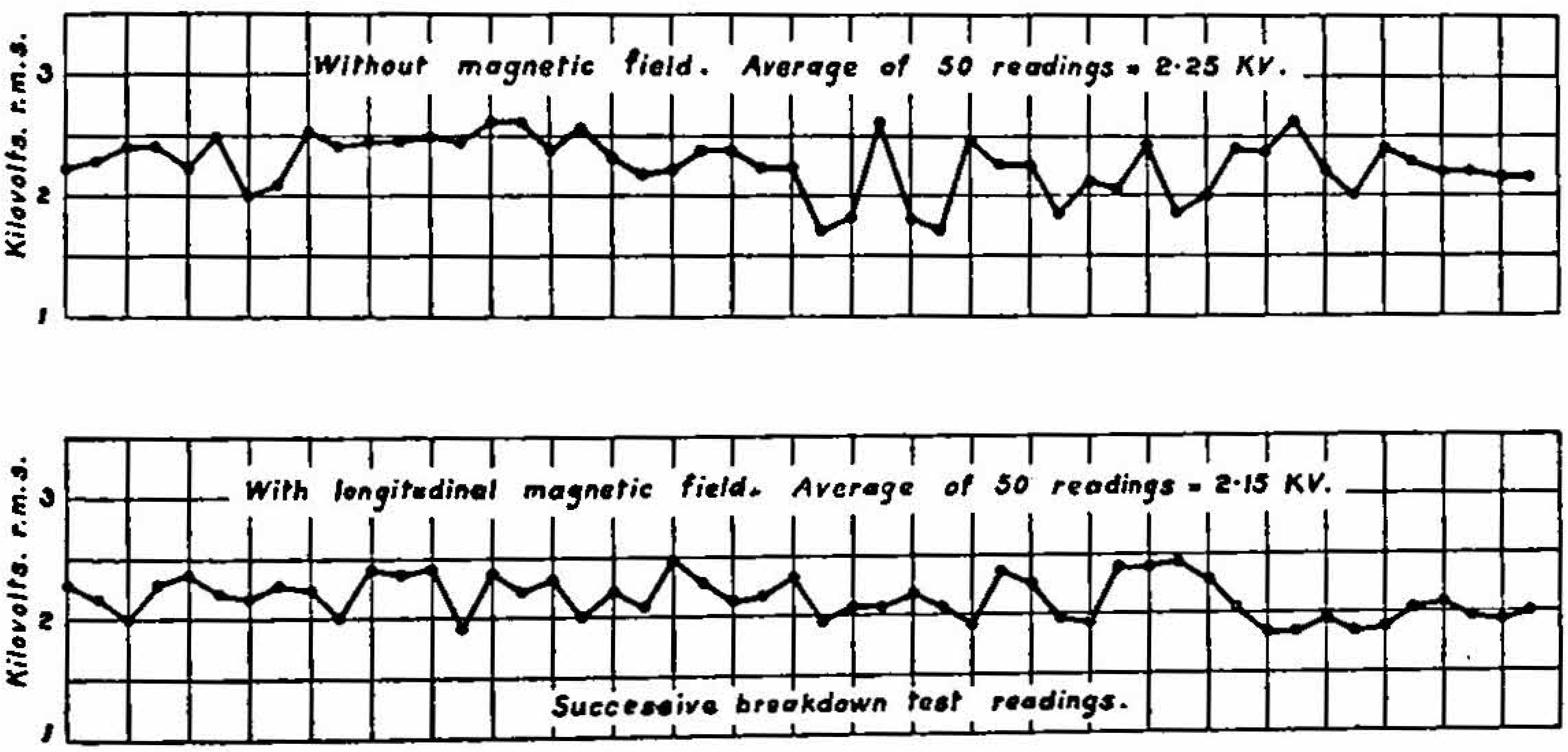

Fig. 10.

Variation of B. D. V. of Pressboard in Successive Tests.

SUMMARY.

The effect of superimposed unidirectional magnetic fields on the 25-cycle breakdown voltage of air, liquid and solid dielectrics has been studied and the following conclusions drawn :—

(1) Longitudinal magnetic fields up to 12 500 gauss and transverse fields up to 11 500 gauss do not affect the B. D. V. of air at the laboratory temperature and pressure.

(2) The effect of longitudinal magnetic fields up to 14 000 gauss and transverse fields up to 11 500 gauss on the B. D. V. of mineral oils is negligible.

(3) Magnetic fields up to 18 000 gauss, whether transverse or longitudinal, have an inappreciable effect on the B. D. V. of manilla paper.

(4) A longitudinal magnetic field of 18 000 gauss decreases the B. D. V. of presspahn by about 4 per cent.; a transverse field of the same strength increases it by about 6 per cent.

(5) A longitudinal magnetic field of 18 000 gauss decreases the B. D. V. of pressboard by about 4 per cent.; a transverse field of the same strength increases it by about the same amount.

(6) A longitudinal magnetic field of 18 000 gauss increases the B. D. V. of kraft paper by about 2 per cent. and a transverse field of the same strength increases it by about 4 per cent.

(7) The increase in the B. D. V. of glass by a longitudinal magnetic field of 18 000 gauss is about 3 per cent.

(8) All these changes are much smaller than those reported by Monkhouse and Smurrow working with weaker magnetic fields.

In conclusion, we wish to express our thanks to Mr. B. Nanjundiah, B.Sc., for considerable assistance in the construction of the electromagnet and in the preliminary experiments.

Department of Electrical Technology,
Indian Institute of Science,
Bangalore.

[Accepted, 3–5–1934.]

APPENDIX.

Specifications of Materials.

Transformer Oil: Transil No. 10–C.

Specific gravity	..	.. 0·900
Flash point ..	..	not lower than 270°F.
Fire point ..	..	„ 300°F.
Redwood Viscosity at 75°F.	..	.. 62–65″
Alkalies, sulphur, etc.	..	.. None.

Switch Oil: Transil No. 6.

Specific gravity	..	.. 0·885
Flash point ..	..	not lower than 360°F.
Fire point ..	..	„ 400°F.
Redwood Viscosity at 75°F.	..	.. 100–105″
Alkalies, sulphur, etc.	..	.. None.

Manilla paper.—This material is a tough, pliable paper made from manilla rope stock and is used for wrapping on wires and cables and in the manufacture of pad and layer insulation for transformers and also in the manufacture of treated paper tape.

Colour: dull brown; Thickness, 5 mils.

Presspahn.—This is a tough, smooth, flexible fibre material with a high mechanical strength, and is very moisture resistant. The surface is calendered. It is used in the manufacture of slot tubes and as inter-coil insulation in transformers.

Colour: yellowish brown; Thickness, 10 mils.

Pressboard.—This is a paper composed of 50 per cent. cotton fibre and 50 per cent. jute and the material is given a varnish treatment to improve its moisture-resisting properties. It is used extensively in the insulation of oil-immersed transformers.

Colour: grey; Thickness, 5 mils.

Kraft paper.—It is made from wood fibre and is practically a pure cellulose and is characterised by freedom from mechanical wood, sulphite pulp, bleaching or sizing material and other soluble salts. It has a highly calendered surface. It is used in small thicknesses for cable insulation and large thicknesses for layer insulation of coils.

Colour: brown; Thickness, 10 mils.

Glass.—Microscope cover slides of glass 1·2″ × 1·2″ × 4 mils. were used.