STUDIES IN DIELECTRICS.

PART III. THE EFFECT OF SUCCESSIVE DISCHARGES ON THE DIELECTRIC STRENGTH OF LIQUIDS.

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The dielectric strength of the liquids commonly used as insulating media has been extensively studied all over the world; nevertheless, a test for dielectric strength as carried out normally at present is not a true index of the breakdown strength of the liquid. This is due to the large differences in the values of the breakdown voltage that are obtained in tests carried out under presumably identical conditions. In many cases, particularly in impure oils, the values for two successive tests may differ from each other by as much as 50 per cent. While the differences are smaller in pure oils, they are large enough to render the results of individual tests valueless. It is, however, possible to get a representative value for the B. D. V. of a specimen of oil from the breakdown tests by taking either the arithmetic mean or the most probable value of a number of readings.

Hayden and Eddy (*Journal A. I. E. E.*, 1922, **41**, 491) have passed as many as 500 discharges through samples of transformer oil and benzene in order to ascertain if more uniform values can be obtained after a number of discharges, but found that the differences were of the same order throughout the test. The values differ from the mean by as much as 25 per cent. in transformer oil, 14 per cent. in commercial benzene, 12 per cent. in pure benzene and 4 per cent. in air. They ascribe the large differences in transformer oil to the complexity of its chemical structure. Rebhan (*E.T.Z.*, 1932, **53**, 556) has studied the application of the statistical method to the determination of the B. D. V. of transformer oil by applying the Gauss's correction curve. In the case of pure oil the difference between the arithmetic mean and the most probable value estimated by this method for 30 successive readings was found to be 4 per cent. His results show that the difference between the arithmetic mean and the most probable value diminishes as the number of readings increases. Hence the arithmetic mean of a large number of values can be taken to represent the breakdown strength of a sample without any great error.

However, the passage of a large number of discharges through a liquid alters its composition and thus introduces a fresh complication. Due to the high temperature attained in the path of the discharge, a small quantity of the liquid evaporates while another small quantity is decomposed. Thus impurities are introduced into the liquid in the shape of the oil vapour and the products of decomposition, namely, carbon and gases. Further, with repeated discharges metallic impurities are also introduced into the oil from the electrodes. The experiments of Gemant (*Zeits. f. Physik*, 1925, **33**, 789), Koppelmann (*E.T.Z.*, 1930, **51**, 1457) and others have shown that in moist liquids, on the application of an electric stress, moisture is drawn into the test gap in the form of fine globules. At each discharge a portion of the moisture evaporates and the oil becomes drier.

The experiments of Hayden and Eddy (*loc. cit.*) and Koppelmann (*loc. cit.*) have not revealed the effect of the progressively changing composition of the oil with successive discharges. The present experiments carried out with 3 000 successive discharges in each set of tests clearly show a definite drift in the mean value of the B. D. V. due to the combined effects of increasing impurities and the progressive drying of the oil.

The present investigation was originally undertaken with a view to standardising the preparation of oil for various studies of its dielectric behaviour. As a preliminary, it was decided to investigate the conditions causing the divergences in the values of the breakdown voltage. It was in the course of this investigation that the drift was first observed and carefully studied.

EXPERIMENTAL.

High Voltage Supply.—The scheme of connections for the test circuit is shown in fig. 1. A 50 volt, 25 cycle supply was connected

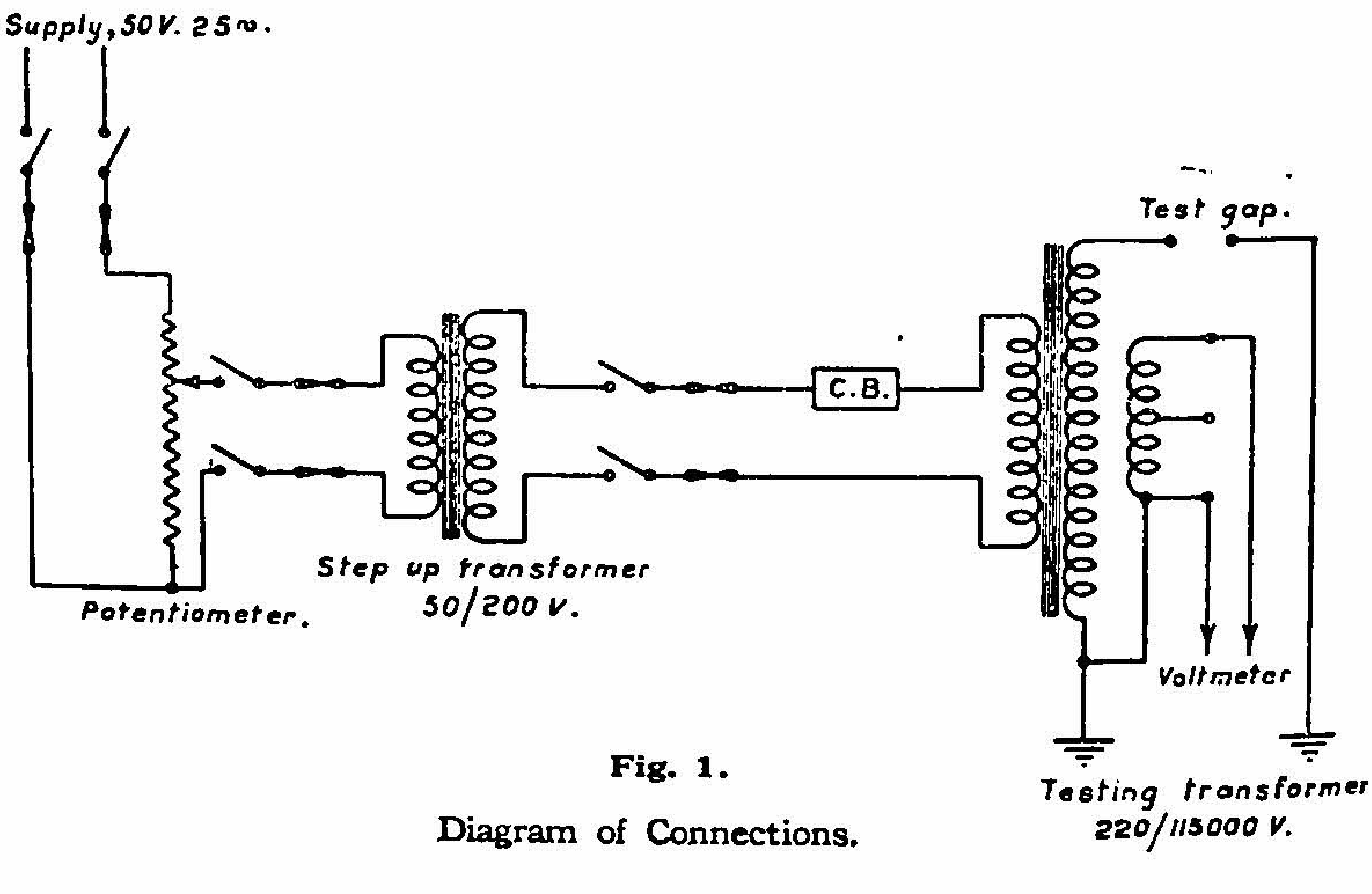

Fig. 1.

Diagram of Connections.

across a potentiometer, the variable voltage output from which was supplied to a step-up transformer. The secondary of this transformer supplied the high voltage testing transformer having a ratio of 220/115 000 volts. The secondary voltage of the testing transformer was measured by means of a low tension voltmeter connected to a tertiary winding provided in the transformer.

In order to obtain comparable results the test voltage was increased at a constant rate of about 12 kV per second throughout the tests. This high rate of increase was adopted in order to minimise the time for each set of 3 000 discharges which required about four hours.

Test cells.—Two rectangular glass vessels were used in the experiments. The larger one had a capacity of 1 000 c.c. of the test liquid while the capacity of the smaller one was 450 c.c. The two cells of different capacities were required for the purpose of investigating the effect of the volume of the liquid on the drift of the mean B. D. V.

The electrodes consisted of ½″ diameter brass spheres complying with British Standard Specification No. 148 of 1927 and were supported as shown in fig. 2. The gap was adjustable and was maintained at 0·15″ throughout the tests.

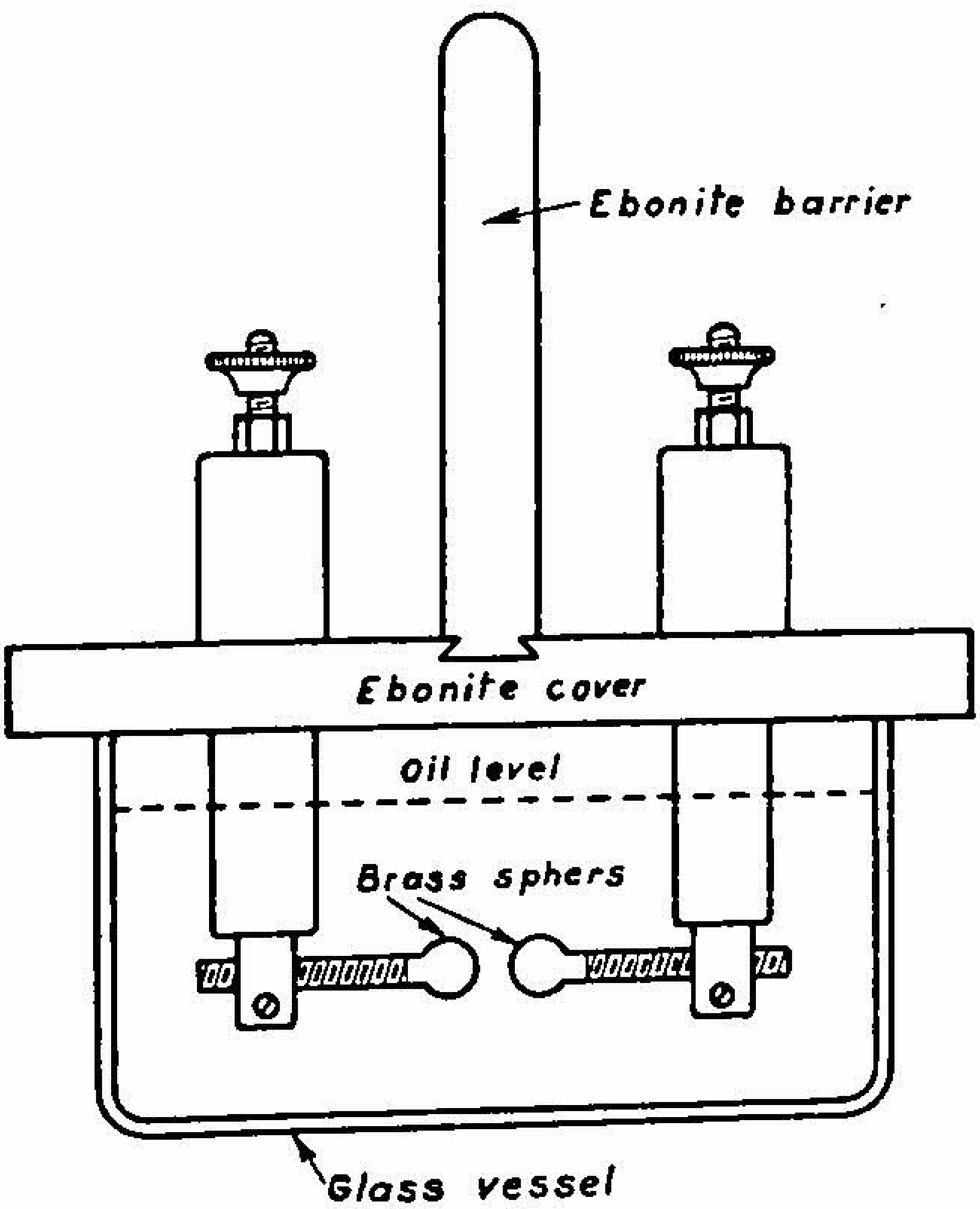

Fig. 2.

Test Cell and Electrodes.

Liquids tested.—The *transformer oil* used in the investigation was Transil No. 10 c supplied by the International General Electric Company of America. It was pale yellow in colour and had the following constants:

Specific Gravity	..	0·885
Flash Point	..	295°F.
Redwood Viscosity	..	62″ at 25°C.

The oil from stock was purified by passing it twice through well-dried filter paper in a filter press after which it was stored in clean dry glass bottles.

Moist oil required for the experiments was prepared by blowing moist air through the purified oil. For this purpose air was forced through a bottle of water by means of a blower. It was next allowed to pass through an empty bottle which served as a water trap and then bubbled through the test sample. The arrangement is shown in fig. 3.

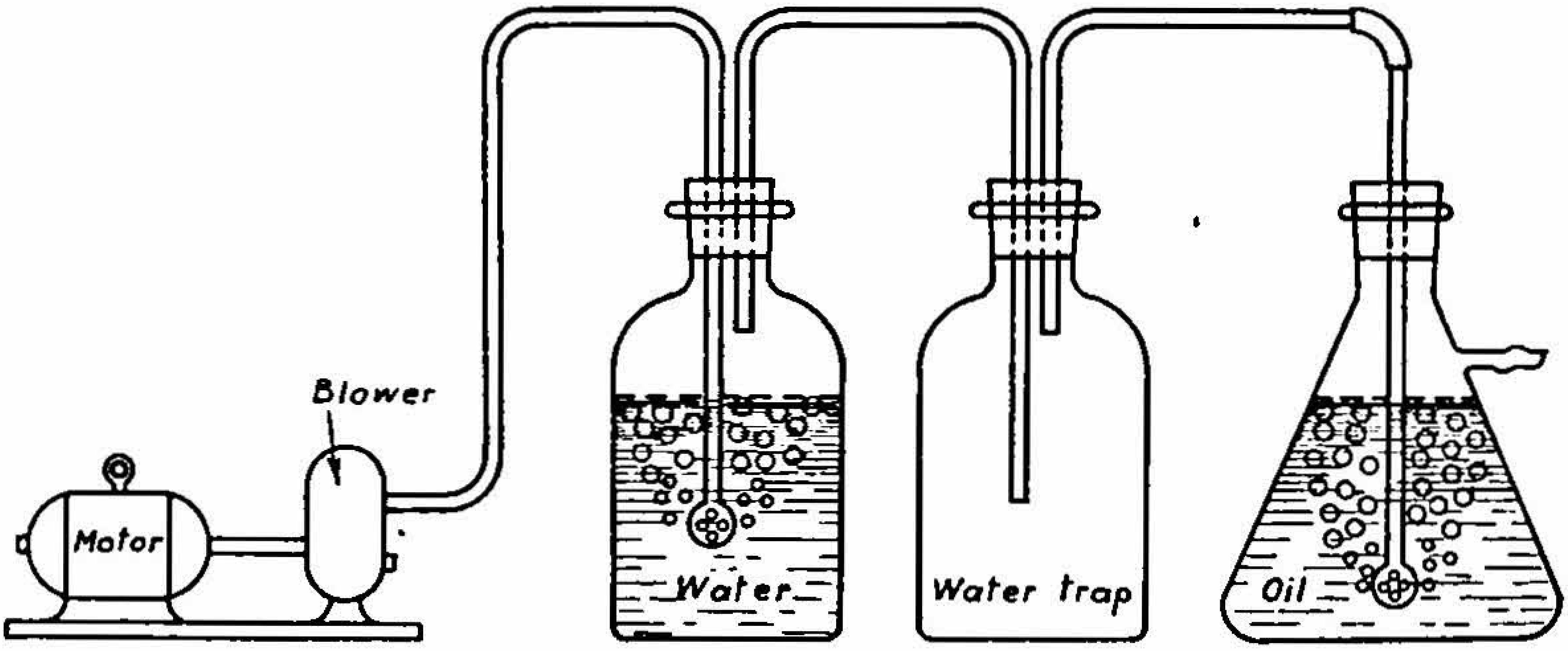

Fig. 3.

Arrangement for Preparing Samples of Moist Oil.

The moisture content of the specimen depended upon the length of time the moist air was blown through it.

Benzene was also experimented with. In this case it was found sufficient to pass the samples through a number of dry filter papers for drying. Moist benzene was prepared by shaking up pure benzene with small known quantities of distilled water. The moisture content was therefore known accurately in this case.

Method of testing.—Extreme precautions were taken to prevent fibres and other impurities from getting into the test sample. For this purpose the test cell was first scrupulously cleaned and rinsed two or three times with pure oil, after which it was filled with oil. The electrodes which were carefully cleaned previously were then immersed into it and the voltage applied. The voltage, equal to the maximum that the oil could withstand without breaking down, was maintained for half an hour. It was then switched off and, after rinsing the electrodes, the oil was rejected. This process was repeated two or three times until all the fibres from the electrodes and the test cell were removed.

The test sample was then introduced into the vessel and the test voltage applied and increased at the prescribed rate until the liquid broke down. The voltage at which breakdown occurred was noted each time. From the readings thus obtained, the averages of every hundred shots, starting from the first, were calculated.

RESULTS.

Tests with oil.—Fig. 4 represents the results of tests carried out in the larger vessel with 1 000 c.c. of oil. Curve 1 shows the effect of

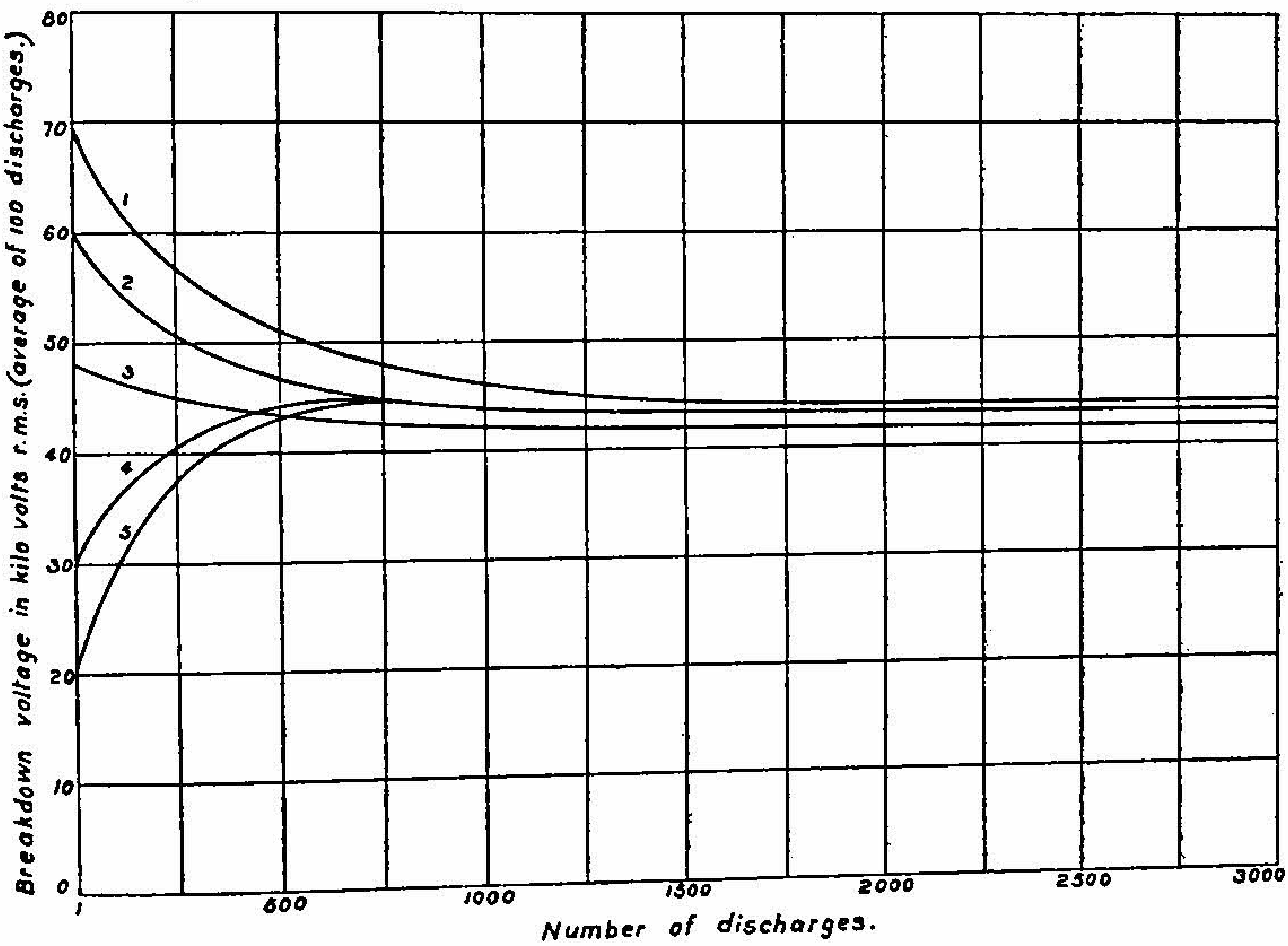

Fig. 4.

Successive Discharges in 1 000 c.c. of Transformer Oil.

successive discharges in the case of pure dry oil. Curves 2 to 5 show the results obtained with the same oil having progressively increasing moisture content. The values of B. D. V. plotted in these graphs are the averages of 100 readings.

With increasing moisture content, the initial B. D. V. drops from 70 kV in the case of pure oil to 20 kV in the case of saturated oil. In the case of dry oil with an initial B. D. V. of 70 kV (curve 1) the effect of successive discharges is to lower the value of the B. D. V. which decreases very rapidly at first, but less and less rapidly as the number of discharges increase, until it reaches a steady value of about 44 kV after about 1 500 discharges. With slightly moist oil having an initial B. D. V. of 60 kV (curve 2) the rate of decrease is less rapid and the final steady value of 43 kV is reached after about 1 000 discharges. With moist oil having an initial B. D. V. of 48 kV, the fall is very small but the steady value of 42 kV is again reached after about 1 000 discharges. With very moist oils (curves 4 and 5) there is an initial rise, instead of a fall, of B. D. V. The rise is more rapid in the case of the moister sample (curve 5), but in both cases the final steady value of 43 kV is attained after about 1 000 discharges. Thus, allowing for errors of observation, we obtain the remarkable result that in all cases the B. D. V. settles down to a final steady value of about 43 kV after about 1 000 discharges. It may be concluded from these graphs that in a sample with an initial B. D. V. of about 43 kV, there would be little change in B. D. V. at all points.

The above results can be explained as follows: As mentioned before, the effect of each discharge is (1) to produce a small quantity of carbon and other products of decomposition and (2) to remove a small quantity of moisture from the oil. These two factors affect the B. D. V. in opposite directions. The addition of carbon tends to lower the B. D. V. while the removal of moisture tends to increase it. It was found by a separate experiment that the total amount of carbon produced by each of the three thousand successive discharges was the same. It may therefore be assumed that the same quantity of carbon is produced by each discharge in the case of each sample. On the other hand the amount of moisture removed at each discharge may be regarded as varying with the samples, depending upon their moisture content. Thus it can be assumed that in moist oil a larger quantity of moisture would be removed at each discharge than in a drier sample.

In the case of dry oil (curve 1) the entire change of B. D. V. may be regarded as being due to the accumulation of carbon and the B. D. V. therefore drops. The curve is similar to that in fig. 5, obtained for pure oil by adding increasing doses of carbon previously prepared by passing discharges through a quantity of oil. It can be seen from fig. 5 that the effect of the addition of carbon is to lower the B. D. V. The fall is very rapid at first but becomes less and less rapid as the carbon content increases until finally a steady value is reached and further addition of carbon produces no effect on the B. D. V. In the case of the samples containing small quantities of moisture (curves 2 and 3), there is the further effect of the removal of moisture at each discharge, which tends to raise the B. D. V. However, the effect of accumulation of carbon predominates and the net result is that the B. D. V. falls, the decrease being more rapid in the case of the drier sample but not as rapid as in the case of the dry sample (curve 1). In very moist oils (curves 4 and 5) the effect of the removal of moisture is

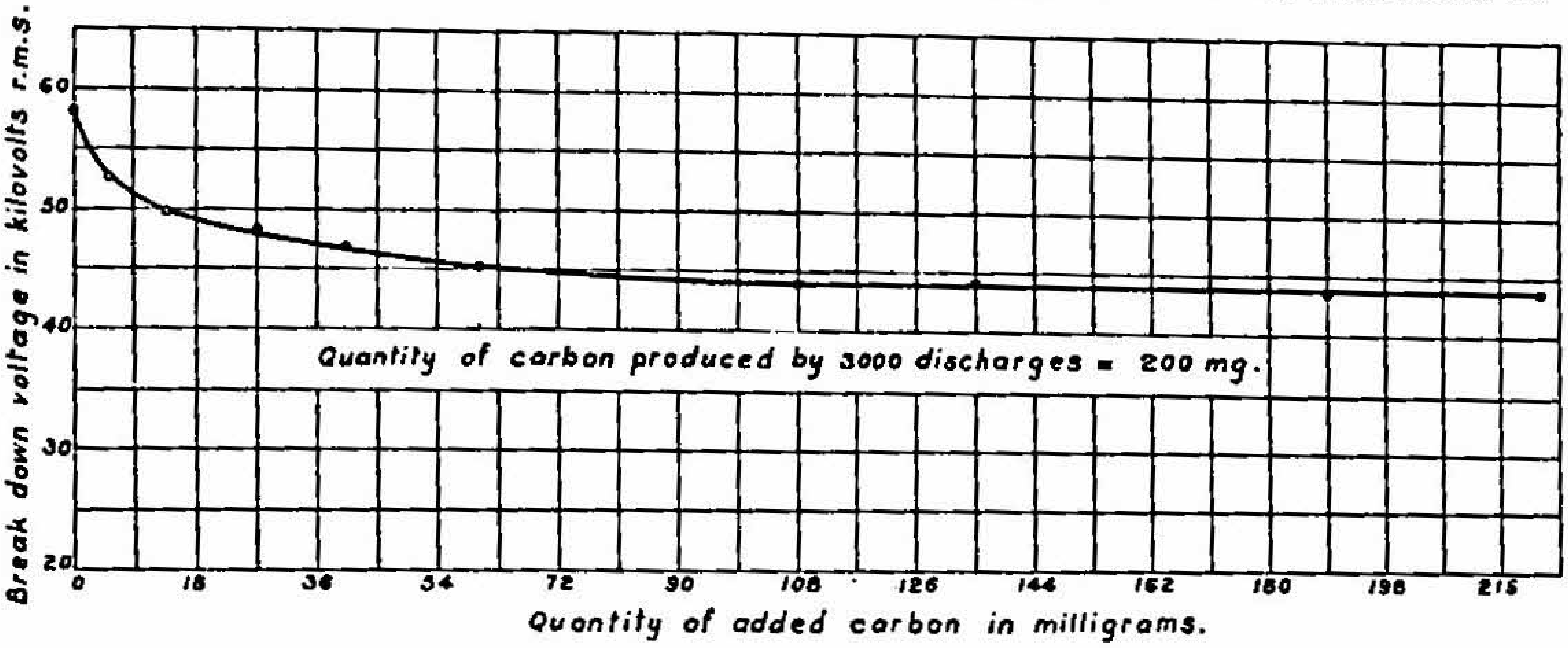

Fig. 5.

Effect of added Carbon on the B.D.V. of Transformer Oil. (Quantity of Oil, 450 c.c.)

predominant and the B. D. V. rises, the increase being more rapid in the case of the moister sample. In all cases so long as the carbon content is small, the B. D. V. is determined jointly by the moisture and carbon content but, after about 1 000 discharges, when a large amount of carbon has accumulated and the moisture content has become very small even in the wettest sample, the B. D. V. is determined solely by the carbon content and all curves become coincident.

Effect of size of test cell.—Fig. 6 shows the results of similar tests carried out in the smaller vessel with 450 c.c. of oil. The curves are similar to those in fig. 4 but, for corresponding samples, the rate of change of B. D. V. is greater and the final steady value is reached in all cases after about 500 discharges instead of 1 000 discharges. This can be explained as follows:

Quantitative tests have shown that 0·2 g. of carbon was produced in both large and small vessels as a result of 3 000 discharges in each case. The quantity of carbon produced at each discharge may therefore be regarded as being the same in each case. Similarly, it may be assumed that under similar conditions of moisture content the amount of moisture removed at each discharge is the same in the case of tests carried out in both the vessels. Consequently, starting with similar samples of oil, the increase of concentration of carbon and the decrease of concentration of moisture in the smaller vessel would be more rapid than in the larger vessel and the B. D. V. would change more rapidly.

This is borne out by the result that the final steady values in the two sets of tests are reached after 500 and 1 000 discharges, respectively,

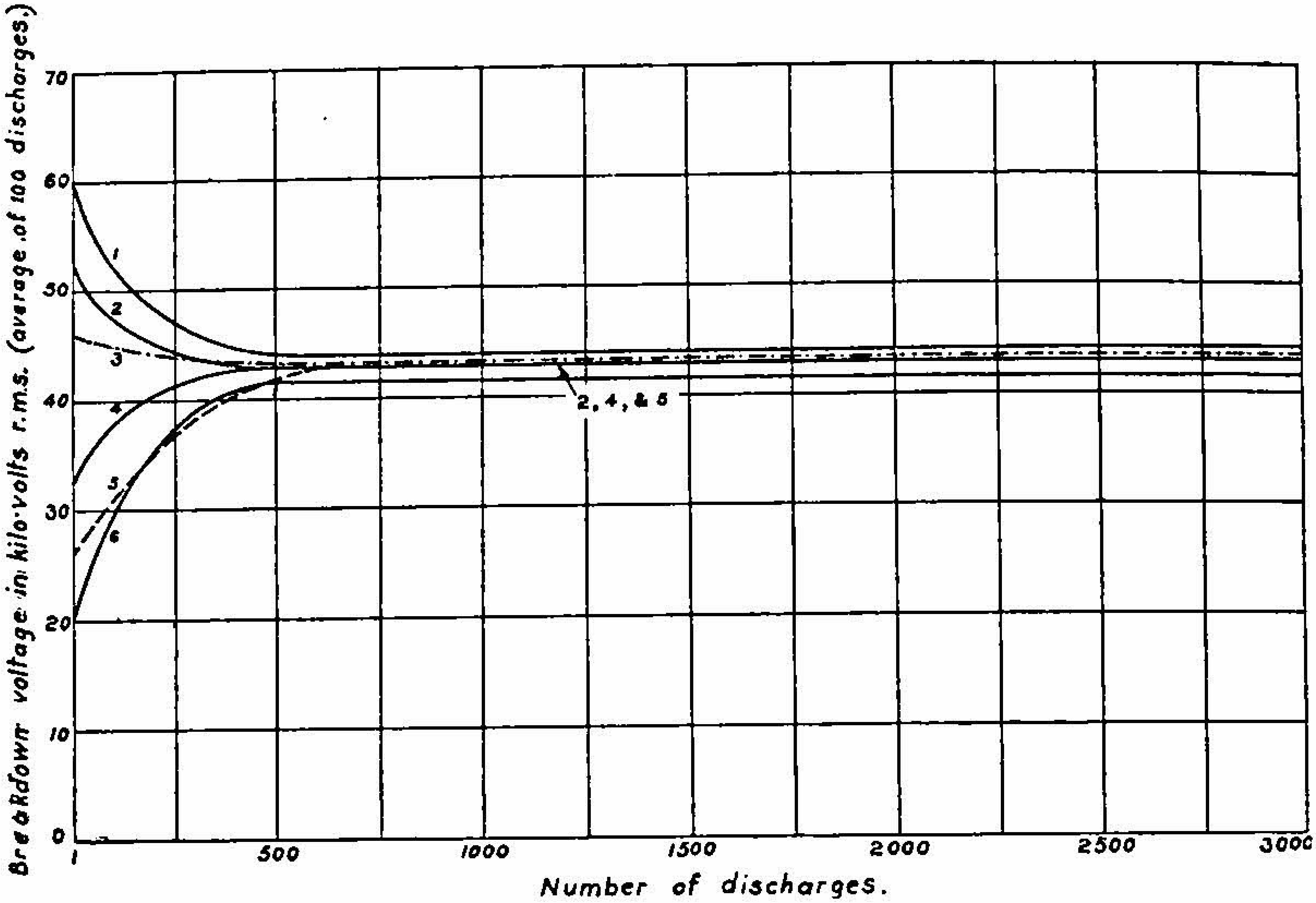

Fig. 6.

Successive Discharges in 450 c.c. of Transformer Oil.

since the ratio of these figures is approximately the same as the ratio of the capacities of the two vessels.

Tests with benzene.—Similar tests were also carried out in the smaller test vessel with 450 c.c. of (*a*) dry benzene and (*b*) benzene containing respectively, 0·067, 0·134, 0·20, and 0·267 c.c. of water. The results given in fig. 7 show the same characteristics as those obtained with oil. The curves clearly indicate the two-fold effect, namely, the lowering of B. D. V. due to the accumulation of carbon and the increase due to the expulsion of moisture. In the case of the dry sample there is an initial fall and in all the moist samples there is an initial rise. The final steady value is reached in all cases after 1 000 discharges. There is, however, a noteworthy difference. In the case of moist samples of benzene, each curve shows a maximum value of B. D. V. These maxima can be explained as follows. Initially, the effect of expulsion of moisture is more important than that of the accumulation of carbon with the result that the B. D. V. increases. With increasing number of discharges the improvement of B. D. V. due to expulsion of moisture becomes less and less rapid until (in the case of curve 5) this effect becomes exactly neutralized by the effect of accumulation of carbon after about 400 shots beyond which the effect of the increasing carbon content becomes more predominant and the curve drops again. Considering the other curves the maximum value is reached after a progressively smaller number of shots with benzene of increasing dryness. This is because with drier benzene the effect of removal of moisture becomes less and less important as compared with

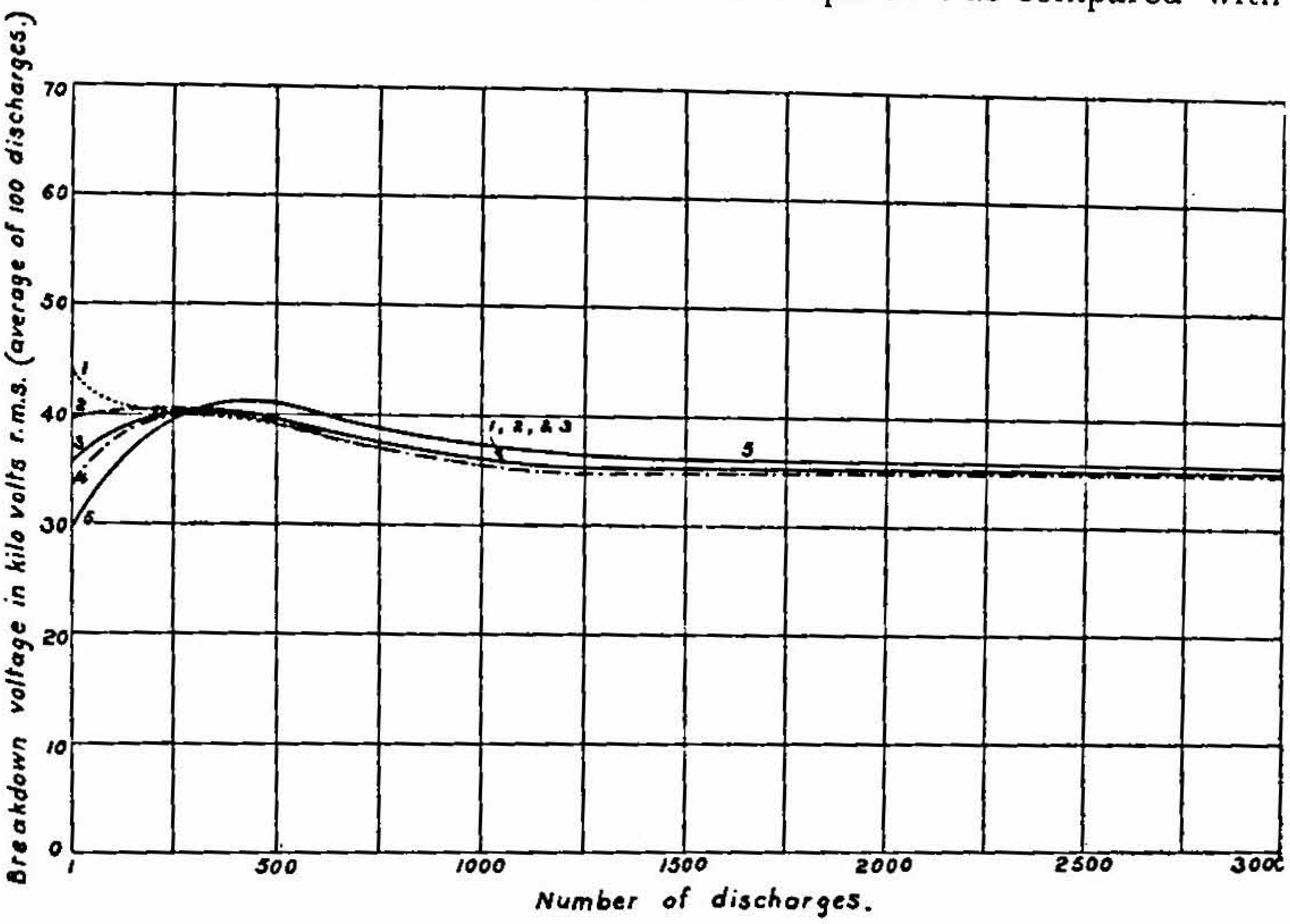

Fig. 7.

Successive Discharges in 450 c.c. of Benzene.

that of accumulation of carbon. It will also be noticed that the portion of the curves before the maximum value is reached is steepest for curve 5 and progressively less so for curves 4, 3 and 2, respectively. It may be presumed that similar maxima would be exhibited by the curves for oil if at each discharge the removal of moisture were more rapid or the production of carbon smaller.

Application to Oil Circuit-Breakers.—The above results have an important bearing on the insulating value of oil used in circuit-breakers. The minimum B. D. V. of oil used in transformers and circuit-breakers as specified in British Standard Specification No. 148 of 1927 under standard gap conditions is 22 kV. This corresponds to the very moist oils used in the above tests and in the case of such oils the effect of successive discharges is to improve the B. D. V. instead of lowering it, as indicated by the results shown in figs. 4 and 6. It would thus appear that the carbon produced by the discharges has no deleterious effect on the insulating strength of moist oils, and from the point of view of the B. D. V. of oil it would not be necessary to filter out the carbon produced by the discharges due to the automatic opening of the circuit-breaker under fault conditions. In the case of dry oil, although the accumulation of carbon does lower their B. D. V. the minimum value attained on account of this cause is not less than 43 kV and as this value is well above the specified minimum no difficulty can arise from this source.

CONCLUSIONS.

The B. D. V. of comparatively dry specimens of transformer oil having B. D. V. exceeding 43 kV (BSS test gap), when subjected to successive discharges, decreases until it reaches about 43 kV after about 1 000 discharges after which it remains constant when subjected to further discharges. The B. D. V. of moist samples of transformer oil having B. D. V. below 43 kV, when subjected to successive discharges, increases until it reaches the steady value after the same number of discharges. This is explained by the joint action of the accumulation of carbon and the removal of moisture. With smaller test cells the same result is obtained with a smaller number of discharges. The B. D. V. of benzene when subjected to successive discharges similarly decreases to a final steady value of about 35 kV. In this case, however, maximum values are obtained which are explained in the paper. The bearing of these results on the operation of oil circuit-breakers is discussed and it is shown that in the case of moist oil the effect of the discharge when the circuit-breaker opens under fault conditions is to improve rather than lower its B. D. V.

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