Time-lag Studies with Uniform-field Spark Gaps.

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SUMMARY.

From a study of previous experimental work on spark discharges, it is evident that an investigation of the impulse breakdown of uniform-field gaps under various conditions of irradiation would provide data for assessing the superiority anticipated for this form of gap, (a) for studying discharge phenomena whose effects would be masked by the dispersion of the results with other forms of electrode, and (b) for impulse-voltage measurement. Further, any information obtained, relating to the formative time-lag of spark breakdown in atmospheric gaps of length $\geqslant 1$ cm., at very low overvoltages, would extend spark theory.

With non-standard impulse waveforms of either polarity applied to a 2 cm. uniform-field gap in atmosphere, breakdown characteristics have been recorded for three conditions of irradiation, viz. (i) irradiation by ultra-violet light, (ii) irradiation from radium source, and (iii) no deliberate irradiation. Transition curves, showing the voltage range (δV) for a transition from 0 to 100 percent frequency of sparkover, and curves of "time-lag vs. percentage overvoltage" are drawn for all conditions. Comparative data for a 2 cm. gap between 6.25 cm. diameter spheres confirm the advantages to be expected from the uniform-field gap.

The impulse waveform restricts the maximum values of formative time-lag (T_f) that can be observed, owing to the fall /

fall of voltage on the wave tail. For this reason, formative time-lag data have also been obtained for air in uniform fields with static applied voltages up to 110 kV; and the very long formative times (greater than 10^{-4} sec.), predicted by theory for such conditions, have been recorded. Comparison of the static-voltage and impulse-voltage time-lag data indicates an impulse ratio of the order of 1.01 for the latter condition.

Static-voltage breakdown figures, for the uniform-field gap in air at atmospheric pressure, covering a range of 24 to 135 kV., are also given, and the data indicate that the breakdown voltage is increased by about 0.15 percent per gm/M^3 increase of water vapour present in the atmosphere. No polarity effect is observed in this data, and a radium source inserted in the high-voltage electrode produces negligible change in the static breakdown voltage.

In order to compare the experimental formative time-lag data with those from theoretical determinations, a knowledge of the values of the initial photoionization current in the gap (I_0) and of the ionization current which may be taken to indicate breakdown of the gap is essential. These two values have been estimated for 1 cm. and 2 cm. gaps in the atmosphere, by investigation of the mean pre-breakdown current in the range from 97.5 percent of the sparking potential (V_S) up to V_S. In addition, unidirectional pre-breakdown current pulses /

pulses have been recorded oscillographically within 1.5 percent of V_S, and comparison of the mean current and pulse current data for both the irradiated and non-irradiated condition suggests that the former measurement may be the average effect of the latter. Under similar conditions, pulses of light, emitted from the gap in the region close to sparkover, have been detected using a photomultiplier tube and high-gain amplifier. These pulses exhibit similar properties to the current pulses, magnitude increasing with applied voltage, and frequency of recurrence varying with irradiation. Visible and audible pre-breakdown phenomena are also reported.

Qualitative analysis of the mean pre-breakdown current measurements suggests the presence of a considerable secondary ionization effect within 1.5 percent of the spark breakdown of 1 cm. and 2 cm. irradiated gaps in a normal atmosphere ($pd \simeq 760$ and 1520 mm.Hg.cm. respectively, where $p \doteq$ pressure in mm.Hg. and d = gap spacing in cm.). Further, the static time-lag data, obtained for the 1 cm. air-gap at atmospheric pressure, are in general agreement with the formative times predicted on the basis of the Townsend theory of sparkover, and the comparison suggests the nature of the secondary processes operative in the experimental case. The linear relationship, found in the present series of experiments to exist between time-lag and gap spacing, for a given percentage overvoltage, suggests no change in the spark mechanism evident for /

for the 1 cm. gap in atmosphere (pd = 760 mm.Hg.cm) to that for a 4 cm. gap (pd $\simeq$ 3000 mm.Hg.cm.).

CONTENTS.

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1. INTRODUCTION.

[1] Characteristics of the spark discharge provide the experimental data which must be satisfied by any theory of the spark mechanism, and the sparkover voltage under given conditions between spherical electrodes in air is a recognised standard [2,3] for high-voltage measurement.

In the Standard Rules [2,3] for spheres of a particular size, the Tables give values of breakdown voltage for spacings up to about a sphere diameter only, and the recommendation is made that the sphere spacings should not exceed the sphere radius if accurate measurements are required. In the British Standard Rules, No. 358 - 1939, an accuracy of within 3% is quoted for the values given in the Tables, for both power-frequency alternating-voltage breakdown and impulse-voltage breakdown.

Little attention is given in the various Standards to the amount of pre-ionization which is required in the gap in order to ensure consistency of results with impulse voltages. B.S. 358 - 1939 suggests that, "In localities where the random ionization between the spheres is likely to be low, irradiation of the gap by radioactive or other ionizing media should be used when voltages of less than 50kV. peak are being measured". A more definite statement is given in the American I.E.E. Standards No. 4, which recommends irradiation by ultra-violet light for sphere-gaps of 6.25 cm. diameter /

diameter or less, for spacings up to one-third the sphere diameter, and suggests the use of a quartz mercury-arc lamp within a specified distance of the sphere-gap.

The recommendations in the Standards[2,3] appear to be supported by most of the previous experimental evidence, but Meek[4] has shown that large errors may be introduced in the measurement of impulse voltages by sphere-gap, when non-irradiated, even for gaps considerably in excess of the limit prescribed in the Standards.

[5]Many difficulties inherent in the use of spherical electrodes for spark-gaps would be overcome if the path of the spark lay wholly within a region of uniform-field strength. Electrodes with contours as suggested by Rogowski[6] or Stephenson[7] have been shown to give the desired characteristic of uniform field. Bruce[8], in a calibration of uniform-field gaps between electrodes to Stephenson profile, achieved remarkable accuracy and consistency in the measurement of high alternating voltages; and he subsequently[9] suggested that the uniform-field gap would be the better form of gap with which to study the mechanism of spark breakdown, and that there was a sound case for the consideration of this gap as a standardized method of high-voltage measurement.

[1]With increasing knowledge of the factors that influence the sparkover voltage, and data for alternating, static and impulse /

impulse voltages, it has become necessary to define more precisely the conditions apertaining to experimental data to be used to assess the validity of spark theory[10] or to compile calibration tables. Two important factors are the irradiation of the gap to provide an adequate supply of initiatory electrons to eliminate the statistical time-lag (T_s) and the subsequent formative time-lag (T_f) required for the development of the discharge across the gap. The latter not only provides some indication of the active secondary ionization processes[11], but must be taken into account when using a spark-gap to measure rapidly varying voltages such as impulse waveforms.

The aims of the present work are, therefore, (i) to compare the performance in atmosphere of uniform-field and sphere gaps with applied impulse voltages of different waveforms, and with different conditions of irradiation; (ii) to obtain relevant formative time-lag data from the above impulse investigations, and compare with similar data to be obtained with static applied voltages and (iii) to investigate any other relevant discharge effects, such as the value of gap current reached just before sparkover, which may be necessary for analysis of the formative time-lag data obtained, in the light of the streamer[12] or Townsend[13, 14] theory of sparkover.

2. REVIEW OF PREVIOUS WORK.

[10] The process of electrical breakdown, that is the rapid transition of a gas from the insulating to the conducting state, involves the production of an extremely large electron and ion current from the electrons initially produced from, say, an external source. Consequently, for the development of a spark in a gap which is subjected to an impulse voltage, at least one electron must appear in a favourable position in the region of the cathode during the brief period for which the voltage is maintained across the gap.

Thus the time-lag between the application of an impulse voltage and the subsequent breakdown of a gap may be divided into two components, (i) the statistical time-lag (T_s) which is the time from the application of the voltage to the occurence of an electron favourably placed to initiate break-down, and (ii) the formative time-lag (T_f) which is the time for the spark-discharge channel, once initiated, to bridge the gap. The statistical time-lag depends on the amount of pre-ionization of the discharge gap. By suitable irrad-iation of the gap, T_s can be reduced to negligible proportions, and the time to breakdown will be the formative time-lag only.

[1] When impulse voltages of increasing magnitude are applied to a gap, a value is first reached at which repeated impulses will produce only an occasional sparkover; at some higher value still there will be sparkover for each impulse /

impulse applied. The change in voltage ($\delta V\%$) between 0 and 100 percent frequency of sparkover is reduced by irradiation of the gap to eliminate T_s and consequently time-lags that are excessive relative to the time that an impulse-voltage wave is maintained above a given voltage level.

Investigation of impulse spark breakdown, therefore, normally involves the determination of the effect of different conditions of irradiation in reducing the transition voltage δV, and/or the determination of time-lags to breakdown; and previous research related to the present work can best be described under these two headings.

2.1. Irradiation and Spark-gap Breakdown.

The influence of irradiation on the impulse breakdown of short gaps has been known for many years, experimenters finding that increased irradiation provided an increased consistency, reduced time-lags and lowered the impulse breakdown voltage for a given gap. Various methods of irradiation were used, and included radioactive materials [15], and ultra-violet illumination as supplied by a mercury-arc lamp [16] or by spark [17,18,19] or corona [20] discharges.

Little information is available concerning the effect of irradiation on the impulse breakdown of long gaps (1cm. or greater), but it is of interest to examine the results

of /

of previous related research where, in many cases, the amount of irradiation has been uncontrolled or unknown.

In 1930, McMillan and Starr [21] made a study of the 6.25 cm. and 25 cm. diameter spheres with one sphere earthed, when subjected to power-frequency and impulse voltages. For short gap-spacings, the breakdown curves coincided, but, with increasing spacing, the positive impulse breakdown curve rose above the negative impulse breakdown curve which was found to coincide with the power-frequency curve. The difference between the positive and negative breakdown voltages, for a spacing of 15 cm. between 25 cm. diameter spheres, amounted to some 20 percent. The investigation was continued by McMillan [22] who explained the results in terms of space charges in the gap. No studies were made of the influence of irradiation on the behaviour of the gaps.

Experiments by Fielder [23], Meador [24], Bellaschi and McAuley [25], Dattan [26], and Davis and Bowdler [27], showed that similar results obtained for large spheres up to 200 cm. diameter. The measurements were checked by oscillographic observations. It was noticed that the 6.25 cm. and 12.5 cm. diameter spheres behaved more erratically than spheres of larger diameter, and the suggestion was made by Meador that this was due to the effect of statistical time-lag; but the effect of varying the amount of irradiation was not investigated./

investigated. In the measurements by Davis and Bowdler [27], using breakdown voltages up to about 1000 kV., it was found that the negative impulse breakdown voltage exceeded the power-frequency value by up to about 6 percent for a gap-spacing of a sphere radius, while the corresponding difference for the positive impulse breakdown voltage was as great as 10 percent. The percentage difference between the positive and negative impulse breakdown voltages at a spacing of a sphere radius was not more than 4 percent, as compared with a difference of up to 8 percent in Meador's results [24]. The difference between the positive and negative breakdown voltages as given by Dattan [26] varied up to 15 percent.

Studies of the effect of irradiation on the impulse breakdown of gaps between 6.25 cm. diameter spheres have been made by Nord [28], who used a quartz mercury-arc lamp for illuminating the gap. He found that irradiation caused only a slight change (about 4 percent) in the breakdown voltage of a 40-kV. gap. Larger differences were observed for shorter gaps, for which time-lags up to about 100 microseconds were recorded when the gap was non-irradiated. Irradiation had no noticeable effect on gaps which required above about 70 kV. to cause breakdown. Similar results for gaps up to 6 cm. in length were observed by Strigel [29].

The use of radioactive materials for the irradiation of gaps up to 0.5 cms. when subjected to impulse voltages has been /

been described by Berkey [30] and van Cauwenberghe [31]. The latter showed that 10 mg. of radium inside a sphere produced ionization at the rate of 2.4×10^6 electrons/sec. in a gap of length 0.14 cm. and sparking area of about 0.2 cm. diameter, and found that this amount of radium improved the consistency of the behaviour of the gap, and lowered the breakdown voltage. Later experiments by Garfitt [32] and Meek [33] showed that the use of 0.5 mg. of radium, which would provide about 1.2×10^5 electrons/sec., was insufficient to produce adequate irradiation in short gaps of less than 1 mm. between small spheres. They found, however, that the same amount of radium caused an increasing improvement in the consistency of the gap with increasing spacing.

The many measurements which have been made with power-frequency, alternating voltages indicate that irradiation has little effect on the breakdown voltage, except for short gaps between small spheres. Edwards and Smee [34] found that the breakdown voltage of a non-irradiated gap of 0.8 cm. between 1.3 cm. diameter spheres was about 8 percent higher than that when the gap was irradiated by radium contained in the high-voltage sphere; but that with larger gaps and larger spheres the error decreased. This is an indication that the presence of irradiation has a decreasing effect on the statistical time-lag as the gap length is increased, because of the greater gap volume and the consequent increase in the probability /

probability of the appearance of a suitably-placed electron to initiate the discharge. A slight improvement in the consistency of the power-frequency breakdown of gaps between 50 cm. diameter spheres, when subjected to ultra-violet illumination,has been reported by Sprague and Gold [35]. They found that the breakdown voltage of the illuminated gap was 1-2 percent lower than the non-irradiated value for gaps up to 15 cm.

A number of investigations have been made of the voltage required to cause the breakdown of sphere-gaps as a function of the time interval between the application of the impulse-voltage wave and the ensuing breakdown. With impulse voltages having a wavefront rise-time of 1.5 microseconds and a wavetail of 40 microseconds, Bellaschi and Taegue [36] studied the breakdown of several gaps between three different sizes of spheres. They defined the impulse ratio as the ratio of the voltage causing breakdown at a specified time to the voltage causing breakdown after 2 microseconds; they found that this ratio increased gradually with decreasing time to breakdown, being about 1.5 when breakdown in 0.2 microsecond was required. In similar measurements by Hagenguth [37,38], for gaps between spheres of 25 cm. and 50 cm. diameter, it was found that, for a 4 cm. gap between 25 cm. diameter spheres, with an impulse voltage rising at the rate of 1000kV/ microsecond, the overvoltages required to cause breakdown in times /

times of 1, 0.5, and 0.2 microsecond were 13, 54, and 91 percent respectively. Hagenguth also showed that ultra-violet light from a mercury-arc lamp had no effect on the results, and it may be concluded that the overvoltage required to cause breakdown in the shorter times was necessitated by the mechanism of the spark formation rather than by statistical time-lag.

The impulse breakdown of short gaps between spheres of 2 cm. diameter has been studied by Cooper [39], who used pulses of duration 0.1 to 4.0 microseconds. The pulses were applied recurrently to the gap at repetition rates of between 100 and 3000 pulses/sec. For gaps between 0.2 and 0.7 cm., irradiated by 0.2 mg. of radium, the impulse breakdown voltage exceeded the static breakdown voltage by nearly 6 percent, the difference being greater for shorter gaps. The static breakdown voltage of gaps up to 1 cm. spacing between spheres of this size has been shown to be the same as the power-frequency breakdown voltage [40].

More recently, in 1946, Meek [41] has made measurements up to 400 kV.(peak) with 1/5 and 1/50 impulse voltage waves, of positive and negative polarities, for gaps between spheres of 6.25 cm., 12.5 cm. and 25 cm. diameter. His investigation showed that errors in the measurement of impulse voltages by sphere-gap, in the absence of deliberate irradiation, may not only occur for short gaps, in which the need for irradiation /

irradiation had long been realised, but also for gaps in excess of 1 cm. above which irradiation was generally considered to be unnecessary. Widely differing results were obtained according to the position of the sphere-gap relative to the impulse generator; and, consequently, it was concluded that the irradiation provided by the ultra-violet illumination from the impulse-generator trigger-gaps had a marked influence on the behaviour of the sphere-gap being investigated, in the absence of other forms of irradiation. This factor does not seem to have been considered in the previous investigations described on the preceeding pages, and may have been a contributory cause of the widely different results obtained in the calibration of sphere-gaps with impulse voltages.

In addition, Meek investigated the effect of irradiation provided by 0.5 mg. of radium in the high-voltage sphere. Measurements of the impulse breakdown of the non-irradiated sphere-gap showed that there was a gradual transition from the voltage which caused breakdown for 10 percent of the applied impulses to that which caused 90 percent breakdown, whereas a sharply defined breakdown voltage was obtained when the gap was irradiated, that is, the transition voltage $\delta V\%$ was much less for the irradiated gap. The mean breakdown voltage of the non-irradiated gap exceeded that of the irradiated gap by an amount which varied with the gap length. The difference between the breakdown voltages for the non-irradiated gaps and the irradiated gaps amounted to 13 percent /

percent for a 3 cm. gap between 12.5 cm. diameter spheres; with larger gaps, for which a polarity effect was observed, this difference was greater for positive impulse breakdown than for negative impulse breakdown. The mean breakdown voltage for a non-irradiated gap of 9 cm. between 12.5 cm. diameter spheres was 20 percent higher than the irradiated value for a positive impulse, and 1.5 percent higher for a negative impulse. In comparing his results with those of Meador[24] and of Davis and Bowdler[27], Meek pointed out that Meador's results may have been obtained under conditions of weak irradiation, whereas it is possible that stronger irradiation, possibly by illumination from the impulse-generator trigger-gaps, may have been present in the experiments of Davis and Bowdler.

The use of 0.5 mg. of radium in the high-voltage electrode was considered by Meek to be the most effective method of irradiation, giving the most consistent and sharply-defined breakdown voltage - δV was about 2 to 3 percent for this condition. The values for the breakdown voltage obtained with the gap irradiated in this manner were in close agreement with the values given in the B.S.358 Tables, for gap lengths up to that at which a polarity difference is given. For longer gaps, the negative impulse breakdown voltage for the irradiated gap agreed with the B.S. 358 Tables, but the positive impulse breakdown voltage was appreciably /

appreciably lower than that given in the Tables.

Further, Meek found that the mean breakdown voltage of the non-irradiated gap decreased with increasing length of the wavetail of the applied impulse, because, he suggested, of the greater chance of breakdown when the voltage remains within a given proportion of its peak value for a longer time interval. In the presence of adequate irradiation the breakdown voltage was unaffected by the duration of the wave. The variation of the impulse breakdown voltage with humidity was not investigated in Meek's experiments,but, as humidity effects the number of ions normally present in the atmosphere[42], Meek anticipated that differences in the mean breakdown voltage of a non-irradiated gap and in the scatter of measurements would occur. Irradiation may be expected to reduce this effect.

Meek concluded from his experiments that some revision of the Standard Rules for the use of sphere-gaps was necessary, and, in particular, that more definite recommendations should be made concerning irradiation.

It should be pointed out however, that,in Meek's results, transition curves have been drawn as straight lines in every case, and there is no justification for this procedure. Since percentage sparkover curves follow a probability law, these can only be obtained by making a very large number of observations particularly at the upper and lower ends of the /

the curves. Further, since the difference in behaviour between irradiated and non-irradiated sphere-gaps depends on the presence of a suitable initiatory electron at the right time and place, then the percentage sparkover curves for the two cases should meet at zero. This does not occur in most of Meek's diagrams, and may be the result of an insufficient number of observations.

It is evident from the preceeding account that, even under conditions of controlled irradiation, some discrepancies still exist when sphere-gaps are used for spark-breakdown investigations. The polarity characteristic of the sphere-gap has been described by Bruce [9], and he has suggested [5,8] that many of the difficulties and inconsistencies encountered in sphere-gap investigations would be overcome if the spark-path lay wholly within a region of uniform-field strength. There have been few investigations of the impulse breakdown of gaps in uniform fields, but, as the present work is concerned mainly with uniform-field breakdown, it will be of interest at this stage to examine some of the more important power-frequency, alternating-voltage calibrations of the uniform-field gap along with what impulse-voltage data are available.

The most extensive, recent calibration of uniform-field spark -gaps is that given by Bruce [8] for power-frequency, alternating /

alternating voltages, which shows that, for all three sizes of electrode investigated, covering a range of 9 to 315 kV. (peak), the sparkover voltages for a gap of length S cm., in air at 20° C. and 760 mm.Hg. pressure, are within 0.2 percent of the values given by the emperical law,

$$24.22\ S + 6.08_2\sqrt{S}\ \text{kV}.$$

In these measurements ,the uniform field was obtained by the use of electrodes of the form suggested by Stephenson [7]. With increasing gap length ,the size of the electrode was increased to maintain uniform-field conditions in the gap, and three sets of electrodes were used in the investigation, their diameters of flat surfaces being 5.7, 11.2 and 19.8 cm. All measurements were made with vertical gaps, the lower electrode being earthed, and the effects of surrounding objects and of faulty alignment of the electrodes were found experimentally. The accuracy of his results is such that Bruce states that this form of uniform-field gap can be used to measure high,power-frequency voltages to within an accuracy of 0.2 percent.

Earlier calibrations of uniform-field spark-gaps, due to Schumann [43], Ritz [44] and Holzer [45], have provided results which differ appreciably from those of Bruce. The relationship between sparking voltage V, at 20° C. and 760 mm.Hg. pressure, and gap length S cm. is given by Ritz as

$$V = 24.55\ S + 6.66\sqrt{S}\ \text{kV.},$$

and /

and that given by Holzer is

$$V = 23.85\ S + 7.85\sqrt{S}\ \text{kV}.$$

Both Ritz and Holzer used electrodes designed to conditions specified by Rogowski [6], and Ritz has quoted an accuracy of within 0.5 percent for his measurements.

In all cases, the influence of gas density modifies the breakdown voltage equation as follows,

$$V = A\rho S + B\sqrt{\rho S}\ \text{kV., where } \rho \text{ is gas density.}$$

Meek [46] has drawn attention to the differences between the calibrations of Bruce and the previous investigators, and has pointed out that in Bruce's experiments no records of humidity were kept, whereas, in the investigations by Holzer and by Ritz, a change in humidity is observed to cause a measurable change in the breakdown voltage. The different type of electrode used should not cause significant variations in the breakdown characteristics.

Bruce [47], in reply, has emphasised that the accuracy of calibration of uniform-field spark-gaps depends on the precision of the voltage measurement and of the uniformity of the field, the latter being determined by the mechanical finish of the electrodes and the accuracy with which they can be adjusted to lie in parallel planes at a specified distance apart. In these two respects, and particularly with regard to the accuracy of voltage measurement, the work carried out by the early investigators is of limited value compared /

compared with the calibration of Bruce; the maximum deviation in Ritz's measured breakdown voltages are about 0.8 percent, compared with about 0.15 percent recorded by Bruce. Further, it is pointed out by Bruce [47] that humidity effects, if present, were not expected to be great, and the investigations were conducted on the basis that any such effects would be revealed by inconsistencies in the calibration data over the nine months period of the investigation; no such inconsistencies were observed. From considerations of the measuring techniques, greater reliability must be placed on Bruce's calibration data compared with that of the early investigators.

The above measurements have been made for power-frequency, alternating voltages, but the experimental evidence to date suggests that they may be considered to apply equally well for static-voltage breakdown. No divergence has been recorded between the two for small gaps between spheres [40], and the static-voltage breakdown figures determined by Trump, Safford and Cloud [48] for gaps up to 3.5 cm. appear to agree closely with the power-frequency calibrations. Fisher's results [49] for the static-voltage breakdown of uniform-field gaps of length 1 cm. are lower than those obtained by other investigators, and this Fisher attributed to the influence of the walls of the discharge chamber on the gap. Fisher also noted a small but definite spread in his measurements of /

of breakdown voltage when water vapour was present in the chamber. The results given by Klemm[46] for the static-voltage breakdown of uniform-field gaps again show no noticeable deviation from the values obtained for power-frequency voltages. It may therefore be assumed that, within the limits of the accuracy of the experiments, no difference has been detected for the static and power-frequency breakdown voltage of uniform-field gaps. The erratic results obtained in some measurements of the power-frequency breakdown of short gaps of the order of 1 mm. has been shown[34] to be a result of lack of irradiation.

Few investigations would appear to have been carried out on the impulse breakdown of gaps in uniform fields. In measurements of the impulse breakdown of air in a uniform field, Holzer[45] varied the rate of rise of the impulse voltage up to 9.3 x 10^8 kV./sec., and found that, for this maximum rate of rise used, the impulse breakdown voltage exceeded the power-frequency breakdown value by about 2 to 4 percent for a 12 cm. gap, the difference becoming less as the gap length was reduced. In Cooper's measurements[39], pulse voltages of 1 microsecond duration were applied recurrently to the uniform-field gap at the rate of 400 pulses per sec., and the peak value of the pulse voltage required to cause breakdown was measured for various time intervals between the application of the voltage and the onset /

onset of breakdown. In these experiments then, a time interval of say 15 secs. would imply that approximately 6000 applications of the pulse voltage, with the same peak value, would be made to the gap before breakdown took place. For these conditions, a small transition region, not greater than 2 percent, was recorded by Cooper between the maximum voltage which failed to cause breakdown in 5 minutes and the minimum voltage causing breakdown within 1 sec. The pulse breakdown voltages were considerably higher than the corresponding peak, power-frequency, alternating values, and irradiation by 0.2 mg. of radium did not affect the results for gaps $>$0.2 cm. Cooper [39] also calibrated uniform-field gaps with static and power-frequency, alternating voltages, and observed breakdown voltages which are within 1 percent of the values given by the emperical formula of Bruce. This is the only other later independent check available in Britain of Bruce's calibration [8].

2.2. Time-lags to Spark Breakdown.

Early studies have been made by Laue [51] and Zuber [52] of the time-lags to spark breakdown of gaps subject to impulse voltages, and as a function of the intensity of ionization. The lags were found to be purely statistical in nature, the number of lags n out of n_0 $(\frac{n}{n_0})$ that exceeded t secs., /

secs., plotted to a base of time (t), showed the curve to be of the form $n = n_o e^{\beta pt}$ where $p = \frac{1}{T}$, T ($= T_s + T_f$) being the average time-lag. Laue pointed out that β represents the chance that an electron is liberated by the ionizing agent. In Zuber's case, the volume of the gas was ionized by γ rays, and β depended not only on the number of electrons liberated per unit volume, but also on the chance that they were liberated in the effective volume of the gap. Thus β here depended both on ion current and the volume, p being the chance that an electron will initiate the discharge. The range of investigations carried out by Zuber was not very extensive, but he established the law, and showed that T was dependent on intensity of illumination.

At that time, no lower physical limit to T was looked for. It was believed that the statistical lag was caused merely by the fact that a single electron had to be liberated at a propitious time and position in the gap to initiate the discharge; and it was taken for granted that there must be a finite time which comprised the actual time to break down the gap (T_f), once the electrons were produced in the gap with sufficient frequency to eliminate the statistical lag. Pederson[53] estimated that this time could be of the order of 10^{-7} secs., and, within a year, the papers of Torok[54], Beams[55], Tamn[56], Rogowski[57] and others had appeared confirming Pederson's short time intervals. The short time-lags, down /

down to 10^{-8} sec., were obtained for short gaps with impulse voltages applied, and occurred only under conditions of high overvoltage and strong illumination. No measurements were made at low overvoltages, probably because at that time no instrument existed combining the necessary speed of operation with the precision of voltage measurement required in that overvoltage region.

Later, Tilles[58] undertook the measurement of time-lags in a gap of length 0.068 cm. between spheres of 0.95 cm. diameter, and he developed an ingenious device for recording the time lags lying between 10^{-5} and 1 sec. He measured with a ballistic galvonometer the constant output current given by a modified vacuum-tube voltmeter between the time of application of the sparking potential and its fall during the spark. Two series of investigations were run, one in which impulse voltages of short duration were applied to the gap, and the second, under static-voltage conditions, using an approach voltage of 96 percent V_s with the sudden application of a voltage V_0 to make the applied voltage from 1 to 5 percent greater than V_s, V_s being the sparking potential. Tilles recorded statistical time-lags up to 1 sec. for the particular gap studied, but found that, with increasing irradiation, there was a transition from a statistical lag of decreasing value to a formative lag of 10^{-4} sec. with sufficiently intense photo-emission ($I_0 \cong 2 \times 10^{-12}$ amp./cm^2) the /

the overvoltage remaining constant at 3 or 5 percent. Thus, long formative time-lags were shown to exist for the static condition, but only at low values of percentage overvoltage.

At about the same time, H. J. White[59] studied time-lags of the order of 10^{-8} sec. in short sphere-gaps of length up to about 10 mm. in air at atmospheric pressure. Applying a constant voltage to the non-irradiated gap, he used the ultraviolet light from a nearby spark to trigger the gap, and, by means of a Kerr Cell[60] shutter, observed the time between the flash of the initiating discharge and the breakdown of the gap. Time-lags of a non-statistical nature were observed as a function of gap length, intensity of illumination and overvoltage. As the intensity of illumination increased, the time-lag for a given overvoltage decreased. With high intensities of illumination, formative time-lags of the order of 10^{-8} to 10^{-7} sec. were recorded for overvoltages of about 20 percent. White observed a lower limit to the value of formative time-lag measured as the percentage overvoltage increased, but pointed out that the same time intervals were of the order of time taken for the rapid initial rise of intensity of light emission in the starting of the spark source, so that the upward bend of the "overvoltage vs. time-lag" curves had to be ascribed to a rapidly decreasing intensity of photoelectric emission.

This /

This difficulty was not present in the later investigations of Wilson[61], who carried White's experiments further, and used a quartz mercury-arc lamp as a source of irradiation which was steady but only 10^{-5} times as strong as that used by White. Wilson used an approach voltage about equal to the normal sparking potential, and suddenly applied an overvoltage. He raised the overvoltage in successive steps until a spark could be seen in his optical system with a given time setting. He then increased the overvoltage by steps, and recorded the percentage number of sparks observed when the same overvoltage was applied repeatedly. This he plotted as a function of overvoltage, and from these curves he chose as his overvoltage for a spark in the time interval used, the point at which 50 percent of the applications gave a spark. He found that corroded electrodes or a decrease in intensity of illumination produced a decrease in the slope of the curves, and thus increased the overvoltage for a given lag. He found that higher voltages were required with his weak illumination than were observed by White for the same lags. Wilson's overvoltages decreased continuously as the time-lag increased, but he found no lower limit to his lags, even down to 10^{-9} sec., if sufficient overvoltage were applied.

The later studies of Strigel[62] (1939), Newman[63] (1940) and Fletcher[64] (1949), with short gaps between spheres and with /

with gaps between parallel plates, confirmed the short formative time-lags of White, Wilson and the previous investigators; but no extensive investigation of the formative time-lags at low overvoltages (less than about 2 percent above the static sparkover voltage) was undertaken until the experiments of Fisher and Bederson [65] (1951). The latter work is described later in this review.

It has long been accepted that the characteristics of the generalized Townsend mechanism [13,14] of spark breakdown are in accordance with observations at low pressures, and, up to 1926, this mechanism was considered to account for a spark in the atmosphere. As described above, however, the experiments of Rogowski [57] and others [53,54,55,56] at that time, and which were verified by later investigators [58,59,61,63,64], indicated values of formative time-lags of breakdown, for millimetre gaps in the atmosphere under high impulse conditions, which were much less than the transit times of positive ions crossing the gap to the cathode to produce secondary ionization; and this was considered in some quarters to indicate that the Townsend mechanism no longer applied. Further, at about the same time, another crucial class of experiments, involving the classical test of measuring the amplification of the small initial electron-current in a uniform-field gap up to spacings at which breakdown occurred at various pressures, did not appear to support the application of the Townsend theory /

theory to the higher pressures. These experiments were carried out by Paavola[66]; Masch[67]; Sanders[68]; and Hochberg and Sandberg[69], and their measurements of the pre-breakdown current (I) did not reveal the up-curving of log I as a function of the spacing (d) required by the Townsend theory[13,14]. A streamer theory[12] of breakdown was accordingly advocated, based upon positive-ion space-charge and photo-ionization of the gas, and it was stated to account for breakdown at values of pd greater than about 200 cm.mm.Hg., where p is the gas pressure in mm. of mercury and d the gap spacing in cm. The theory was claimed to be independent of the cathode, and to account for very small values of formative time-lag.

It was thereafter commonly accepted that in air the Townsend mechanism of breakdown was valid for values of pd below about 200 cm.mm.Hg., and that above this value the breakdown proceeded by the streamer mechanism.[5] The apparent change in the mechanism at a critical value or range of pd indicated most clearly the need to explore this region experimentally.

Fisher and Bederson[65] consequently undertook to measure formative time-lags in air in an attempt to establish the region of validity of the streamer and Townsend mechanisms of spark breakdown. With the cathode illuminated by ultra-violet light from a quartz mercury vapour arc, and using

a /

a static approach voltage of two to four kV. below the breakdown voltage for a given gap spacing, they made measurements of formative time-lags in a uniform field for overvoltages of a few percent down to as close to threshold as possible. The measurements were carried out as a function of pressure (atmospheric to a few cm. of mercury) and plate separation (0.3 to 1.4 cm.). For pressures greater than 200 mm.Hg., they found that the formative time-lags very close to threshold were of 100 microseconds and longer, times longer than any previously recorded. For all pressures studied, the time-lags decreased as the percentage overvoltage increased, until, at about two percent above threshold, the formative time was of the order of 1 microsecond. The "time-lag vs. overvoltage" curves were independent of pressure from atmospheric down to 200 mm.Hg., whilst, at a given overvoltage, the time-lags increased linearly with plate separation. Variation of approach voltage, from 2 to 4 kV. below the breakdown voltage for a given gap, did not appreciably affect the results. The number of initiating electrons at the cathode was varied by a factor of about seven, and this again did not materially alter the results.

Fisher and Bederson stated that the long time-lags recorded, and their dependance on pressure and percentage overvoltage, could not be explained by secondary emission of electrons from the cathode by positive ion bombardment, but /

but that the explanation lay in the enhancement of field-intensified ionization due to field distortion acting in conjunction with a photoelectric secondary process. Their experiments, they added, required an extension of the streamer concept of breakdown, and made very questionable the role of positive ion bombardment of the cathode in spark breakdown for the pressures and plate separations studied. No transition region for change of streamer to Townsend mechanism of breakdown was found.

At the same time, the research group at Swansea [70], under F. Llwellyn Jones, undertook the investigation of the growth of pre-breakdown currents in the crucial region just prior to the appearance of a spark in air. The results showed that, over a restricted distance, the log I/d graphs were linear as previous workers had found; but, when d was increased to the crucial region near breakdown, an up-curving of the graphs was observed, contrary to previous work, and the graphs were exactly as found for low pressures. Determination of the first and second Townsend ionization co-efficients, α and $\frac{\omega}{\alpha}$ respectively, from these data enabled a theoretical determination of the sparking potential for a given gap to be made, which was found to be in full agreement with the observed sparking potential. The success of these investigations was made possible by improved methods of measurement and stability, and by the correct design of the experiments /

experiments, which enabled the pre-breakdown currents to be recorded in the critical region close to sparkover.

Further to this, detailed calculations of formative time-lags, taking into account various secondary ionization processes, have recently been made at Swansea [11] for a 1 cm. gap at atmospheric pressure. The value of current taken as indicative that the gap has broken down in a given case was made a parameter, and the time to breakdown calculated for a range of values of that current.

[11] The general result showed that, at voltages close to the static sparking potential, the time-lag, calculated on the generalized Townsend theory, may be large, $\geqslant 10^{-4}$ sec., because a large number of avalanches must traverse the gap before the current builds up to the value required for breakdown. As the overvoltage increases, the efficiency of ionization increases, and fewer avalanches are then required to give the same current. The theory outlined, predicts that the time-lag decreases rapidly with increasing overvoltage, and may be as small as 1 microsecond with overvoltages as low as 2 percent, even if only 50 percent of the secondary emission ($\frac{\omega}{\alpha}$) were photoelectric.

General agreement was found between these theoretical results and the experimental work of Fisher and Bederson [65] previously described, and it has been suggested [11] that the secondary mechanism, operative in the particular case examined by them, was the liberation of electrons from the cathode /

cathode predominantly by the incidence of photons, but that there was also some emission due to the incidence of positive ions.

The significance of this theoretical work of Dutton et al.[11] is that it has shown that the short time-lags recorded by previous experimenters, and which were interpreted by them and others[12] as being contrary to the Townsend theory of sparkover, are quite consistent with a breakdown mechanism dependent on primary and secondary ionization processes of the Townsend type, because these same processes have been shown to be sufficient in themselves to produce the rapid breakdown observed for fairly low overvoltages. A similar conclusion has been expressed by Kachickas and Fisher[71] after their recent measurements of formative time-lags in nitrogen.

Further, the above theoretical work and the experiments of Fisher and Bederson have shown that, for gaps of the order of 1 cm. in atmosphere, the long formative time-lags (100 microseconds and longer) exist only in the region within a fraction of one percent above the static breakdown voltage of the gap; the time-lags decrease very rapidly as the overvoltage increases, and are of the order of 1 microsecond with overvoltages as low as about 2 percent. Very precise forms of measurement would therefore be required to investigate the very low overvoltage region, and most of the previous time-lag /

lag experiments were carried out at considerably higher overvoltages. In the one case described, where measurements were made at very low overvoltages, Tilles[58] observed formative times of the order of 100 microseconds. In addition many of the early investigations were carried out using impulse-voltage waveforms which impose a limit on the time to breakdown, and these could not be expected to reveal the high values of formative time-lag predicted by theory for very small overvoltages above the static breakdown voltage of the gap.

It has been shown, therefore, that the Townsend mechanism, by virtue of photoelectric action at the cathode, can account for the short formative time-lags which had been observed for short gaps at fairly low overvoltages (2 to 3 percent). Experiments to investigate the formative time-lags of spark-over in long gaps ($>$1.5 cm.) have been carried out[72,73,36], but only under impulse-voltage conditions with the consequent imposed limitations on the range of possible time-lags due to waveform. These results indicate time-lags of the order of 0.5 microseconds with overvoltages of about 2 percent; but no measurements have been made for the longer gaps under static-voltage conditions, so that the region within about 2 percent above the static breakdown voltage remains to be investigated. With such data available over the complete range of overvoltages above the static breakdown voltage /

voltage as datum, comparisons may be made with data for the short gaps, to observe if any change in the breakdown mechanism is evident at larger spacings.

2.3. Conclusions.

The wide divergence of results obtained when sphere-gaps are used for high impulse-voltage measurement, in different laboratories and/or under different conditions of irradiation, indicates clearly the need for a more stable and consistent form of gap when high orders of accuracy are required. Considerable improvement in this respect should be effected by the use of uniform-field spark-gaps; but further experimental investigations of this gap are necessary to check the only formal calibration [8] to modern standards of accuracy that has yet been carried out, and to study its performance with impulse voltages applied and under different conditions of irradiation.

Furthermore, the investigation of the formative time-lags of spark breakdown of uniform-field gaps of length 1 cm. and greater, at atmospheric pressure, under carefully controlled impulse and static-voltage conditions, would provide results for correlating existing data and for assessing the validity of spark theory [11] for these gaps.

Some of the data detailed in the above review has been described by Professor F. M. Bruce in his "Review of Spark Discharge /

Discharge Phenomena" (1951) [9], and the work of the present thesis was initiated as part of the programme of research outlined by him at the close of that paper.

3. IMPULSE VOLTAGE INVESTIGATIONS.

With $^{0.2}/240$ or $^{1.2}/240$ microsecond impulse waveforms of either polarity applied to a 2 cm. uniform-field gap in atmosphere, breakdown characteristics have been recorded for three conditions of irradiation, viz. (i) irradiation by ultra-violet light from impulse-generator spark-gaps, (ii) irradiation from radium source and (iii) no deliberate irradiation applied. Transition curves, showing the voltage range δV for a transition from 0 to 100 percent frequency of sparkover, and curves of "time-lag vs. percentage overvoltage" are drawn for all conditions.

Comparative data for a 2 cm. gap between 6.25 cm. diameter spheres confirm the advantages to be expected from using uniform-field gaps for impulse investigations.

Relevant formative time-lag data are examined analytically, and the short time-lags obtained at the apparently low over-voltages explained.

Similar experiments undertaken preliminary to this work have been described previously [5].

3.1. Apparatus.

3.1.1. Electrodes and Supporting Structure.

The electrodes used in the "uniform-field" investigations were designed to Stephenson profile for an estimated range up to 100 kV. The geometry of the electrodes is as described /

described by Bruce [8], and fig. 3.1 gives the principal dimensions obtained from measurement of the actual electrodes used in this work. The electrodes were made from solid brass castings, and had a central boss at the back, tapped to accommodate mounting rods. Further, a hole was drilled centrally at the back of the electrodes to within 1 to 2 mm. of the sparking surfaces to allow for the insertion of radium capsules. Examination of the surface contour of the electrodes over the flats indicated that the surfaces were within 0.0001" of being flat.

Spheres 6.25 cm. in diameter, spun in copper, were used in the comparative sphere-gap measurements.

The electrode supporting structure, which was designed and constructed in the laboratory, is shown pictorially in plate 3.1 and in section in fig. 3.2. The spark-gaps were mounted vertically, the upper, high-voltage electrode being moveable, and the lower, earth electrode being fixed. The lower support terminated in a levelling device which enabled the plane surface of the lower electrode to be set parallel with that of the upper electrode. This device consisted of two plates separated by a ball-bearing which gave a smooth action to the adjustment of the four bolts connecting the plates. Once the lower electrode has been levelled with the upper, it is essential that the latter should not rotate during subsequent variations in the gap-spacing, since /

since the flat surface of the electrode may not be truly perpendicular to the axis of the rod. The method of obtaining smooth vertical movement of the upper electrode without rotation is shown clearly in the diagram; a taper pin, fixed in the outer tube and passing through a vertical slot in the inner moveable tube, prevented rotation. Lateral displacement of the upper electrode was allowed for by making the bolts connecting the supporting rod to the bakelite roof a loose fit.

The supporting structure was made of paxolin tube, with bakelite pieces top and bottom for attachment to the electrode shanks. The dimensions of the structure were designed from a consideration of the clearances required for sphere-gap measurements as described in B.S. 358 - 1939. These clearances are greater than those required in uniform-field gap investigations.

3.1.2. Irradiation.

The test gap was investigated under three conditions of irradiation, (i) non-irradiated, (ii) irradiation by ultra-violet light from the impulse-generator spark-gaps, and (iii) irradiation by radium source.

When reference is made to a non-irradiated gap, this implies that no deliberate irradiation was used, but not that the gap was altogether free from irradiation. To achieve /

achieve this condition, the gap-supports were housed in a large hardboard box (45" x 45" x 34" high), access being possible by means of two sliding doors situated at opposite ends of the box. It is probable that, in the so-called non-irradiated condition, some 1000 ions/cm.^{3} [42] were present in the gap due to normal ionization processes in the atmosphere.

During all the present investigations, the gap-supports were housed in the hardboard box, and situated about four feet from the impulse generator and in line with it. To investigate the effect of ultra-violet light on the breakdown, the end doors were removed from the box to allow the light from the impulse-generator spark-gaps to illuminate the gap. For irradiation by radioactive materials, a small metal capsule containing 0.5 mg. equivalent of radium was inserted in one or other of the electrodes, close behind the sparking surface. In the latter condition the box was closed to ultra-violet illumination from the impulse generator.

3.1.3. Impulse Generator and Auxiliary Equipment.

Impulse voltages of varying wavefront time (say 0.1 to 1 microsecond) and nominal wavetail of about 250 microseconds were required.

The impulse voltages were derived from an impulse generator designed and constructed in the laboratory; the design /

design is similar to that described by Aked and Husbands[74]. The generator was of five stages, each stage comprising 2 x 0.25 microfarad capacitors of the metal-cased "non-inductive" type rated at 10 kV. The output capacitance was therefore 0.025 microfarads, and the maximum impulse voltage available was 100 kV.

The "Marx" circuit was used, but was modified slightly to obtain the potential on the split-stage capacitors and to give a first-stage spark-gap having one side earthed. The circuit is shown in fig. 3.3. The metal cases of the two capacitor units of each stage were joined together, and to the centre connection of the two units. This point was then maintained at a potential of half the charging voltage by the resistors R_3 during the charging period. The 5400 - ohm resistances R_1, R_2 and the 10000 - ohm resistance R_3, effectively in parallel, provided a discharge or tail resistance for the generator, and gave a nominal 240 micro-second wavetail.

The stage capacitors were assembled as a ladder arrangement, as shown in plate 3.2. A sloping arrangement was employed to make adequate clearances between the different parts and to earth. The spark-gaps were all arranged in the one vertical plane and in view of each other, so that full advantage could be taken of the illumination between them to ensure rapid successive flashover of all gaps.

The /

The spark-gaps consisted of half-inch diameter spherical brass electrodes, the supporting shanks of which were carried on an adjustable lever which enabled the five gaps to be set simultaneously. The initial settings were made by screwing the spheres along their supporting shanks.

The first gap of the generator was of the triggered-type, similar to that described by Husbands and Higham [75], and is shown in section in fig. 3.4. The trigger-gap was operated by a pulse of about 5 kV., with a delay network inserted in the lead to the trigger-gap. An oscillograph was also triggered from the pulse, but without delay. The details of the circuit used are shown in fig. 3.5. With this controlled tripping technique, the need for a delay cable from the potential divider to the oscillograph is obviated; this has a number of advantages particularly in connection with the permissible range of potential-divider constants which may be used for a given accuracy of recording [76].

As well as consistent tripping of the generator, it was desirable, for the sake of convenience, that the generator could be operated over a reasonable range of charging voltages without re-setting the generator spark-gaps. For this purpose, it is necessary that the overvoltage across each gap subsequent to the triggered one shall be a substantial fraction of the charging voltage, a requirement which /

which depends on the stray capacitance between stages being small or the stray capacitance to earth being large. It was possible to trigger the generator under consideration with the stage charging voltage in the range 90 to 100 percent of the flashover voltage for a particular stage gap setting. This was a workable range but smaller than desirable. Adding a capacitance of 500 picofarads from the mid-point of the second-stage condensers to earth, as shown in fig. 3.3, improved this range to about 30 percent.

The voltage-doubler charging circuit is shown in fig.3.3. The transformer was rated at 12kV. R.M.S. with a current of 5mA., and both the high-voltage winding terminals were insulated for the rated voltage. Selenium rectifiers rated for a mean current of 5mA. were used.

The charging voltage of the generator was controlled by a Variac transformer supplied from a stabilized mains source, and was measured by means of a 20-megohm resistance voltmeter. The resistance was made from a string of $\frac{3}{4}$-megohm high-stability, cracked-carbon resistors, and used in conjunction with a moving-coil meter. It was not essential for the present experiments that the absolute value of the charging voltage be known accurately, but, in order to investigate the spark mechanism at very small overvoltages, a high order of accuracy was necessary in the measurement of voltage changes. To achieve this, the voltage developed across the last /

last resistor in the chain at the earth end was balanced against an equal voltage produced by a subsidiary stabilized source connected across a standard resistor acting as a potentiometer; a known small fraction of the latter voltage was balanced against a standard cell. Thus the total high potential of the first stage was given in terms of the voltage of the standard cell. With this circuit, using a sensitive moving-coil galvonometer as detector, the sensitivity to changes of charging voltage was 1 cm. deflection for 0.12 percent change of voltage at the setting used to investigate the 2 cm. gap; the period time of the instrument was unimportant here in the measurement of charging voltages. The fractional changes in charging voltage were considered to be the same as the changes in output impulse voltage, assuming the generator efficiency to be constant.

Experimental investigation of the period of self-oscillation of the generator, using a 300 picofarad loading capacitor, showed that the circuit inductance of the impulse generator was about 10 microhenris. As it was desired to investigate breakdown with impulse waveforms having wavefront rise-times of the order of 0.1 microseconds, a loading capacitor of 200 picofarads and very low inductance was obtained. This value was also suitable for use as the high-voltage unit of a capacitance potential divider, in conjunction with an oscillograph incorporating a 10kV. sealed-off tube. The /

The series damping resistance of the generator circuit was entirely external to the generator, and this provided a means of varying the wavefront rise-time. To limit circuit inductance, and at the same time provide for ease of variation of the wavefront resistance, morganite resistors of 45-watt rating and various ohmic values were used, the units being clipped to a bakelite supporting structure as shown in plate 3.2. With the generator just critically damped, the fastest wavefront rise-time available was about 0.18 microseconds.

As stated above, the loading capacitor of the generator was also employed as the high-voltage unit of the capacitance potential divider. The work of Aked [77], and initial experiments with potential dividers incorporating various lower arms and screening and earthing arrangements, indicated that, for optimum performance, (i) considerable attention would have to be given to limiting lower-arm inductance and to screening the lower arm from stray "pick-up" and (ii) the earthing point for the whole system should be at the lower end of the potential divider. Consideration of these points led to the design of the potential divider shown in position in plate 3.2. and in section in fig. 3.6a. The circuit is shown in fig 3.6b. Three 0.01-microfarad mica capacitors connected in parallel formed the lower capacitance, the lower-arm inductance thereby being $\frac{1}{3}$ rd of the /

the self-inductance of each capacitor. The nominal ratio of the divider was 150:1. A 1-watt carbon resistor, adjusted to the required value, was used as the matching resistance with the lead-covered co-axial cable leading to the oscillograph. As stated previously, the present investigations are concerned mainly with comparative values, and the absolute value of the generator output voltage is not essential. The frequency response of the divider, therefore, was not investigated, the divider-ratio merely being obtained by comparison with that of another capacitance divider [77] on which very stringent frequency response tests had been carried out, and for which the divider ratio to impulse voltages was known to within ±1% for 1/50 microsecond waveforms. The impulse output of both dividers for the same generator charging voltage was compared oscillographically, and the unknown ratio determined. The ratio of the present divider was thus found to be 150.3:1, and, from consideration of the comparison technique used to obtain this ratio, may be said to be accurate to within ±1.5% for the 1.2/240 microsecond waveform. For a given charging voltage, no significant difference was observed in the peak values of the two impulse waveforms investigated.

The potential divider was used in conjunction with a high-speed, single-sweep oscillograph incorporating a 10-kV., sealed-off tube, and providing sweeps in the range 1 micro-second /

second to 1000 microseconds. Suitable calibration oscillations are included. To provide an accurate voltage-calibration of the tube, an external circuit was constructed using battery voltages and a standard voltmeter.

Typical photographic records of the impulse waveforms used in the present investigations - $^{0.2}/240$ and $^{1.2}/240$ microsecond waves - are shown in plates 3.3a and 3.3b.

The assembly of apparatus, without the hardboard box for screening the test spark-gap, is shown in plate 3.2.

3.2. <u>Experimental Procedure</u>.

Before commencing a series of tests, the uniform-field electrodes were aligned in the vertical plane by sighting a plumb-line in contact with their edges against vertical lines on the laboratory walls. This adjustment was checked at two positions 90° apart on the circumferance of the electrodes, and for the gap-length to be used.

At the start of a test, the electrodes were cleaned with metal polish followed by a dry rub with a soft duster. When mounted on their supports, they were cleaned with ether, and finally polished with a silk cloth in order to remove surface fouling.

The electrodes were then set at the requisite spacing by inside micrometer gauge. Observations were made at four points towards the edge of the flats on the electrodes, repeated levelling and adjustment of the spacing being made until /

until the electrodes were level at the required spacing.

Before sparking was commenced, the impulse generator was charged to the maximum voltage, and left in this condition for about twenty minutes to allow the measuring circuit components to attain a stable value.

A few sparks were passed to remove dust etc. from the electrodes. Commencing at the maximum voltage output from the impulse generator, corresponding to about 40 percent above the zero sparkover voltage for the gap under consideration, a number of applications of voltage to the test spark-gap were made, the oscillographic record of each breakdown being photographed. These recordings constitute a run. Runs were made at various percentage overvoltage down to the voltage at which no breakdown of the gap occurred for a large number of applications. In the overvoltage range where sparkover occurred on each application, 10 impulses were applied in each run, but, in the transition region from 100 to 0 percent frequency of sparkover, the number of applications in each run was increased to 20, and an additional record was kept of the number of sparkovers and the number of failures. The entire procedure thus far described constitutes a series. Such a series normally occupied about five to six hours, and involved the photography of about 200 to 300 oscillograms; the time interval between each spark was about 1 minute. All oscillograms /

oscillograms for one series were recorded on one length of film. Sections of a typical series of wavefront breakdowns, for each waveform, are shown in the oscillograms of plates 3.4a and 3.4b.

Measurements were made of temperature and barometric pressure at regular intervals during a test series, and the breakdown voltages were corrected to the standard air density corresponding to a temperature of 20° C. and a pressure of 760 mm.Hg. Air pressure was measured by standardised Fortin Barometer to ±0.05 mm.Hg., while air temperature in the vicinity of the gap could be measured by thermometer to ±0.05° C. Readings of relative humidity were also taken.

Series, as described above, were made for each of the possible conditions of experiment derived from the following:-

(i) Electrodes - Uniform field (100 kV.) or 6.25 cm. diameter spheres,

(ii) Irradiation - Ultra-violet, radium (in upper or lower electrode), or non-irradiated,

(iii) Impulse Waveforms - $^{0.2}/240$ or $^{1.2}/240$ microsecond waves,

(iv) Polarity - Positive or negative impulse waves to upper electrode, lower electrode earthed.

3.3. Experimental Results.

The experimental data, showing the transition from 0 to 100 percent frequency of sparkover of the uniform-field and sphere /

sphere gaps, for the various conditions of irradiation, waveshape and polarity, are illustrated graphically in figs. 3.7 - 3.12, where percentage sparkover is plotted against the peak value of the applied impulse voltage in kV., the gap-spacing being 2 cm. in all cases. The absolute value of the breakdown voltage in kV., as determined by potential-divider and oscillograph technique, can only be taken as accurate to within $\pm$1.5%, but the relative values will be correct to within $\pm$0.1%.

It will be observed that, for the irradiated uniform-field gap, sharp transition curves and a remarkably consistent breakdown voltage for all conditions were obtained, although the individual experiments were carried out at widely different times. Later (Section 4.2) it is suggested that a possible humidity correction of +0.15 percent per gm/M^3 increase of water vapour present may exist for the uniform-field gap; this may account for some of the slight variations experienced in the present experiments, and humidity figures are shown on the diagrams. With the irradiated sphere-gap, on the other hand, although the transition curves, obtained at different times for any one particular condition of irradiation polarity and waveshape, show approximately the same change in voltage (δV) from 0 to 100 percent frequency of sparkover, the actual breakdown voltage may be quite different. This may be due to general inconsistencies in the sphere-gap and/or variations /

variations in atmospheric humidity, the values of which are again shown.

The relative effects of the various experimental conditions have been further determined by the transition curves shown in figs. 3.13 - 3.15. In these, the voltage range δV for a transition from 0 to 100 percent frequency of sparkover is plotted as a percentage of the voltage for zero breakdown in all cases. These therefore give a direct comparison of the transition curves for the various conditions, without reference to the previously-mentioned inconsistencies which occur in the actual breakdown voltage.

In the irradiated condition, one transition curve could serve for all combinations of irradiation, polarity and waveform as applied to the uniform-field gap; but for the sphere-gap the ultra-violet irradiation has been less effective than the radium in reducing δV, although no polarity effect is observed, nor any noticeable variation due to change of wavefront.

With no external irradiation, δV for the uniform-field gap is much less than for the sphere-gap, and is relatively unaffected by the polarity or wavefront variations. In the case of the non-irradiated sphere-gap, a large polarity effect is observed, and, with negative impulses applied, the maximum generator output was insufficient to achieve 100 percent frequency of sparkover. The extremely large δV in /

Irradiation	6.25 cm.dia.spheres				100kV. Uniform-field electrodes			
	Positive		Negative		Positive		Negative	
	Waveform				Waveform			
	0.2/240	1.2/240	0.2/240	1.2/240	0.2/240	1.2/240	0.2/240	1.2/240
Non-irradiated	30	34	66	85	10	14	12	16.5
Ultra-violet	2.6	3.0	2.6	3.0	1.0	0.9	1.0	0.9
Radium (H.V.Elect.)	1.7	1.8	1.7	1.8	1.0	0.9	1.0	0.9
Radium (Earth Elect.)	1.7	-	1.8	-	1.0	-	1.0	-

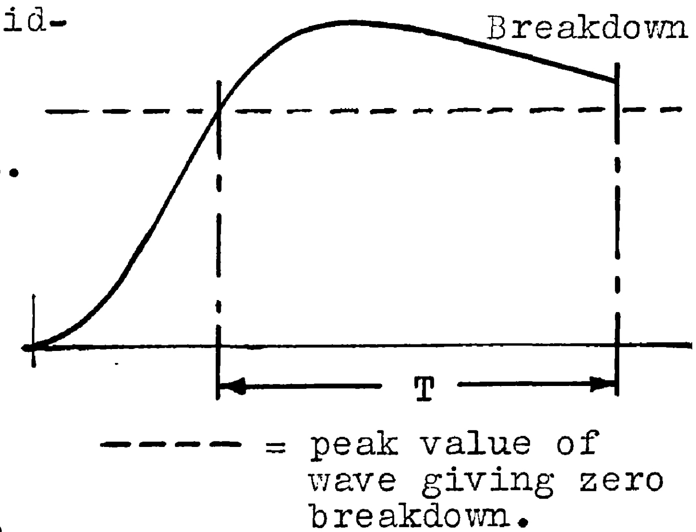
Table 3.1. - Figure of merit for 2 cm. gap investigated.

in the latter condition is difficult to explain. It is thought, however, that the electrostatic field between the charged impulse generator and the earthed (lower) electrode is the main contributory cause, since the impulse generator was only about 4 feet distant from the test gap. This field collapses during the application of the impulse voltage, and may cause some asymetry of the field in the test gap, which will be a maximum at the surface of the earthed electrode. The observed polarity effect can therefore be explained by assuming that the initiation of breakdown is determined by conditions at or near the cathode, the field here being a maximum when the cathode is also the earthed electrode, that is, for the application of a positive impulse to the upper electrode. This effect has not been investigated in detail, but it shows how the edges of the uniform-field electrodes shield the spark path, and serves to emphasise the superiority of the uniform-field gap which exhibited only negligible polarity effect under this condition of irradiation.

As a means of readily comparing the different characteristics recorded in the above graphs, table 3.1 (opposite) has been compiled which gives each experimental condition a figure of merit [5]. This has been defined as the value of δV percent for 0-100 percent transition in frequency of sparkover.

From /

From the oscillograms taken during the experiments, the time-lag to breakdown of each spark has been measured, and curves of "time-lag vs. percentage overvoltage" have been drawn for each experimental condition, figs. 3.16 - 3.19. The overvoltage $\Delta V\%$ is given as the percentage by which the peak value of the applied impulse - or the prospective peak value where breakdown occurs on the wavefront - exceeds that for zero breakdown on the δV transition curves; the time-lag (T) is measured as the time from the instant at which the applied voltage reached the peak value of the voltage which gave zero breakdown, to that at which breakdown occurred. This measuring procedure is illustrated in the inset diagram.



All time-lags reported represent the average of the individual measurements of a run, and surprisingly smooth curves, figs. 3.16 - 3.19, have been obtained, except for the non-irradiated sphere-gap which gave scattered points.

With the irradiated uniform-field gap, for a given waveshape, one curve could be drawn for all conditions of irradiation and polarity; and the consistency of performance is emphasised by the detailed curves of figs. /

figs. 3.20 and 3.21 which are drawn for low overvoltages. It is shown later (section 5.1) that the initial ionization current in the uniform-field gap with radium irradiation is of the order of 8 x 10^{-13} A. (c. 5 electrons/microsecond), which is large enough to reduce statistical variations in the time-lags. Furthermore, the minimum time-lag in a run was usually about half of the average time-lag, while the maximum time-lag was about twice the average; and no abnormally short time-lags were recorded in this condition. From the latter two considerations, and the fact that the same values of time-lag were obtained with U.V. or radium irradiation, it may be concluded that these measurements represent formative time-lags (T_f). The observations are extended to very high overvoltages, and include the extremely low values of T_f frequently mentioned in the literature. For a given overvoltage, corresponding to values of T_f less than about 1.5 microseconds, T_f is lower for the 0.2 microsecond wavefront, as would be expected from the greater rate of rise of voltage; but, as the overvoltage decreases and T_f increases, the effect of the wavefront rise-time diminishes, and T_f is the same for both waveforms: Comparative data for the irradiated sphere-gap indicate average values of time-lag similar to those for the uniform-field gap, but figs. 3.22 and 3.23 show a slightly lower degree of consistency in the performance of the gap, although there are no apparent differences /

differences due to changes of polarity or the method of irradiation.

In the non-irradiated condition, the uniform-field gap (figs. 3.16 and 3.18) again gave average measurements from which smooth curves could be drawn. The scatter of the individual measurements in a run was greater than with deliberate irradiation applied, and the average time-lag for a given percentage overvoltage was longer. This is an obvious indication of the reduced irradiation and an increase in the statistical time-lag (T_s). At the lower overvoltages, although the frequency of sparkover is less, the time-lag curve for the non-irradiated gap tends to approach that for the irradiated condition - the relative effect of the statistical time-lag is reduced as the formative time increases: For the non-irradiated sphere-gap, only scattered points are shown (figs. 3.17 to 3.19). A decreased consistency in this respect relative to the uniform-field gap is to be expected, since uniformity of the field is maintained over a much smaller area of cross-section, and the probability that fortuitous ionization will reduce T_s is thereby decreased. Many of the individual recordings in the latter condition, which are not shown on the diagrams, indicate that long time-lags exist even for high overvoltages. This is an obvious effect if it is considered that, as the overvoltage increases, the time for which the voltage remains above the static /

static-breakdown voltage of the gap increases, so that the probability of breakdown and of long statistical lags increases with increasing overvoltage.

3.4. Discussion of Results.

The data summarised in Table 3.1, and the smooth "time-lag-overvoltage" curves obtained even in the absence of external irradiation, confirm the advantages that were expected from using uniform-field gaps for impulse investigations. Consistent results were obtained over a testing period of several months, and, for the conditions investigated, the results were independent of polarity and wave-front changes. Any humidity correction is expected to be small.

Comparative data for the sphere-gap show that irradiation was essential to consistent performance with impulse voltages, and, further, that the more effective method of irradiation was that produced by the insertion of radium in either sphere. No polarity effect was observed for the irradiated gap. This data is in general agreement with the work of previous investigators in sphere-gap breakdown, but the polarity effect observed for the non-irradiated gap, namely a higher negative impulse breakdown than positive, is contrary to their evidence. The most probable explanation of this phenomenon may be found in the proximity of the impulse /

impulse generator to the test-gap, but this has not been investigated experimentally. Even with irradiation applied, fairly large variations in the actual breakdown voltage of the sphere-gap still occurred for any given condition. Part of this variation may be due to changes in atmospheric humidity, but the general inconsistency of the sphere-gap makes it unsuitable for investigating this effect in detail.

The relative lack of influence of the wavefront variation on any of the transition curves is probably explained by the fact that the important waveform factor in determining a transition curve is the time for which the applied impulse remains above the static breakdown voltage of the gap. With applied impulses having long decay times, as used in the above experiments, the time above the static voltage level would be relatively unaffected by the order of wavefront change investigated.

The formative time-lag data obtained with the irradiated uniform-field gap indicate the short time-lags frequently mentioned in the literature, but do not apparently reveal the long time-lags predicted by theory for low overvoltages.

It was observed, however, by analysis of the impulse waveforms used, that the maximum value of formative time-lag that can be observed is restricted, owing to the fall of voltage on the wavetail. Referring to fig. 3.24, it is evident that, as the percentage overvoltage of the peak value of /

of an impulse voltage above a given datum decreases, so the duration of the impulse above that datum also decreases, thus limiting the possible values of time-lag; whereas the formative time-lag increases. The result is that the zero percent sparkover criterion, chosen in the above experiments as the datum for specifying overvoltages, will be higher than the static sparking potential, the ratio "zero percent sparkover voltage/static sparkover voltage" being defined here, and for the remainder of the experiments, as the "impulse-ratio" of the gap. Further, the static sparking potential is the datum to be considered for specifying overvoltages for analytical purposes, and the formative time-lags recorded here will correspond to higher overvoltages when referred to this new datum.

In view of the limitations imposed by an impulse-voltage waveform on the magnitude of possible time-lags, and of the difficulty in relating impulse time-lag data to the static sparking potential datum, it was decided at this stage to measure formative time-lags in a uniform field under static-voltage conditions. The data so obtained would be related with the impulse time-lags already recorded, and further used for analytical purposes.

4. Static Voltage Investigations with Uniform-field Gaps at Atmospheric Pressure.

The objects of these investigations were (i) to measure formative time-lags of spark breakdown in uniform fields in atmosphere, by applying a static voltage to the gap (less than the sparking potential), and, at some later instant, applying a pulse voltage sufficient to cause breakdown, and (ii) with the static voltage equipment designed for (i), to carry out a voltage calibration of the uniform-field spark-gaps in atmosphere.

The two investigations are best described separately.

4.1. Measurement of Formative Time-lags of Spark Breakdown[77].

Formative time-lags were measured in a uniform field for overvoltages in the range from a few percent down to about 0.02 percent above the threshold voltage. Such measurements have been carried out in a normal atmosphere for gap lengths in the range 1 to 4 cm. The time-lags at voltages very close to threshold are of the order of 100 microseconds and longer, and decrease as the percentage overvoltage increases, until, at about 2 percent above the threshold voltage, the formative times are less than 1 microsecond. At a given percentage overvoltage, the time-lags increase linearly with plate separation.

The time-lags are of the same order as those measured by /

by Fisher and Bederson[65], and are comparable with recent theoretical determinations[11].

The present data indicate an impulse ratio of the order of 1.01 for the previous impulse-voltage measurements.

4.1.1. Apparatus and Procedure.

The uniform-field electrodes and the electrode supporting structure used in this study were the same as for the previous impulse-voltage investigations, and the same procedure was adopted in the levelling and polishing of the electrodes, the measurement of electrode separation and the measurement of temperature and pressure.

To eliminate statistical time-lags, irradiation was provided by the insertion of 0.5 mg. equivalent of radium in the high-voltage electrode. It is shown later (section 5.1) that this amount of irradiation produces an initial ionization current I_0 in a 1 cm. gap of the order of 8×10^{-13} A. Hence the probable number of electrons in the gap per microsecond was about five, and is large enough to prevent statistical variations in the time-lags. The current density corresponding to the above initial ionization current is of the order of 5×10^{-14} A/cm^2, and may be assumed small enough to prevent distortion of the electrostatic field[79]. Hardy and Craggs[80] have measured the ionization currents produced in spark-gaps by various amounts /

amounts of radium inserted at different thicknesses behind the sparking surface of brass plates; for a given set of conditions, the ionization current increased with gap spacing, quite rapidly at first, but above spacings of about 1 cm. the increase of current was only very slight. For the present experiments, therefore, the above initial ionization current may be assumed reasonably constant for all gap spacings investigated.

In order to determine the formative time-lag (T_f), an approach voltage Va (Va $<$ the sparking voltage V_s) was applied across the gap. Then, at some later instant, an additional voltage V_p (the pulse voltage) was applied so that Va + Vp $>$ Vs. The time that Va + Vp had to be maintained before the gap broke down gave the formative time-lag.

The circuit diagram of the apparatus is shown in fig. 4.1, and the values of the circuit elements are given in table 4.1. (opposite diagram).

The Va power supply is shown in the upper section of the diagram. The single-stage rectifier circuit employed 16 selenium rectifiers each rated at 5 mA., and was fed from a high-voltage transformer through a Variac transformer supplied from a stabilized mains source. The smoothing circuit consisted of a 0.08-microfarad, 175-kV condenser, followed by a filter circuit of two stages, the first consisting of a 5-megohm resistor and a 0.01-microfarad, 150-kV condenser /

condenser in series, and the second consisting of a 1-megohm resistor in series with a 0.08-microfarad, 175-kV condenser. Calculation showed that any ripple was negligible (c. 10^{-4} %) and, in fact, no ripple could be detected. The voltage regulation was satisfactory, the voltage remaining fixed to within several volts over some minutes.

Corona losses, which caused variations in the anode potential, were eliminated by covering sharp edges with plasticene, and by using large spherical terminals where possible.

The output voltage (Va) was measured by the most direct method, that of measuring the current through a high resistance in parallel with the source. To avoid excessive voltage drop across the smoothing resistors, the current drain had to be small. A drain of about 0.5 mA., when the anode potential was 100kV., was decided upon. Investigation of the performance of cracked-carbon-type resistors under load, showed that any variations of resistance were due to temperature rise, and could be reduced by immersion in oil. Consequently, the completed high resistor chain was constructed of two hundred and sixty-five 3/4-megohm, high-stability, cracked-carbon resistors of 1 watt rating, mounted in a spiral as shown in plate 4.1. The chain was immersed in a cylinder of oil, the cylinder being made of paxolin tube with aluminium end-caps. The change in value of /

of the high resistance, as measured by a high-voltage Wheatstone Bridge before and after a test series, was negligible. The present experiment did not require that the absolute value of anode potential be known accurately, but precise measurement of voltage changes was essential. To achieve this, a standard decade-resistance box was placed in series with the 200-megohm resistor to earth, the voltage developed across the decade resistance being balanced against a standard cell. Hence the output voltage Va was given in terms of the voltage of the standard cell, and the variation of Va was given in terms of the change in value of the decade resistor required to maintain balance. Using a "D'Arsonval-type" galvonometer as detector in the potentiometer circuit, a sensitivity of 1 cm. deflection for 0.01 percent change of voltage at 60 kV. was achieved. The period time of the detector instrument was unimportant here in the measurement of charging voltages.

The pulse voltage V_p applied to the gap was derived from the single-stage impulse generator shown in the centre section of fig. 4.1. The power supply charging C_6 consisted of a single selenium-rectifier unit rated at 5mA., fed from a transformer which was supplied through a Variac transformer from a stabilized mains source. The smoothing circuit consisted of a 0.25-microfarad, 10-kV. condenser followed by a filter circuit consisting of a 4-megohm resistance and another /

another 0.25-microfarad, 10-kV. condenser in series. Charging voltages of from 0 to 5kV. were available with a maximum ripple of about 0.03 volt. Measurement of the charging voltage (V_1) was by measuring the current through the high resistance R_8 which consisted of a chain of 3/4-megohm, high-stability, cracked-carbon resistors strung between two bakelite strips in air. The total value of the resistance was 18.75 megohm, and this was used in conjunction with the standard decade-resistance box R_9 to form a potentiometer circuit, the voltage across R_9 being balanced against a standard cell. A sensitive moving-coil galvonometer was used as detector, the sensitivity of the circuit being 1 cm. deflection for 0.07 percent change of voltage at 2kV. Again, relative rather than absolute accuracy was required in the measurement of V_1.

The pulse voltage was applied to the gap by means of a spark-gap (S) of the triggered-type, the trigger pulse being supplied from the circuit shown in the lower section of fig. 4.1. This tripping circuit and trigger-gap were the same as used in the first stage of the impulse-generator employed in the earlier experiments (figs. 3.4 and 3.5). When the trigger-pulse is applied, the spark-gap (S) breaks down, forcing the potential of the high-voltage electrode of the test-gap to fall by an amount equal to V_1 minus the voltage drop in S when firing. The voltage across the test-gap /

gap, therefore, was essentially equal to $V_a + V_1$ in a time determined by the resistance R_7 and the grouped capacitance formed by the test-gap capacity and that of the potential divider (C_4, C_5 - c.200pf) in parallel. The pulse rise-time was 0.16 microseconds, and remained approximately constant for all gap-spacings tested. This rise-time could be neglected in comparison with the long time-lags observed in the present experiment. The pulse decay-circuit time-constant was 0.2 seconds.

The spark-breakdowns were recorded by means of the potential divider across the gap, used in conjunction with a high-speed oscillograph. The potential divider and high-speed oscillograph were the same as used in the previous impulse investigations. Suitable calibration oscillations were available, and means were provided for the photography of the oscillograph traces. The oscillograph was tripped from the trigger circuit as shown in fig. 4.1, a delay network being incorporated in the circuit so that the start of the pulse was always visible on the oscillograph tube. A typical trace showing breakdown is given in fig. 4.2.

Before commencing a series of breakdowns, the apparatus was left in the charged condition for some twenty minutes to allow measuring resistors etc. to attain a stable value.

After a few sparks had been passed with the V_a power supply /

supply, in order to condition the electrodes, and the breakdown voltage (V_s) for the gap under consideration had been determined, V_a was adjusted to about 2kV. below V_s, and maintained at this value throughout any one series. V_p was then applied, and the time-lag recorded on the oscillograph.

The overvoltage ΔV was defined by,

$$\Delta V = V_a + V_p - V_s = V_a + V_1 - V^1 - V_s,$$

where V^1 is a correction due to the loss of part of V_1 in the circuit. The percentage overvoltage was given by $\frac{100\Delta V}{V_s}$ %

For each gap spacing, at a selected value of overvoltage (ΔV), about ten applications of the required voltage pulse were made, the oscillograph recording of each breakdown being photographed. Such runs were completed for several values of percentage overvoltage from about two to as close to zero as possible. Temperature and pressure were recorded at regular intervals throughout the above procedure, and appropriate corrections were applied. Corrections for the losses V^1 previously mentioned were made by assuming that the lowest value of V_1 which just gave consistent failure to breakdown corresponded to $\Delta V = 0$.

The entire procedure thus far described constituted a series, and such series were carried out for gap spacings in the range 1 to 4 cm.

4.1.2. Experimental Results.

All /

All time-lags reported represent the average of the individual measurements at each percentage overvoltage. The minimum time-lag in a run was usually about half of the average time-lag, while the maximum time-lag was about twice the average time-lag. Fig. 4.3 shows a typical distribution of measurements for various percentage overvoltage on a 2.4 cm. gap. The spread in the time-lags in a run increases approximately linearly with the average time-lag of the run, and it will be noticed that in many cases the spread is as large as the time-lag itself. However, in no single case was an abnormally short time-lag observed, that is, none was less than about 50 percent of the average. From the above considerations and the fact that the initial ionization current ($I_0 \simeq 8X\ 10^{-13}$ A.) provided several electrons per microsecond in the gap, it may be concluded that the measurements represent formative time-lags. The fluctuation in the time-lag measurements cannot be explained by the lack of initiating primary electrons, and is probably inherent in the statistical nature of the spark.

The time-lags as a function of percentage overvoltage are plotted in fig. 4.4. for gap spacings in the range 1 cm. to 4 cm. 100-kV. electrodes were used in the investigations on gap spacings up to 3.5 cm., but for the 4 cm.gap, 140-kV. electrodes were used, with no radical changes in the trend of /

of the results. It was found that in using the 100-kV. electrodes for a 4 cm. gap spacing, sparking occurred predominantly on the edges of the electrodes, and the larger size was resorted to.

The principal feature of fig. 4.4 is that for very low values of percentage overvoltage, the time-lags are quite long, and increase without apparent limit as the percentage overvoltage approaches zero. As the percentage overvoltage is increased, the average time-lags decrease extremely rapidly, being of the order of one microsecond at about two percent overvoltage, which is in agreement with the work of previous investigators [65]. For the gap spacings greater than 1.5 cm., the above measurements represent essentially a previously unexplored region in the range below two percent overvoltage.

Fig. 4.5 shows several sections of fig. 4.4 at various values of percentage overvoltage. It is seen that, for a given percentage overvoltage, the time-lags increase linearly with increasing plate separation within the region explored.

In the above investigation, the effect of varying the approach voltage or varying the intensity of the initial ionization current has not been studied. Fisher and Bederson [65] have previously shown that such variations do not materially alter the time-lag measurements.

4.1.3 Discussion of Results.

4.1.3.1. Correlation of the Static-voltage and Impulse-Voltage Time-lag Data.

It /

It is of interest to compare the time-lag data obtained using impulse voltages (figs. 3.20 and 3.21) with those where a static voltage technique was employed (fig. 4.4). Corresponding values obtained for a 2.0 cm. gap are shown in fig. 4.6. For a given impulse wave, the voltage will have to be sustained above the static breakdown value for a time of the order of the minimum formative time-lag before breakdown can occur, and the 0 percent sparkover criterion, taken as the datum sparking voltage in the previously-described impulse work (Section 3), will therefore be in excess of the static datum, for which there is no imposed time limit due to waveform. In the inset diagram of fig. 4.6, the horizontal full line represents the impulse datum voltage; the static datum will be at some lower value given by the dotted line. A given impulse, with the overvoltage as defined in the previous data, therefore corresponds to a higher overvoltage when referred to the static datum; an effect which was earlier (Section 3) defined as the "impulse ratio" of the gap, and which accounts for the difference between the curves of fig. 4.6. If the difference between the impulse and static datum voltages is assumed to be 1.15 percent, and the impulse overvoltages are adjusted to the static datum by this factor, then the characteristic coincides exactly with that obtained with static voltages, as shown by the transfer points of fig. 4.6. For the $^{0.2}/240$ microsecond /

microsecond waveform used, therefore, the impulse ratio of the gap relative to the static breakdown is of the order of 1.01; it is of interest to note that this figure is of the same order as that determined by the measurement of the zero-percent impulse breakdown voltage and the static breakdown voltage for the 2.0 cm. gap (fig. 3.7 and table 4.1 respectively), which give an impulse ratio of 1.02 $(= \frac{58.2}{57.6})$. As there is little difference between the time-lag data for the $^{0.2}/240$ and $^{1.2}/240$ microsecond waveforms, at the low overvoltages, the above remarks will also refer to the latter waveform.

In most laboratories, the impulse voltages available are much in excess of the static voltages, and the only measureable datum for specifying overvoltages is that used here in the impulse tests, namely the 0 percent sparkover criterion. As this has been shown to be greater than the static sparking potential, by about 1 percent in the present instance, and, as the static datum is that which must be considered when relating time-lag data to the theory of spark mechanism, it is evident that, irrespective of waveform restrictions, work which is confined to impulse-voltage measurements could not possibly reveal the high values of formative time-lag predicted by theory for very low overvoltages. The impulse data, however, do give the conditions which will relate to impulse voltage measurements.

4. /

4.1.3.2. Significance of the Formative Time-lag Data.

The formative time-lag data obtained in the above static-voltage experiments are compared in fig. 4.7, for the 1 cm. gap, with the results of Fisher and Bederson[65], and with the theoretical data determined by Dutton et al.[11] on the basis of the Townsend theory of spark breakdown. In the latter theoretical determination, it was assumed that the initial ionization current in the gap was $I_0 = 10^{-12}$ A., and "time-lag vs. overvoltage" curves were drawn for various values of the critical gap current I- (o,t) and the ratio δ/ω, where I- (o,t) was the value of current taken to indicate that the gap had broken down, and δ/ω was the ratio $\frac{\delta}{\alpha} / \frac{\omega}{\alpha}$ representing the contribution of electrons liberated at the cathode by photon action to the total Townsend secondary ionization. It is shown later in the present work (Section 5), for the same experimental conditions as used in the above time-lag investigations, that, for the 1 cm. gap studied, $I_0 \simeq 10^{-12}$ A., and I- (o,t) is of the order of 10^{-6} to 10^{-7} A. The theoretical curves of fig. 4.7, therefore, have been extracted from the work of Dutton et al.[11] for $I_0 = 10^{-12}$ A. and I- (o,t) = 10^{-7} A., for various values of the parameter δ/ω. (It should be noted that changing the value of I- (o,t) from 10^{-7} to 10^{-6} A. alters the theoretical curves only very slightly).

It /

It will be observed from fig. 4.7 that there is good agreement between the experimental time-lag data reported here and the measurements of Fisher and Bederson. Further, it can be seen that the theoretical curves are of the same general form as that given by the experimental points, but that the agreement in any one condition is not exact. Better agreement between theory and experiment, for the same values of δ/ω , is obtained if I- (o,t) is assumed to be of the order of 1A.; [11] but too much significance should not be attached to the present diversion of the results because of the assumptions made in the theoretical determination concerning the ion mobilities and the Townsend ionization coefficients α and ω/α . Indeed, it would seem fair to conclude from the comparison, since the experimental curve lies close to the theoretical curves given by δ/ω = 0.8 to 1.0, that the significant secondary process operative in the experimental case considered was the liberation of electrons from the cathode predominantly by the incidence of photons, but that there was also some emission due to the incidence of positive ions.

The formative time-lags recorded for the 1 cm. gap in air may therefore be explained by the Townsend theory of the spark mechanism; and, further, the shape of the "time-lag vs. overvoltage" curves obtained for the gap spacings up to 4 cm. (fig. 4.4), and the linear relationship existing between /

between time-lag and gap spacing, for a given percentage overvoltage (fig. 4.5), would seem to indicate that there is no change in the spark mechanism evident for a 1 cm. gap in the atmosphere to that for a 4 cm. gap.

4.2. Static-voltage Calibration of the Uniform-field Gap.

With the static-voltage equipment designed for the previous formative time-lag measurements, a calibration of the uniform-field spark-gap has been carried out in a normal atmosphere for gap lengths in the range 0.8 to 5 cm. Normal air density corrections have been applied to the results, and, in addition, the measurements have been corrected to an absolute humidity value of 7 gm/M^3, the latter correction being determined from the various calibration data obtained at widely different times.

No polarity effect has been observed, and the presence of 0.5 mg. equivalent of radium in the high-voltage electrode has no significant effect on the breakdown voltages.

4.2.1. Apparatus and Measurements Technique.

The uniform-field electrodes used were those designed for an estimated range up to 100 kV., and, for the larger gap spacings, those designed for the range up to 140 kV. The electrode supporting structure, and the procedure adopted for /

for levelling and polishing the electrodes and measuring the electrode separation were as previously described. Cleaning of the electrodes was carried out immediately before the calibration of each gap, and, for the present experiments, the gaps were not enclosed.

Air temperature was measured in the vicinity of the gap by Thermometer to ± 0.05° C., air pressure by standardised Fortin Barometer to ± 0.05 mm.Hg. and relative humidity by a Hair, Dial-gauge Hygrometer. The latter was frequently checked by a Wet-and-Dry Bulb Hygrometer, and the humidity measurements will be accurate to within about ± 2 percent.

The high-voltage supply to the gap was the same as described in Section 4.1 and as shown in the upper section of fig. 4.1, except that the resistor R_4 was replaced by a resistance of 120 kilohm. Any ripple in this supply was negligible, and corona losses were eliminated by covering sharp edges with plasticene.

The primary elements for measuring the gap voltage were the 200-megohm resistor (R_5 in fig. 4.1) in series with a substandard milliammeter (0-1mA.) or a substandard microammeter (0-200μA.) across the gap. So that the small inconsistencies in the breakdown voltage of a given gap could be recorded more accurately, the potentiometer circuit, P_1 in fig. 4.1, was available.

Before and after each calibration of a gap, the value of /

of the measuring resistor R_5 was determined on the site of the experiments, using a Wheatstone Bridge incorporating a standard 1-megohm resistor (R_a) and two high-quality decade resistors (R_b, R_c). The Wheatstone Bridge had a battery supply voltage of 800 volts, and, using a moving-coil galvonometer as detector, a sensitivity of 1 cm. deflection per 0.05 percent change in R_5 was achieved. $R_5 = R_a \times \frac{R_b}{R_c}$. Further, immediately after the calibration of a gap, the milliammeter (or microammeter) in series with the standard 1-megohm resistor R_a was calibrated on a standard d.c. potentiometer, the voltage v being determined which was necessary to give the same deflection (I) as obtained in the breakdown calibrations. As the meters had negligible resistance, then $I = \frac{v}{R_a}$.

The breakdown voltage applied to the test-gap was therefore given by

$$V = I.R_5 = \frac{v}{R_a} \times R_a . \frac{R_b}{R_c} = v \times \frac{R_b}{R_c} .$$

R_b was approximately 100 kilohm and R_c approximately 500 ohm , so that both could be very accurately determined using a Standard Wheatstone Bridge, whilst v could be very accurately determined using a Standard D.C. Potentiometer. Since the variation in R_5, before and after sparking, was negligible, the overall accuracy of the high-voltage measurement was limited only by the accuracy with which the meter pointer /

pointer could be re-set for calibration. As the zero of the instrument was adjusted during testing so that breakdown always occurred on a cardinal division, this error was estimated as better than ± 0.2 percent.

4.2.2. Experimental Procedure.

After the electrodes had been cleaned, and adjusted to give the requisite spacing, a voltage just below the breakdown voltage of the gap was applied for about fifteen minutes before sparking was commenced, to allow the equipment to stabilize. Thereafter, the high voltage was switched off, and, without removing it from the circuit, R_5 was determined using the Wheatstone Bridge described above.

Sparking was then commenced. Normally, after the passage of two or three sparks of a lower breakdown voltage- probably due to the presence of small particles of dust in the gap -, the breakdown voltage became very consistent, and the zero of the current-indicating instrument was adjusted so that the point of breakdown was a cardinal division on the meter. Ten sparks were then passed, during which no deviation from this reading (I) could be detected on the meter. Small inconsistencies (± 0.1%) in the breakdown voltage were measured on the potentiometer circuit.

Immediately after the completion of such a run of measurements, the measuring resistor (R_5) was again examined on /

on the Wheatstone Bridge, and the milliammeter was calibrated on the Standard D.C. Potentiometer. The variation in R_5, as measured before and after sparking, was in all cases found to be negligible, although day-to-day variations of the order of $\pm$ 0.5 percent were found.

Readings of temperature, pressure and relative humidity were recorded at various times during the above proceedings.

The above procedure was carried out for various gap spacings in the range 0.8 to 5.0 cm., and for positive or negative voltages applied to the upper electrode, the lower electrode being earthed. Certain of the calibrations were repeated with 0.5 mg. equivalent of radium inserted in the high-voltage electrode, but no significant difference in breakdown voltage was recorded.

All breakdown voltages were corrected [6] to a standard air density corresponding to a temperatureof 20° C. and a pressure of 760 mm.Hg., according to the expression, $V = A\rho S + B\sqrt{\rho S}$, where A and B are constants, S = spacing and $\rho = \frac{p}{760} \times \frac{273 + 20}{273 + t}$; p = pressure in mm.Hg. and t = temperature in °C.

4.2.3. Experimental Results.

Typical dispersion diagrams, showing the consistency of breakdown of a given gap as determined by the potentiometer circuit /

Gap-Spacing (cm.)	Breakdown Voltage (kV.)
0.8	25.05
1.0	30.56
1.5	44.16
2.0	57.57
2.5	70.76
3.0	83.85
3.5	96.93
4.0	109.9
4.5	122.9
5.0	135.8

Table 4.2. - Breakdown voltage figures for uniform-field gaps in air at 20° C., 760 mm. Hg. and 7 gm/M^3 absolute humidity.

circuit, are shown in figs. 4.8a and 4.8b.

For each of the gap spacings investigated, determinations of the breakdown voltage were made in the atmosphere at different times, often separated by several days, so that it was possible, for most of the gap spacings investigated, to construct graphs (figs. 4.9 - 4.18) showing breakdown voltage plotted against absolute humidity in gm/M^3, assuming a linear relationship over the restricted range of the measurements. On these graphs, the breakdown voltages obtained with the upper electrode positive or negative are plotted on the same diagram; no significant variation due to this effect was found, nor was to be expected, since the breakdown in all the conditions investigated occurred in the uniform-field region of the gaps. The breakdown voltages are corrected to 20° C. and 760 mm.Hg. pressure, and the absolute humidity was determined from the "humidity-temperature" curves of Zimmerman and Lavine [82].

From the above graphs, the breakdown voltage corresponding to an absolute humidity of 7 gm/M^3 has been derived for each gap spacing, and these values are shown on the accompanying table, 4.2. In the case of the 4.5 and 5.0 cm. gap spacings, insufficient variation of atmospheric humidity was experienced to allow separate "breakdown voltage-humidity curves" to be drawn, and the average of the /

the humidity corrections obtained for the other spacings has been applied to these gaps (figs. 4.17 and 4.18). In the graph of fig. 4.19, each average experimental value of breakdown voltage for each gap spacing, expressed as a percentage above the derived value corresponding to an absolute humidity of 7 gm./M^3, is plotted against absolute humidity, and the average correction to the breakdown voltage is indicated as + 0.15 percent per gm./M^3 increase of water vapour present in the atmosphere; the maximum deviation of any one measurement from the "0.15 percent per gm./M^3 line" is about 0.1 percent.

4.2.4. Discussion of Results.

The investigation of the static-voltage breakdown of the uniform-field gap has revealed the same consistent performance as recorded by Bruce[8] in his alternating-voltage calibration of the same gaps. The present data have shown, however, that the breakdown voltage of the gaps studied is increased by a factor of about 0.15 percent per gm./M^3 increase of water vapour present in the atmosphere; and each of the calibration figures of Table 4.2 is within 0.15 percent of satisfying the emperical law,

$V = 24.39\ S + 6.17\sqrt{S}$ kV., for the breakdown voltage at 20°C temperature, 760 mm.Hg. pressure and 7 gm./M^3 absolute /

absolute humidity, where S is the spacing in cm. No polarity effect has been observed for the gap spacings investigated, nor any measurable effect on breakdown voltage due to the presence of radium in the high-voltage electrode.

The humidity correction of + 0.15 percent per gm./M^3 increase of water vapour present compares favourably with that of Ritz [44], who found that the alternating-voltage breakdown of a 1 cm. gap in air at 760 mm.Hg. pressure was increased by 0.13 percent per gm/M^3.

Further to the above, measurements of the static breakdown voltage of 1.0 cm. and 2 cm. uniform-field gaps, over a wide range of humidity variation, have produced the curves of figs. 4.20 and 4.21. These experiments were carried out with the gaps in a humidity chamber (18" x 18" x 18") designed by a colleague, J.E. Matthews, for humidity investigations with small sphere-gaps. The curves indicate an increase in the breakdown voltage of about 0.3 percent per gm./M^3 increase of water vapour present, and verify the existence of a measurable humidity correction for uniform-field gaps. Too much significance, however, should not be attached to the actual correction figure indicated from this investigation until further experiments have been carried out in a larger humidity chamber, and for other gap spacings.

The data from the above experiments will be combined with /

with similar data,being obtained in the same laboratory for power-frequency alternating and impulse voltages, to provide a comprehensive calibration of the uniform-field gap.

5. Pre-breakdown Current Investigations in Uniform-field Gaps at Atmospheric Pressure[81].

Initially, it was intended to investigate the pre-breakdown current in the condition relating to the previously-determined formative time-lag data, so that the current measurements might be used to correlate theoretical time-lags[11] with the experimental data. This involved the use of a static approach voltage followed by an impulse voltage to break/down the gap. Attempts to record the current for this condition, by using a low resistance in series with the gap, and applying the voltage produced across the resistor to a valve amplifier, were unsuccessful, however, due to saturation of the amplifier with capacitance-currents prior to the main discharge; and, thereafter, the current measurements were proceeded with, using static applied voltages only.

The investigations were carried out for uniform-field, irradiated or non-irradiated spark-gaps of length 1 cm. and 2 cm. in a normal atmosphere, the pre-breakdown currents being recorded oscillographically in the region within a few percent of sparking potential. Two series of experiments were completed, (i) investigation of the mean current growth, using a high resistance in series with the spark-gap and (ii) investigation of uni-directional pre-breakdown current pulses, using a low resistance followed by a high-gain amplifier.

Under /

Under similar conditions, pulses of light, emitted from the gaps in the region close to sparkover, have been recorded using a photomultiplier tube and high-gain amplifier. Visible and audible pre-breakdown phenomena are also reported.

The results are analysed qualitatively, and indicate the presence of a considerable secondary ionization effect within 1.5 percent of the sparkover potential of the gaps considered.

5.1. Apparatus.

The uniform-field electrodes and the electrode supporting structure were the same as used in the previous investigations, and the same procedure was adopted for cleaning the electrodes and setting the gap spacing.

Irradiation, when required, was provided by the insertion of 0.5 mg. equivalent of radium in the high-voltage electrode. The so-called non-irradiated gaps were subject only to fortuitous atmospheric irradiation.

The stabilized, smoothed, high-voltage supply to the gaps was the same as described in Section 4, and measurement of the voltage was by the same means, using the high resistance chain of 3/4-megohm, high-stability, cracked-carbon resistors in series with a milliameter across the test gap. Changes of voltage could again be measured accurately, using a highly-sensitive potentiometer circuit.

5.2. Investigation of the Mean Pre-breakdown Current.

5.2.1. Experimental Procedure.

Initially, to compare the current growth in the irradiated and non-irradiated gaps, the voltage developed across a resistance of approximately 200 megohms (4 x 50-megohm, 1-watt carbon resistors) in series with the test gap to earth was applied to the Y-plates of a C.R.O., photographic records being obtained using a moving film as time-base. As the gap voltage increased to breakdown, recording was commenced at approximately 1.5 percent below sparking potential, and continued to sparkover. A gradual increase of current was observed for the irradiated gaps, but an apparently sudden increase from a steady value was evident for the non-irradiated gaps immediately before breakdown.

In order to investigate the irradiated condition more fully, and to obtain direct oscillograms of pre-breakdown current (I) vs. gap voltage (V) in the region close to sparking, the circuit shown in fig. 5.1 was used. In this, the X and Y deflections of the C.R.O. are directly proportional to gap voltage and pre-breakdown current respectively; the voltage to the X-plates is suitably adjusted by the amplifier arrangement shown, to give visible deflection only in the region from approximately 99 percent sparking voltage (V_s) up to V_s, and allowance is made, by suitable tapping of the 200-megohm series gap resistor, for voltage regulation due to pre-breakdown current flow in this resistor. As the applied voltage slowly increased to breakdown, photographic /

photographic records of the resulting oscillograph traces were obtained. It should be emphasised here, that the value of current taken to indicate breakdown was that value which could just be maintained without causing sparkover - if, at this value of current, the applied voltage were reduced, then the "current-voltage" oscillogram was retraced in the reverse direction.

In the above experiments, several recordings were made for each gap spacing, after the passage of a few sparks to remove dust etc. from the electrodes. The C.R.O. was calibrated for both axes.

To check the lower current values in the "I - V" oscillograms obtained for the irradiated gaps, and to extend the current measurements, a highly-sensitive "D'Arsonval-type" galvonometer (suitably protected) was used in series with the test gaps, readings of current and voltage being recorded as the applied voltage was increased to sparkover. The average values of current for several successive sparks were then combined with the results from the oscillograms to produce "I - V" curves in the range 97.5% V_S up to V_S.

All of the above observations were made for gap spacings of 1 cm. and 2 cm., and for positive and negative polarity of the upper electrode.

5.2.2. Experimental Results.

Comparative records of the current growth in the irradiated and non-irradiated 2 cm. gap are shown in fig. 5.2. These records were obtained on a moving-film time-base (film speed = 1"/sec.), the same rate of rise of applied voltage being employed in each condition. Similar records were obtained for the 1 cm. gap.

A typical "I - V" oscillogram for the 2 cm. irradiated gap is given in fig. 5.3, and graphs of "current vs. voltage" for both the 1 cm. and 2 cm. irradiated gaps are drawn in fig. 5.4.

No polarity effects were observed in the data.

5.2.3. Discussion of Results.

Although no determination of the Townsend ionization coefficients (α and $\frac{\omega}{\alpha}$) can be made from the above data, certain qualitative analysis is possible. Consideration of the curves of fig.5.4 shows that, within 1.5 percent of the sparking potential, the currents increase at a much faster rate than would be given by the simple exponential relation $I = I_0 e^{\alpha d}$ and the change in α anticipated over the relevant range of $\frac{E}{P}$ ($\frac{\text{voltage stress}}{\text{pressure}}$). For example, considering the 1 cm. gap, the change in the value of α required to produce the change of current recorded here in /

in the $\frac{E}{P}$ range 39.84 to 40.3 V/cm/mm.Hg., assuming a simple exponential relationship, is five times greater than that given by the experimental values of α determined by Llewellyn-Jones and Parker[70] for this range of $\frac{E}{P}$.

This suggests a considerable secondary ionization effect for applied voltages within 1.5 percent of the sparking potential (V_S) of the irradiated gaps investigated (pd $\simeq$ 760 and 1520 mm.Hg. cm. respectively). For applied voltages below about 98 percent V_S, the secondary effect is apparently small, the current changes being almost appropriate to the changes in α. Similar curves of "Ionization current vs. Applied voltage", for voltages up to sparking potential, have been obtained by de Bitetto and Fisher[81] in their recent measurements of pre-breakdown currents in hydrogen and nitrogen for values of pd in the range 100 to 800 cm.mm.Hg., and the secondary ionization effect was found to be negligible until the applied voltage was within about 2.5 percent of the sparking potential. For the present experiments, neglecting the effect of secondary ionization at a voltage of 97.5 percent V_S, and using the value of α given by Llewellyn-Jones and Parker[70] for the corresponding value of $\frac{E}{P}$, the data indicate that the initial ionization current (I_0) in the 1 cm. irradiated gap is of the order of 8×10^{-13} A. This value, along with the value of mean current taken to indicate breakdown /

breakdown of the gaps, here shown to be approximately 1.2×10^{-6} A., is necessary for a theoretical determination of formative time-lags for the gaps considered in these experiments, using the technique described by Dutton et al[11], and enables a comparison to be made between their theoretical values of formative time-lag and those obtained experimentally in this present work (section 4 and fig. 4.7).

The comparison obtained, of the growth of the mean pre-breakdown currents in the irradiated and non-irradiated gaps (fig. 5.2), indicates a gradual increase of current up to sparkover for the irradiated condition, but, apart from a few small pulses just before breakdown, an apparently sudden increase of current at sparkover for the non-irradiated condition. A possible explanation for this effect will be discussed later in the light of the results obtained from the pre-breakdown pulse current measurements to be described.

5.3. Investigation of the Pre-breakdown Current Pulses.

5.3.1. Experimental Procedure.

The high-voltage supply circuit was the same as used in the mean current measurements, and as shown in fig. 5.1. The 100-kilohm resistor was retained, but, to detect the current pulses, a 1000-ohm resistor replaced the 200-megohm resistor in series with the gap. The voltage developed across /

across the 1000-ohm resistor was amplified by a factor of about 6000:1, using the amplifier of fig. 5.5., and applied to the plates of a cathode-ray oscillograph.

Initially, so that comparison could be made for the irradiated and non-irradiated gaps, continuous records of the growth of the pulses were obtained, using a slowly-moving film as time-base; as the applied voltage slowly increased to breakdown, recording was commenced at approximately 1.5 percent below the sparking potential, and continued to sparkover.

A single-stroke, high-speed oscillograph was used to obtain greater time-resolution of the current pulses in the irradiated gaps. Recordings were made within 1.5 percent of sparkover, by tripping the oscillograph at random as the applied voltage increased slowly to sparking. The latter procedure was not possible for the non-irradiated gaps, due to the very low frequency of pulse recurrence.

Further to the above, when the applied voltage was within about 1.5 percent of the sparking potential, pulses of light emitted from the gaps were detected, using a photomultiplier tube and the same high-gain amplifier as previously (fig. 5.5.); the stabilized supply to the photomultiplier is shown in the circuit diagram of fig. 5.6. The photomultiplier tube was situated about one foot distant from the /

the test gap,and looking directly into it. Oscillographic recordings of the pulses were again obtained using the same techniques previously described for recording the current pulses. The latter experiments were conducted in complete darkness.

The above observations were made for gap spacings of 1 cm. and 2 cm. in a normal atmosphere, and for positive and negative polarity of the upper electrode. In all cases,several records were obtained after the passage of a few sparks to remove dust etc. from the electrodes.

5.3.2. <u>Experimental Results</u>.

Plate 5.1 shows a comparison of the growth of the current pulses in a 1 cm. gap for the irradiated and non-irradiated conditions, as the sparking potential is approached. The same rate of rise of voltage was employed in each case, and the time-base was provided by a moving film. A typical high-speed oscillogram of the current pulses just before breakdown of the 1 cm. irradiated gap is illustrated in plate 5.2.

Records similar to plate 5.1 were obtained of the light output from the 1 cm. gap, and a typical high-speed oscillogram of the light phenomena close to sparkover is given in plate 5.3. The latter oscillogram is not simultaneous with that of plate 5.2.

Similar /

Similar results were recorded for the 2 cm. gap, and no significant difference was observed for change of polarity of upper electrode.

During the experiments just described, and during the previous mean current measurements, clearly audible discharges could be heard in the gap just before breakdown. The noise appeared to be consistent with the pulse-current recordings, a rapid succession of discharges increasing to breakdown for the irradiated gaps, but intermittent discharges prior to breakdown for the non-irradiated gaps.

Further, a distinct glow, which will be the integrated effect of the light pulses recorded above, has been observed in the region of the anode, when experimenting with the irradiated gaps in complete darkness. Photographs of this phenomena, plate 5.4, indicate that the glow covered the flat surface of the positive electrode, irrespective of the polarity of the upper electrode, and this was detectable within about 1 percent of sparkover.

5.3.3. Discussion of Results.

Although an exact analysis of the pulses recorded is not possible, due to limitations of amplifier bandwidth and present recording techniques, the results supply evidence that unidirectional pre-breakdown current pulses exist in the /

the uniform-field spark gaps investigated, at voltages approaching sparking potential. In the case of the irradiated gaps, the magnitude of the current pulses increased steadily from negligible values at about 98.5 percent sparking voltage to values of the order of 35 μA. peak just before sparkover, when the rate of recurrence of measurable pulses was about 10 per millisecond. For the non-irradiated gaps, only an occasional pulse was recorded as the voltage increased to sparkover, but the magnitude of the pulses just before sparking was again of the order of 35 μA. peak. The audible pre-breakdown phenomena and the light pulses recorded appear to be consistent with the pulse current recordings. The diffuse glow, which was detectable always at the positive electrode, would seem to suggest that this was the region of most intense ionization, and a cathode to anode spark process is indicated.

5.4. Significance of the Pre-breakdown Current Measurements.

The mean current measurements have provided qualitative evidence of the existence of a considerable secondary ionization effect within 1.5 percent of the breakdown of 1 cm. and 2 cm. irradiated gaps in a normal atmosphere (pd $\simeq$ 760 and 1520 mm.Hg. cm. respectively), and data is provided which can be used in the theoretical determination of formative /

formative time-lags for these spacings.

The difference obtained in the growth of the current for the irradiated and non-irradiated gaps, as determined by the first series of experiments described above - namely a gradual increase to breakdown for the irradiated gaps, but an apparently sudden increase at breakdown for the non-irradiated gaps - may find a suitable explanation if it is considered that this current, recorded using a high resistance in series with the gaps, is some average value of the unidirectional pre-breakdown current pulses recorded in the second series of experiments. Any d.c. measuring circuit involving high time-constants can only measure some average effect of any rapid changes of current, and the large difference in pulse recurrence rates, recorded above for the two conditions of irradiation, would result in vastly different average values being recorded.

The mean and pulse current records cannot be directly compared at present, due to limitations of amplifier band-width and present techniques. With an improved amplifier, and a recording technique whereby single pulses may be examined in minute detail, it should be possible to correlate pre-breakdown pulse current data with existing pre-breakdown current data obtained using d.c. measuring techniques.

6. Conclusions.

Data for two impulse waveforms and three conditions of irradiation have shown that the uniform-field gap in air has breakdown characteristics which are independent of polarity and waveform, and that they can be repeated with consistent results. The time-lag characteristic gives a smooth curve even in the absence of deliberate irradiation, although the time-lag values are then greater. Comparative data for the sphere-gap indicate that irradiation is essential to consistent performance on impulse voltages.

Investigation of the static-voltage breakdown of the uniform-field gap in air has further emphasised the above consistent performance, and calibration figures, obtained for gap-spacings in the range 0.8 to 5 cm., satisfy, to within 0.15 percent, an emperical law of the form $V = AS + B\sqrt{S}$ kV., S being the spacing in cm. The presence of radium in the high-voltage electrode has no effect on the static breakdown figures, but a correction for humidity, of the order of + 0.15 percent change of breakdown voltage per gm/M^3 increase of absolute humidity, is indicated.

The impulse waveform restricts the maximum value of formative time-lag that can be recorded, owing to the fall of voltage on the wave tail. Since, for analytical purposes, it is essential that the formative time of the spark should /

should be observed down to very low overvoltages with respect to the static sparking potential, this has been done by static voltage measurements. Comparison of the static-voltage and impulse-voltage time-lag data indicates that the impulse ratio of the 2 cm. uniform-field gap relative to static sparkover is of the order of 1.01. In addition, the static time-lag data for the 1 cm. gap are in general agreement with the formative times predicted on the basis of the Townsend theory of sparkover, and, from this comparison, it would appear that the significant secondary ionization process operative in the experimental case considered was the liberation of electrons from the cathode predominantly by the incidence of photons, but that there was also some emission due to the incidence of positive ions. The linear relationship found to exist between time-lag and gap spacing, for a given percentage overvoltage, suggests no change in the spark mechanism evident for the 1 cm. gap in atmosphere (pd = 760 mm.Hg. cm.) to that for the 4 cm. gap (pd $\simeq$ 3000 mm.Hg.cm).

The direct comparison of the static time-lag data obtained by experiment and the values predicted by theory, was made possible by the estimation of the initial photo-ionization current (I_0) and the value of pre-breakdown current $[I_-(0,t)]$ indicating breakdown of the gap, for the /

the same experimental conditions. Further, the mean pre-breakdown current measurements, which, it is suggested, may represent the average of a series of rapid current pulses (avalanches), provide further evidence (qualitative) of the existence of a considerable secondary ionization effect within 1.5 percent of the sparking potential of 1 cm. and 2 cm. irradiated gaps at atmospheric pressure (pd $\simeq$ 760 and 1520 mm.Hg. cm. respectively).

Further elucidation of the questions raised in the above investigations requires that the experiments be conducted in a controlled atmosphere and with pure non-active gases.

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Time-lag data for spark discharges in uniform field gaps

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Formative time-lags of spark breakdown have been measured for air in uniform fields with static applied voltages up to 63 kV; and the very long time lags (greater than 10^{-4} s) predicted by theory for such conditions have been recorded. Time-lag data have also been obtained for air in uniform fields with impulse spark voltages up to 150 kV for standard impulse waveforms, and also for lower voltages with non-standard impulse waveforms. For the latter condition the data indicate an impulse ratio of the order of 1·01. Comparative data for sphere gaps are included.

Characteristics of the spark discharge provide the experimental data which must be satisfied by any theory of the spark mechanism, and the sparkover voltage under given conditions between spherical electrodes in air is a recognized standard(1) for high voltage measurement. With increasing knowledge of the factors that influence the sparkover voltage, and data for alternating, static and impulse voltages, it has become necessary to define more precisely the conditions appertaining to experimental data to be used to assess the validity of spark theory,(2) or to compile calibration tables. Two important factors are the irradiation of the gap to eliminate statistical time-lag T_s by providing an adequate supply of initiatory electrons, and the subsequent formative time-lag T_F required for the development of the discharge across the gap. The latter not only provides some indication of the active secondary ionization processes,(3) but must be taken into account when using a spark gap to measure rapidly varying voltages such as impulse waveforms. The present data relate to spark breakdown in the uniform field between parallel plane electrodes with suitably curved edges,(4) using static voltages and impulse voltages of various waveforms.

When impulse voltages of increasing magnitudes are applied to a gap, a value is first reached at which repeated impulses will produce only an occasional sparkover; at some higher value still there will be sparkover for each impulse applied. This change in voltage ($\Delta V\%$) between 0 and 100% frequency of sparkover is reduced by irradiation of the gap to eliminate T_s and consequently time-lags that are excessive relative to the time that an impulse voltage wave is maintained above a given voltage level. For present purposes, the requisite level of irradiation for uniform field gaps, whether by exposure to ultra-violet light or to the presence of a radioactive salt, has been taken as that giving the minimum value of $\Delta V\%$. Ultra-violet irradiation was obtained by mounting the gap in a fixed position relative to the trigger gaps of a multi-stage impulse plant, and radioactive irradiation by inserting a capsule of 0·5 mg radium equivalent in one of the electrodes. It was confirmed that either source alone, or both acting together, gave a value for ΔV of 0·8% for uniform field gaps, and this condition was frequently checked.(5) The same sources of irradiation were employed in comparative observations on a sphere gap, using spheres 6·25 cm in diameter. Uniform field electrodes having nominal voltage ranges up to 100 or 140 kV were used, but as sparkover up to these limits occurs in the uniform field region, no significant variation in the observed phenomena for the two sizes was found or was to be expected.

1/50 IMPULSE WAVEFORM DATA

Standard 1/50* waveforms(6) of either polarity were applied to irradiated uniform field gaps. By discharging the impulse generator when the stage capacitors were charged to a given voltage, which could be measured to an accuracy of about ±0·1%, it was possible to measure small changes in output voltage, and hence in ΔV, much more accurately than the determination of the peak impulse voltage which includes oscillography errors. The datum sparkover voltage was taken as that corresponding to the 0% limit of the ΔV range, and higher voltages within that range are expressed as corresponding percentage overvoltages.

The results for three gap spacings are shown in Fig. 1, in which the broken vertical lines denote typical scatter in the values of T_F. There is no observable variation with polarity or spacing. The full line gives the time for which the applied impulse waveform exceeded the datum level corresponding to 0% sparkover frequency, and most of the observed time-lags are in excess of this, indicating that a breakdown, which was presumably initiated during the overvoltage period, was completed after the wave tail had fallen slightly below the assumed datum. These results cannot include the long time-lags predicted by the Townsend theory(3) for low overvoltages,

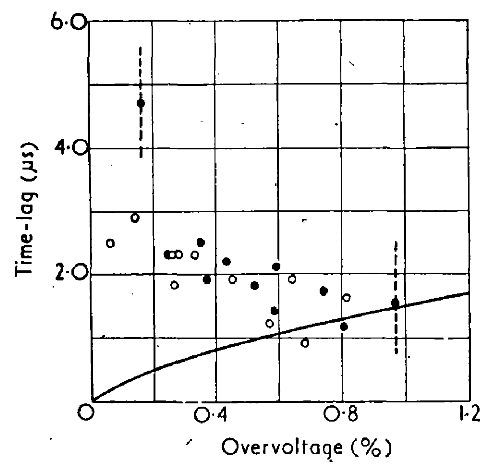

Fig. 1. Uniform field gap data for 1/50 impulse waves
○ = positive polarity
● = negative polarity
Gap spacings 1·34, 3·19, 5·68 cm (about 40 to 150 kV).

* A T_1/T_2 waveform is an impulse wave which reaches the crest value in T_1 μs and decays to half the crest value in T_2 μs.

because of the limitation imposed by the fall of voltage on the wave tail, and the mean values shown by the points can apply only to 1/50 waves, but this is a case of particular interest in high voltage testing procedure.

EFFECT OF IMPULSE WAVEFORM

0·2/240 and 1·2/240 waveforms were applied to a given gap; the results are shown by curves of mean values plotted in Fig. 2, and remarkably good curves were obtained, despite the range covered by the individual observations. The non-irradiated gap gave longer time-lags than for the irradiated

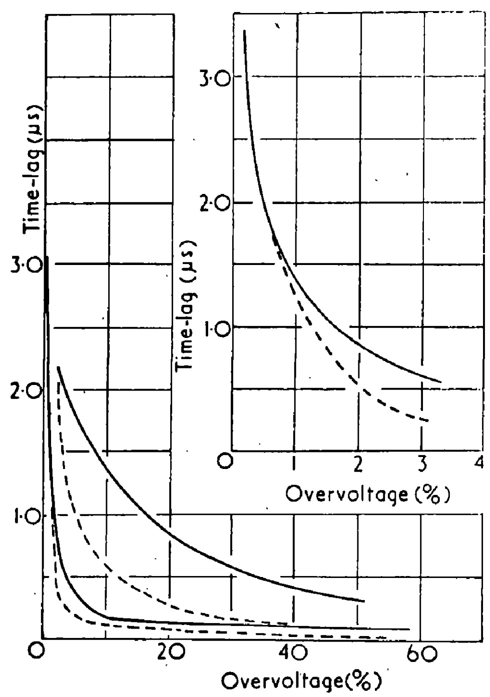

Fig. 2. Uniform field gap data for 2 cm spacing

—— = 1·2/240 waves
- - - = 0·2/240 waves

For each waveform the upper curve is for the non-irradiated gap, and the inset diagram is an enlarged portion of the curves for the irradiated gap.

condition, but the mean values were still very close to the curves drawn. An increased consistency in this respect relative to the sphere gap is to be expected, since uniformity of the field is maintained over a much greater area of cross-section, and the probability that fortuitous ionization will reduce T_s is thereby increased. There was no significant difference due to polarity, or for ultra-violet as compared with radium irradiation. The observations were extended to very high overvoltages giving the extremely low values of T_F frequently mentioned in the literature. Because of the very high overvoltages used, which are much in excess of the 100% sparkover criterion, the percentage overvoltage is defined as the ratio of the prospective peak value to the datum value, and the curves show that, for a given overvoltage, T_F is lower for the 0·2 μs wavefront, as would be expected from the greater rate of rise of voltage.

Comparative data for a sphere gap are shown in Fig. 3. Without irradiation the points are widely scattered; time-lag values for negative waves are greater than those for positive waves, and two of these lie outside the boundary of the figure. The inset figure shows reasonable consistency in the performance of the irradiated gap, with no apparent difference due to polarity or the method of irradiation.

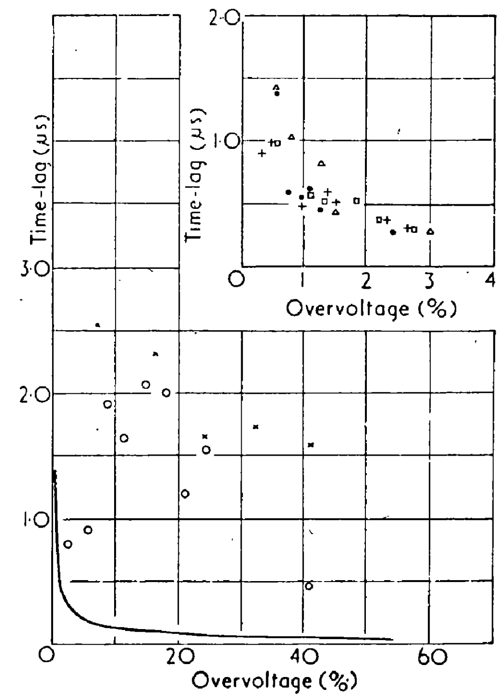

Fig. 3. Data for 6·25 cm diameter spheres at 2·0 cm spacing for 0·2/240 waves

—— = radium or ultra-violet irradiation
○ = positive waves, non-irradiated
× = negative waves, non-irradiated

The inset figure is an enlargement of the curve showing individual points for both polarities and both forms of irradiation.

STATIC TIME-LAG DATA

The use of static voltages overcomes the limitations imposed by an impulse waveform on the range of possible time-lags, and the static sparking potential is easily determined as a datum to which overvoltages can be related. A stabilized and smoothed static approach voltage some 2 kV below the sparking potential was applied to the gap, and on this was superimposed a pulse voltage of relatively low magnitude, and having a rise time of 0·16 μs on the front and a decay time-constant of about 0·2 s. The magnitudes of the approach voltage and the pulse voltage were measured independently by potentiometer methods having sensitivities of the order of 0·01%. The amplitude of the pulse voltage was increased at intervals of ten applications, the datum voltage being taken as the sum of the approach voltage and pulse voltage which just failed to give an occasional sparkover. The mean values of T_F for three gap spacings are indicated by the points on Fig. 4, the scatter of individual observations lying within a range of half to twice the mean value. For the smallest spacing the data link with those of Fisher and Bederson.[7] At very low percentage overvoltages long time-lags are obtained, and within the present range of values appear to increase without limit as the overvoltage approaches zero. The time-lags decrease rapidly at higher overvoltages, being of the order of 1 μs at 2% overvoltage. These values are of the nature and order that has been predicted by theory.[3]

The alternative plot of the data shown in Fig. 5 reveals a linear relationship between T_F and gap spacing for a constant percentage overvoltage, and the very high values of T_F at low overvoltages. Individual values of T_F up to some 400 μs were observed in the course of this work.

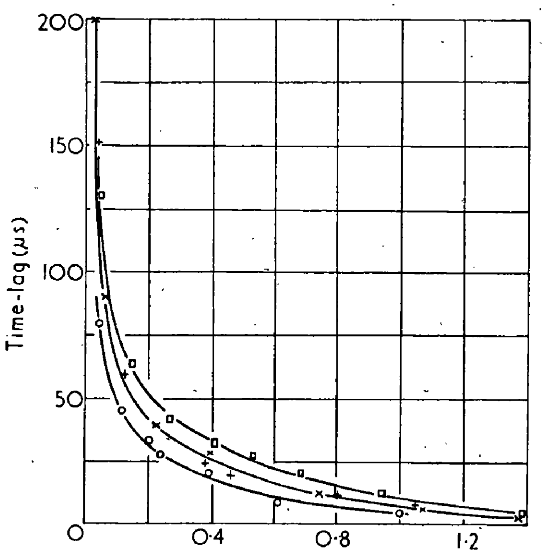

Fig. 4. Static data for irradiated uniform field gap, positive voltages

○ = 1·5 cm spacing
×+ = 2·0 cm spacing (two series)
□ = 2·4 cm spacing

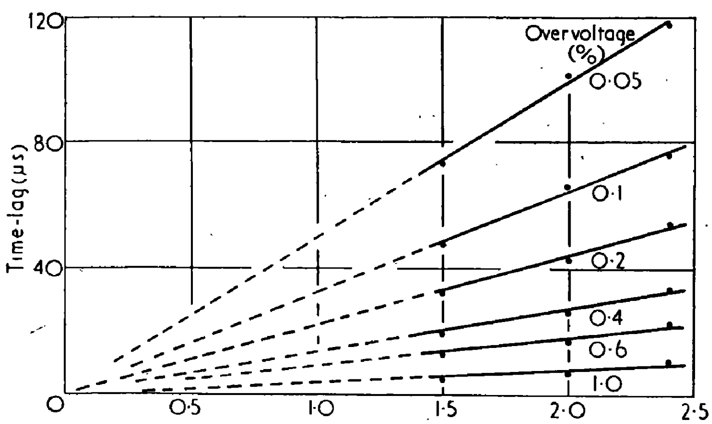

Fig. 5. Time-lag/spacing characteristics derived from Fig. 4

COMPARISON OF DATA FOR STATIC AND IMPULSE VOLTAGE

Corresponding values for a 2·0 cm gap are shown in Fig. 6. For a given impulse wave, the overvoltage will have to be sustained for a time of the order of the minimum T_F before breakdown can occur, and the 0% sparkover criterion taken as the datum sparking voltage in this work will therefore be in excess of the static datum, for which there is no imposed time limit due to waveform. In the inset figure, the horizontal full line represents the impulse datum voltage; the static datum will be at some lower value as indicated by the dotted line. A given impulse overvoltage, as defined in the above data, therefore corresponds to a higher overvoltage when referred to the static datum; an effect which can be termed the impulse ratio of the gap, and accounts for the difference between the curves of Fig. 6. If the difference between the impulse and static datum voltages is assumed to be 1·15%, and the impulse overvoltages are adjusted to the static datum, the characteristic then coincides exactly with that obtained with static voltages, as shown by the transfer points on Fig. 6. For the 0·2/240 waveform used, therefore, the impulse ratio of the gap relative to static sparkover is of the order of 1·01.

In most laboratories, the impulse voltages available are much in excess of the static voltages, and the only measurable datum for specifying overvoltage is that used in the present impulse tests—the 0% sparkover criterion. This has been shown to be greater than the static sparking potential, which is the datum used for static measurements, and that which

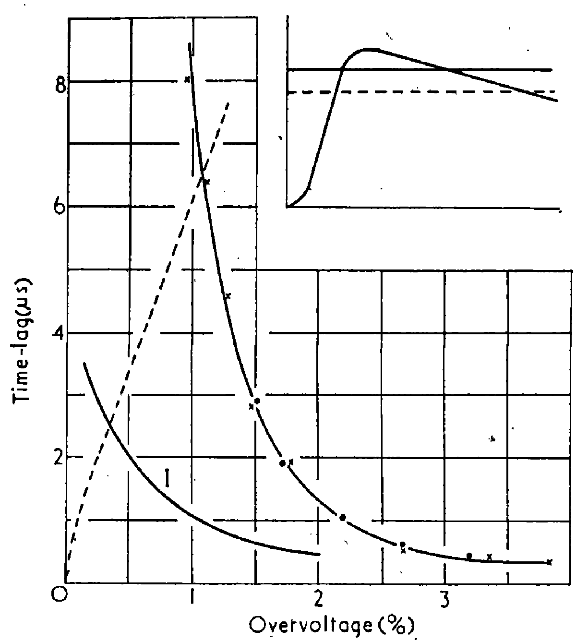

Fig. 6. Comparison of static and impulse time-lag data for an irradiated uniform field gap (2 cm spacing)

I = impulse characteristic for 0·2/240 waveform
× = observed points from d.c. characteristic
● = points transferred from I
- - - = duration of impulse waveform overvoltage

On the inset figure, the full and dotted horizontal lines illustrate relative levels for minimum sparking voltage on impulse and static voltages respectively.

must be considered when relating the data to the theory of the spark mechanism. In the impulse case, a low percentage overvoltage with a steep wavefront has to be written as some 1% higher when referred to the static datum. Irrespective of waveform restrictions, work which is confined to impulse voltage measurements could not therefore be expected to reveal the high values for T_F predicted by theory for very small overvoltages. Nevertheless, the impulse data do give the conditions, however restricted, that will be encountered in impulse voltage measurements.

CONCLUSIONS

Data for three impulse waveforms, including the 1/50 wave, have shown that the uniform field gap in air has sparkover characteristics that are independent of polarity, and that they can be repeated with consistent results. The time-lag characteristic gives a smooth curve even in the absence of external irradiation, although the time-lag values are then greater. Comparative data for a sphere gap show that irradiation is essential to consistent performance on impulse voltages. The level of irradiation required to obtain minimum time-lags with a uniform field gap is conveniently defined as that giving the minimum voltage range between 0 and 100% frequency of sparkover, and this is not difficult to check, in practice.

The impulse waveform restricts the maximum values of T_F that can be observed, owing to the fall of voltage on the wave tail. For analytical purposes, the values of T_F must be observed down to very low overvoltages with respect to the static sparking potential, and this has been done by static voltage measurements, and with results that agree with the order of values predicted by theory. All aspects of the work described in this paper are now being studied at considerably higher voltages.

ACKNOWLEDGEMENT

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(4) Bruce, F. M. *J. Instn Elect. Engrs*, **94**, p. 138 (1947).
(5) Bruce, F. M. *Endeavour*, **13**, p. 61 (1954).
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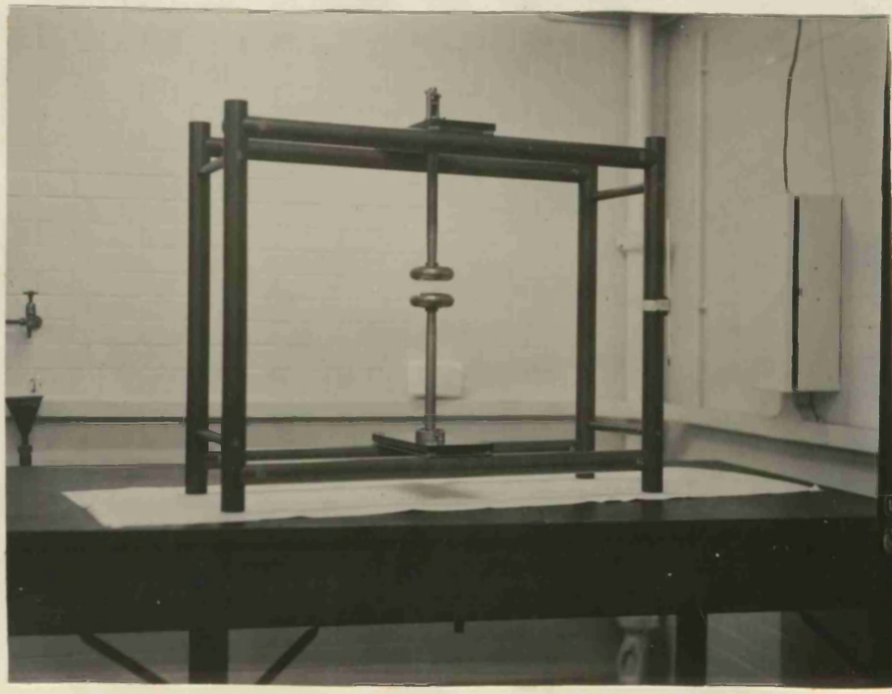


Plate 3.1. - Electrode Supports.

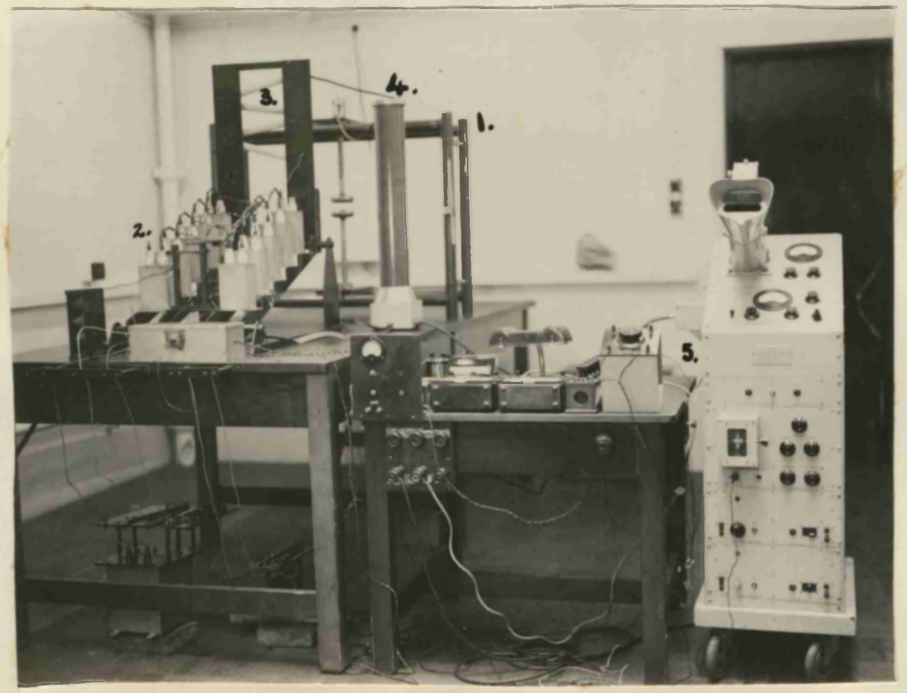


Plate 3.2. - Assembly of Apparatus for Impulse Tests.

1. Electrode supports.
2. Impulse generator, showing ladder arrangement of capacitors.
3. Impulse wavefront resistors.
4. Capacitance divider.
5. High-speed oscillograph.

Plate 3.3(a). - Oscillogram of 0.2/240 waveform.
Timing Oscillation 5Mc/S.

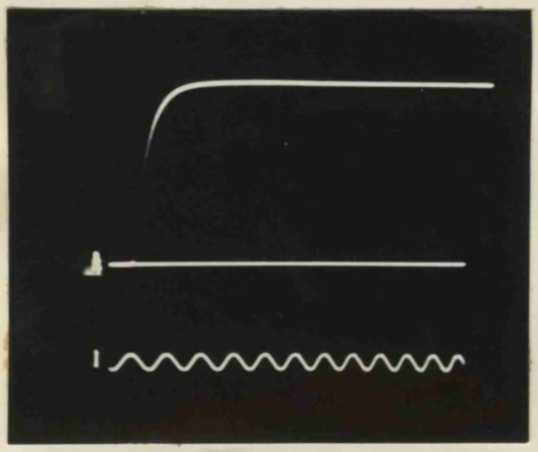


Plate 3.3(b). - Oscillogram of 1.2/240 waveform.
Timing Oscillation 1Mc/S.

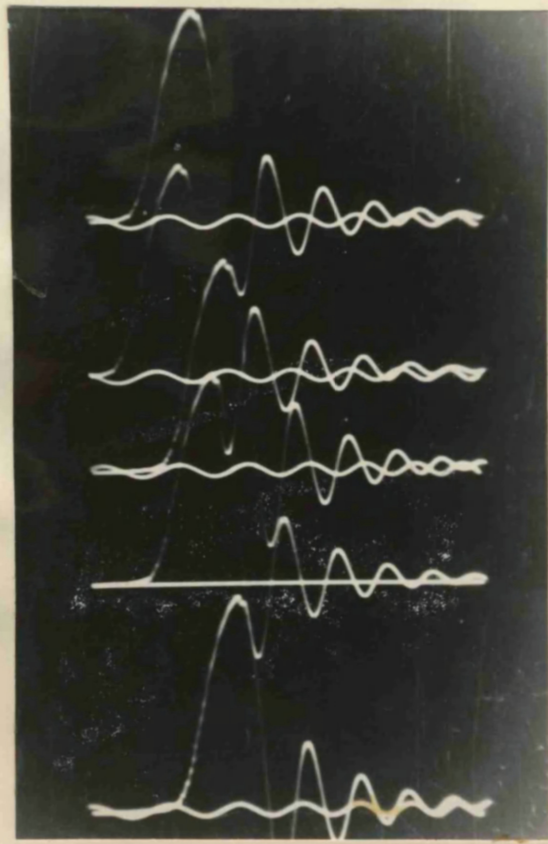


Plate 3.4(a). - Series of Oscillograms of Breakdown of Irradiated Uniform-field Gap (2 cm. spacing). 0.2/240 Waves applied. Timing osc. 5Mc/S.

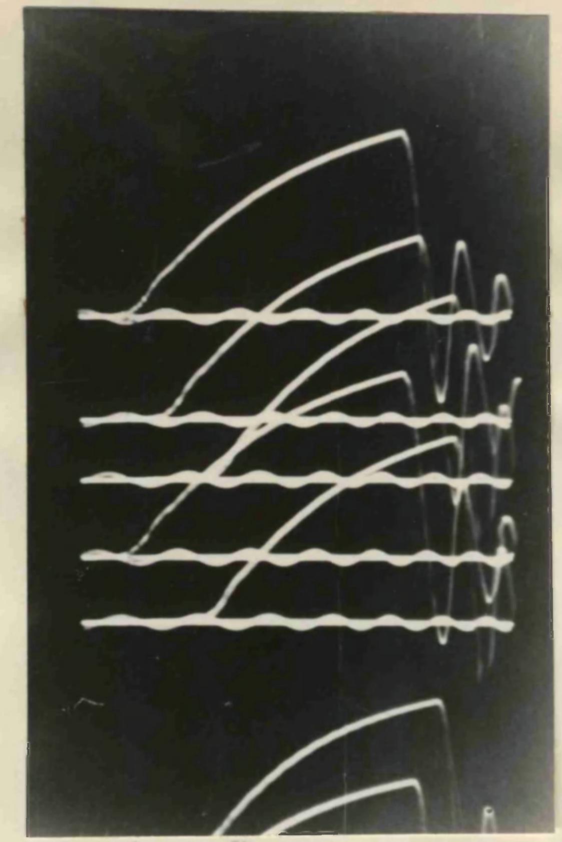


Plate 3.4(b). - Series of Oscillograms of Breakdown of Irradiated Uniform-field Gap (2 cm. spacing). 1.2/240 Waves applied. Timing osc. 5Mc/S.

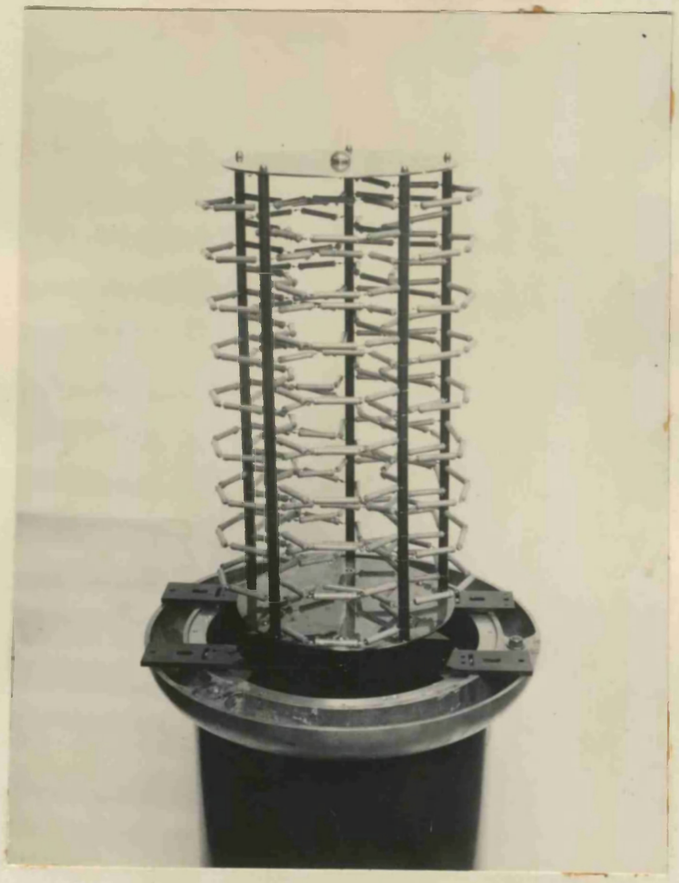
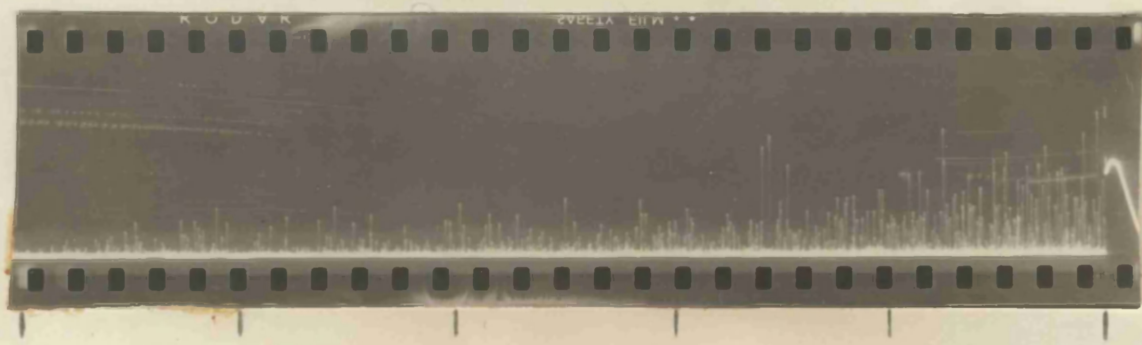


Plate 4.1. - High-voltage Measuring
Resistor.

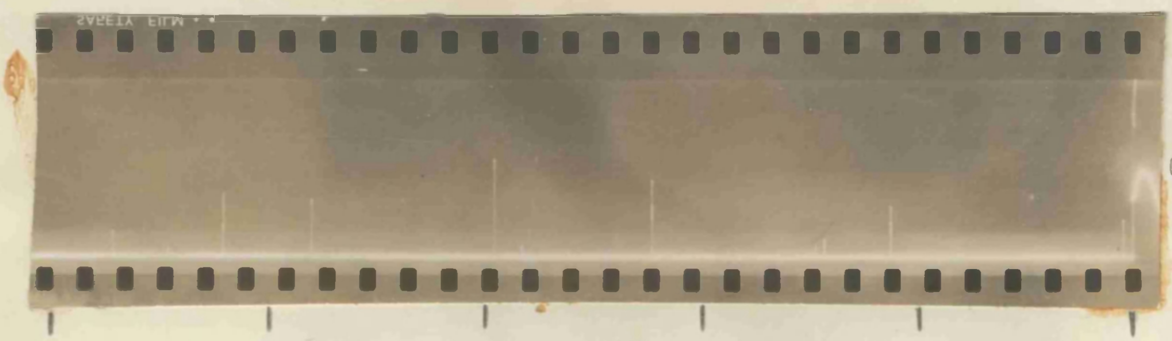
(a) Irradiated.



Current.

1/10th Secs.

(b) Unirradiated.



Current.

1/10th Secs.

Plate 5.1. - Moving-film oscillograms of current pulses in 1 cm. gap. Film speed 10"/sec.

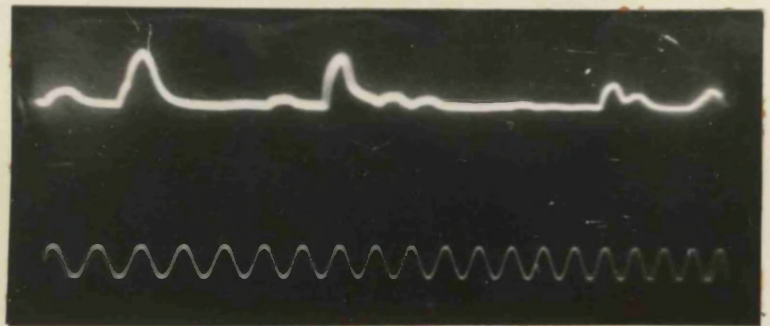


Plate 5.2. - Oscillogram of current pulses in 1 cm. irradiated gap. Sweep = 400 μS. Timing oscillation = 50 Kc/s.

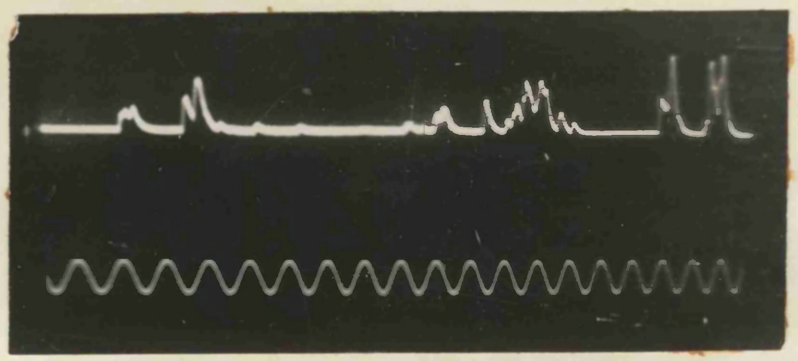


Plate 5.3. - Oscillogram of light pulses in 1 cm. irradiated gap. Sweep ≐ 400 μS. Timing oscillation = 50 Kc/s.

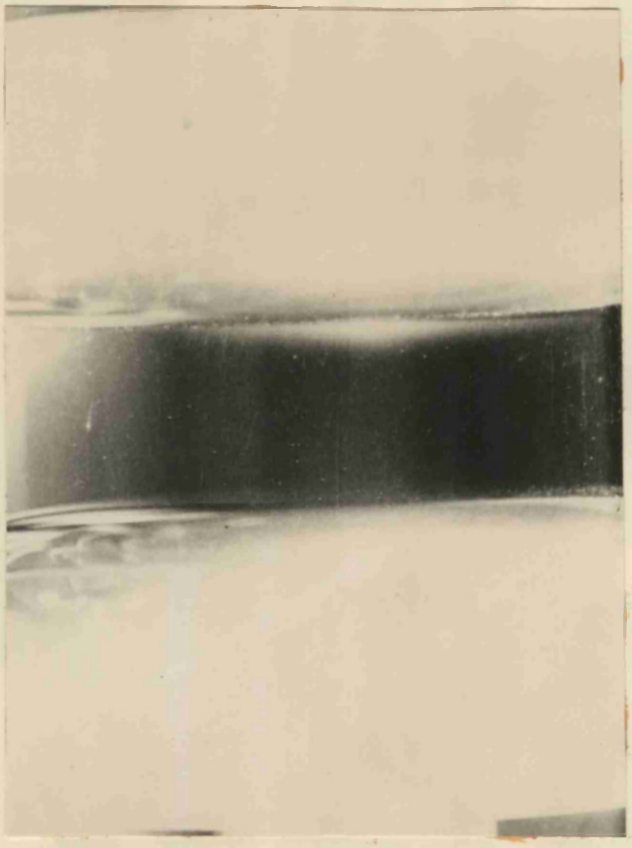


Plate 5.4. - Showing glow on positive (upper) electrode.

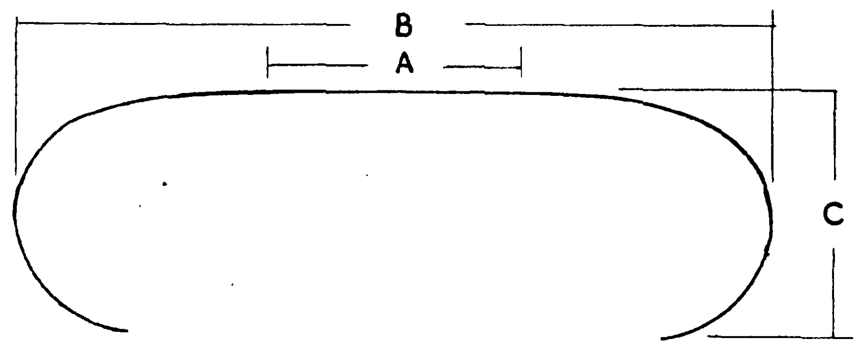
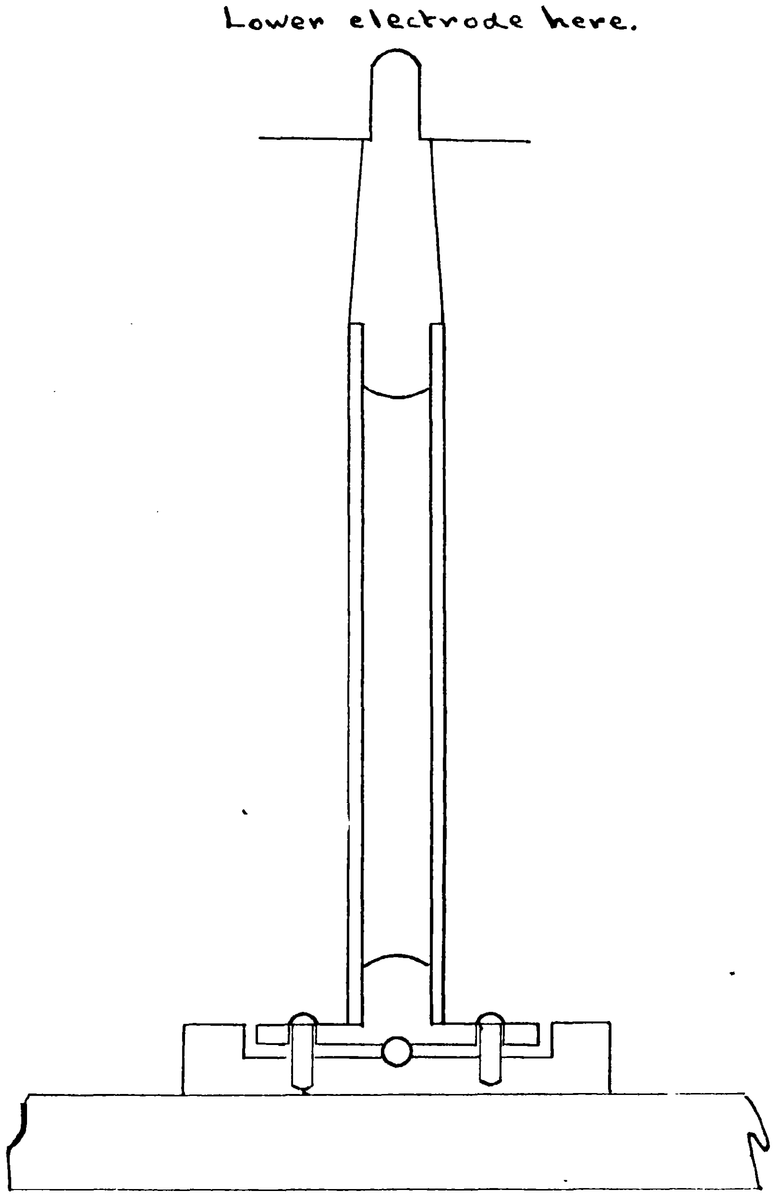
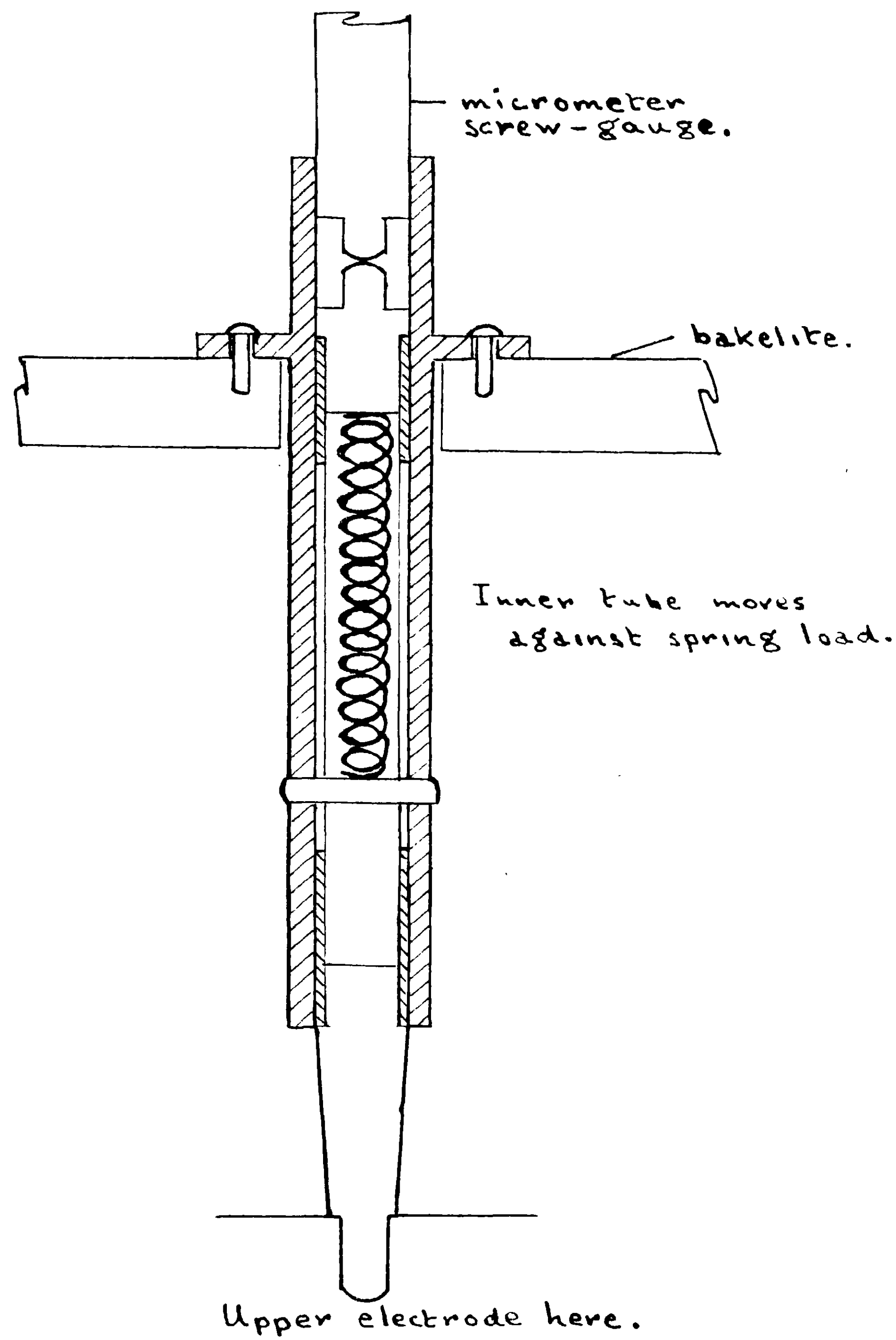


Fig. 3.1. Dimensions of Uniform-field Electrodes.

Maximum Voltage 100 kV; A = 1.44 ins., B = 4.16 ins.,
C = 1.34 ins.

Maximum Voltage 140 kV; A = 2.25 ins., B = 6.5 ins.,
C = 2.1 ins.


Lower electrode here.


micrometer screw-gauge.
bakelite.
Inner tube moves against spring load.
Upper electrode here.

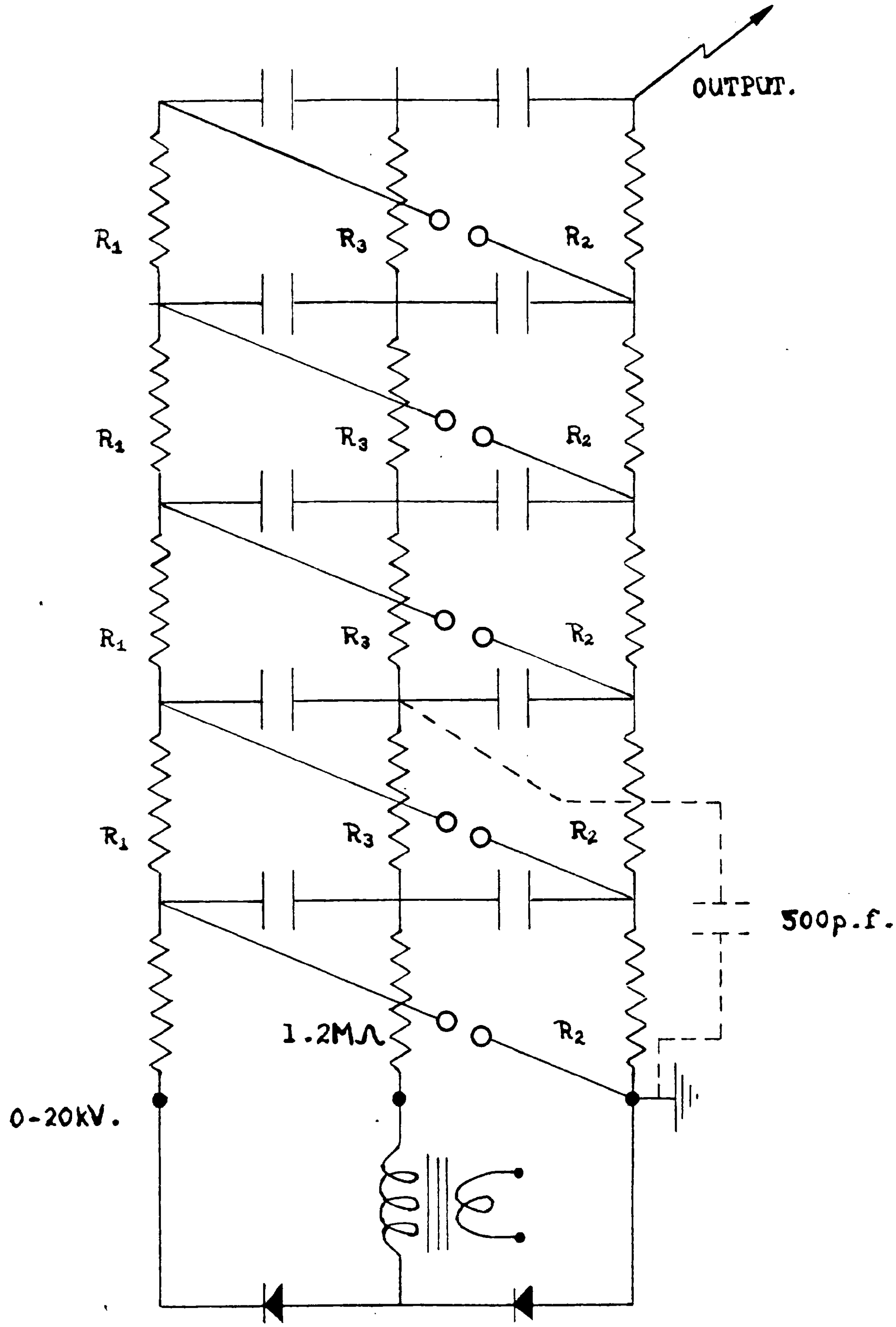


Fig. 3.3. Impulse Generator Circuit.

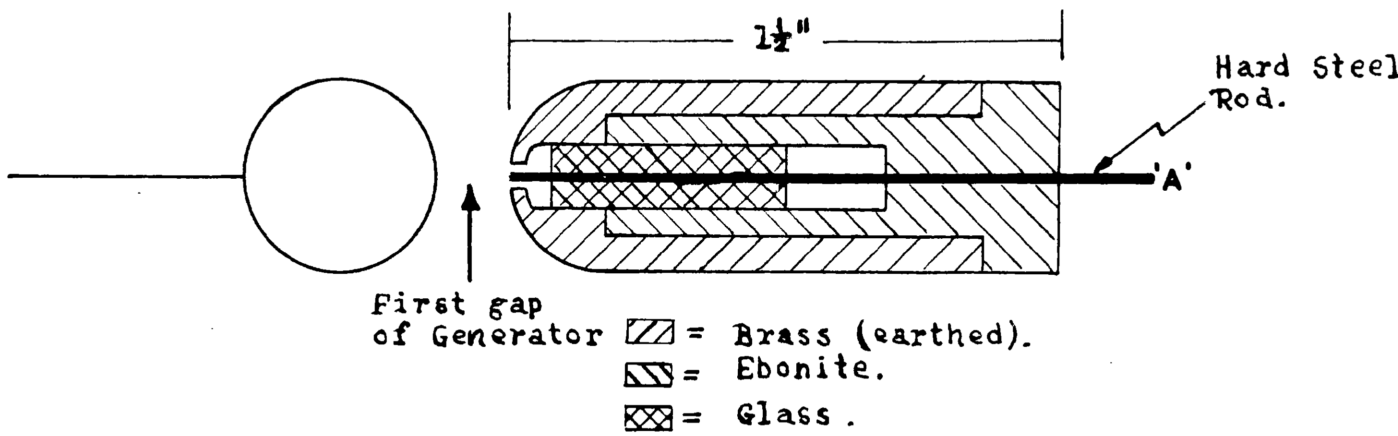


Fig. 3.4. First gap of Impulse generator showing details of "Trigger-gap".

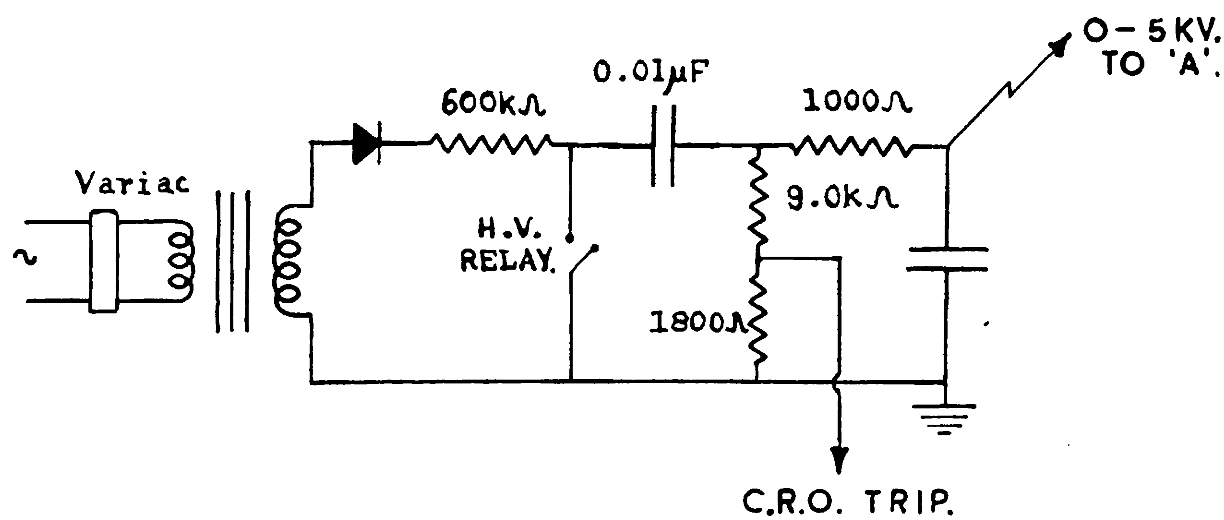


Fig. 3.5. Impulse Generator Tripping Circuit.

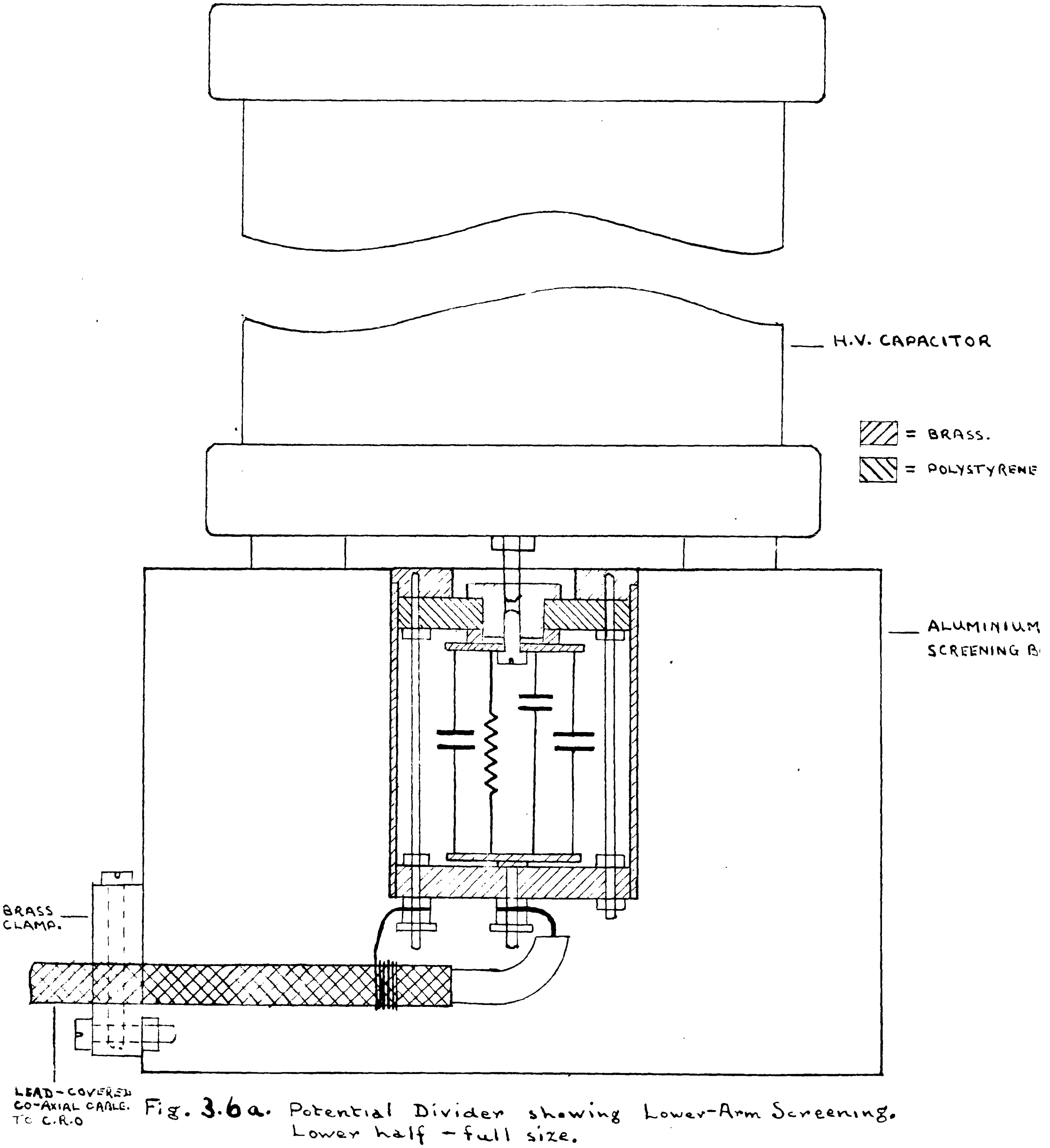


Fig. 3.6a. Potential Divider showing Lower-Arm Screening.
Lower half - full size.

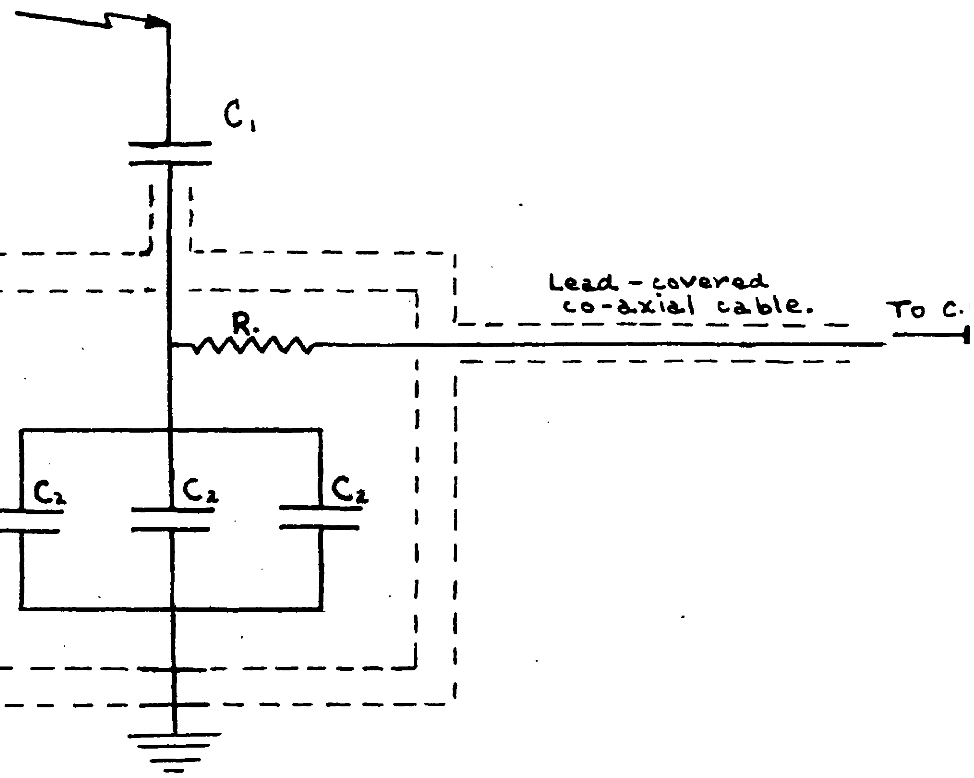


Fig. 3.6b. Potential-divider circuit showing screening arrangement.

C_1 = 200 p.f., 150 kV. discharge rating.

C_2 = 0·01 μF, 1000 V. working.

R = matching resistor, about 70 Ω.

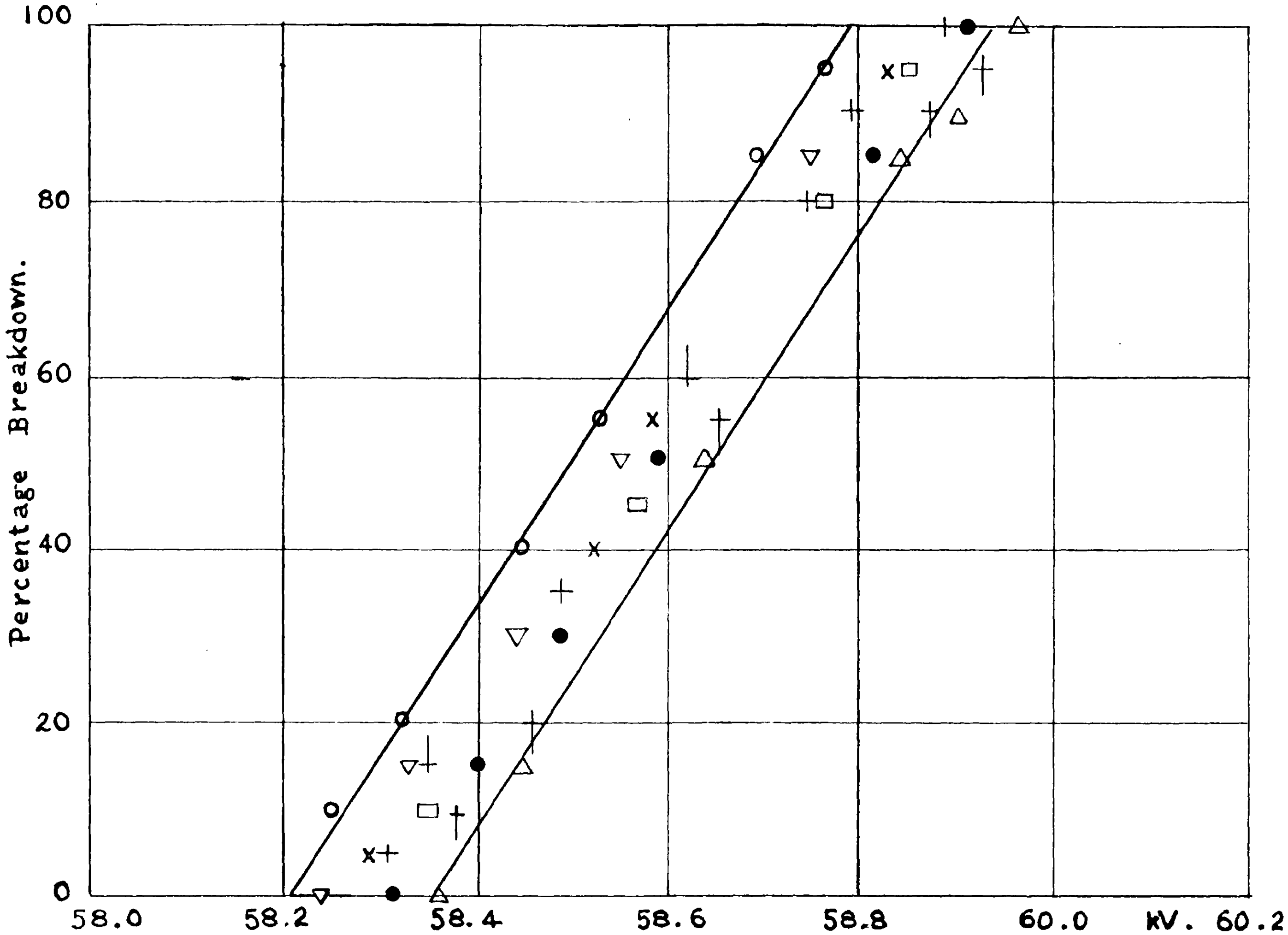


Fig. 3.7. 2cm gap between Uniform-field Electrodes - 0.2/240 waveform.

	Impulse Polarity	Irradiation	Humidity - gm/M³
●	Positive	Ultra-violet	9.1
o	do.	do.	7.8
△	do.	do.	9.3
▽	do.	do.	8.1
x	Negative	do.	8.5
□	Positive	Radium (U.V. [illegible])	[illegible]

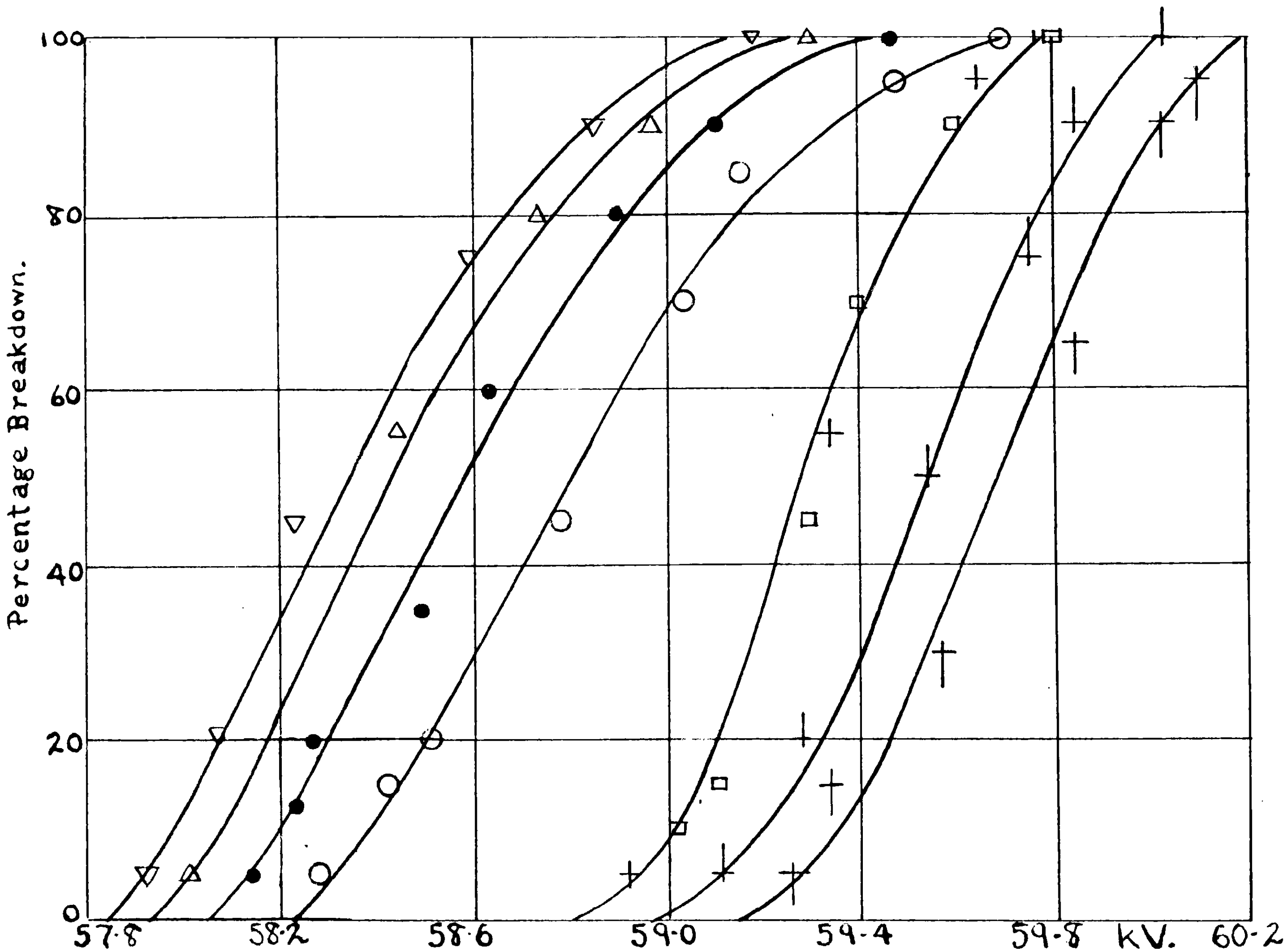


Fig. 3.8. 2cm gap between 6.25cm diam. spheres - $^{0.2}/_{240}$ waveform.

	Impulse Polarity	Irradiation	Humidity gm/M³
●	Positive	Ultra-violet	8.1
○	Negative	do.	8.8
△	Positive	do.	7.0
▽	Negative	do.	7.3
□	Positive	Radium(H.V.Elect.)	9.5
+	Ne[illegible]		

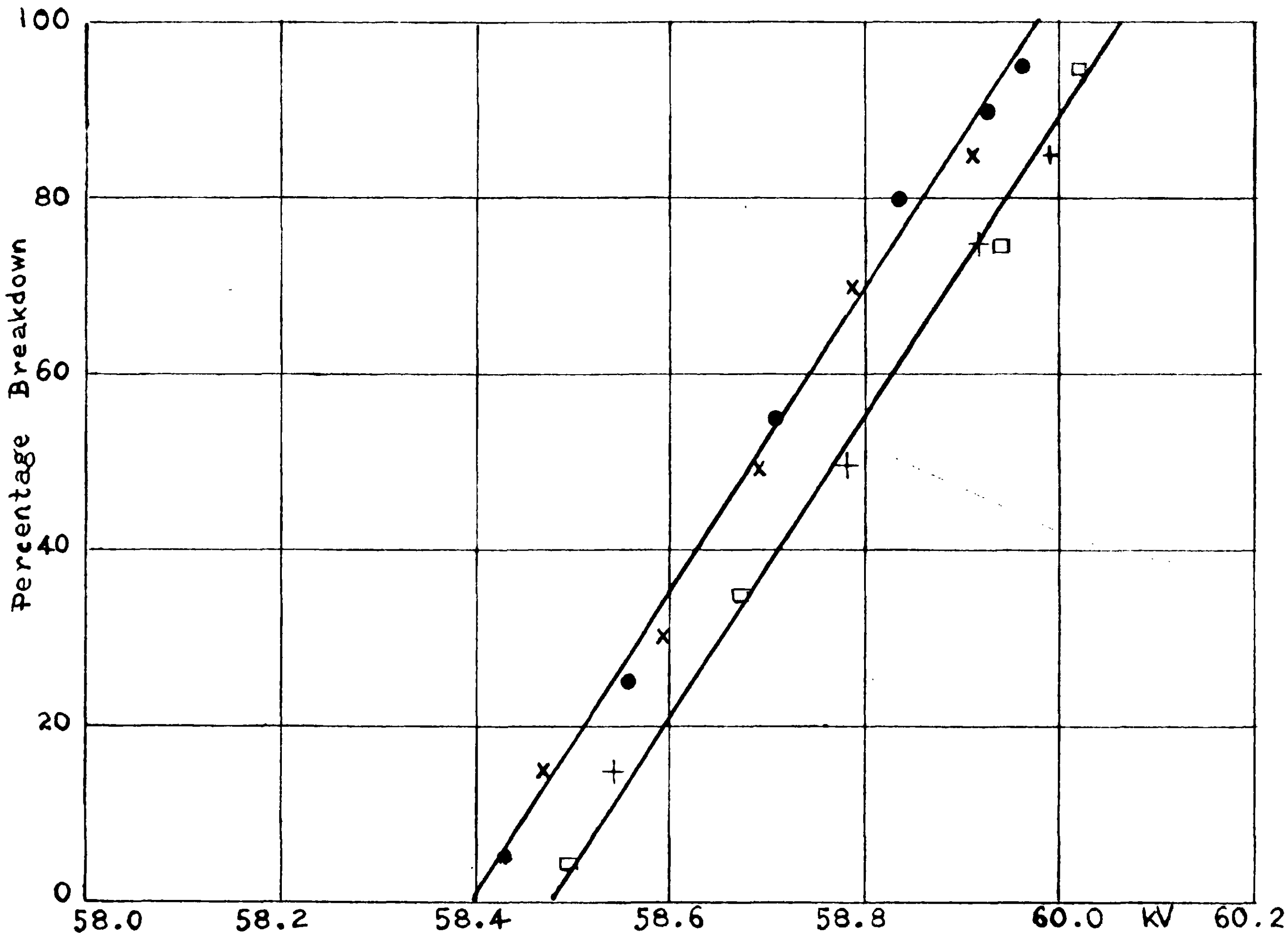


Fig.3.9. 2cm gap between Uniform-field Electrodes. - 1.2/240 waveform.

	Impulse Polarity	Irradiation	Humidity - gm/M³
●	Positive	Ultra-violet	10.0
x	Negative	do.	10.0
□	Positive	Radium(H.V.Elect.)	11.2
+	Negative	do.	11.2

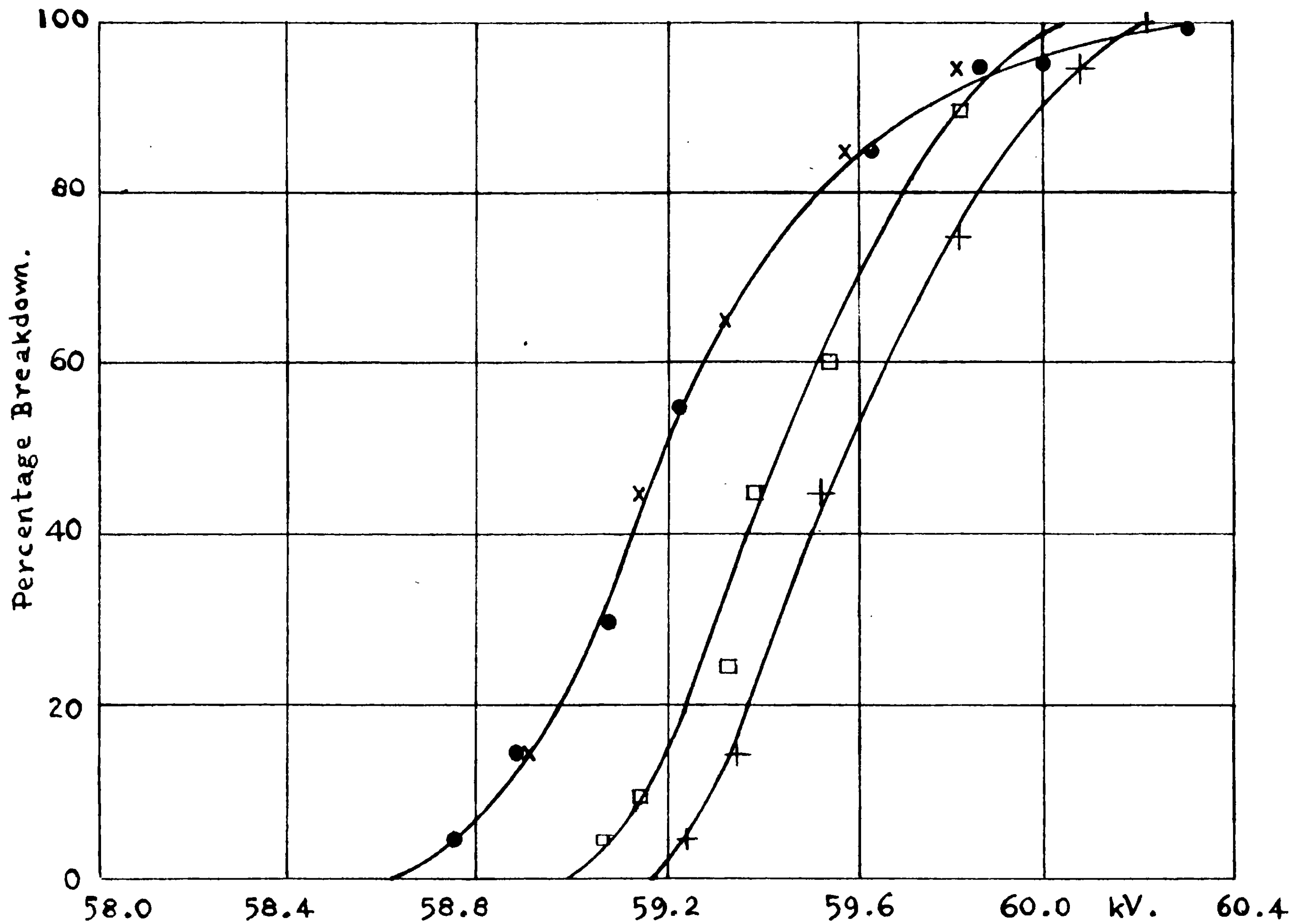


Fig. 3.10. 2cm gap between 6.25cm diam. spheres - 1.2/240 waveform.

	Impulse Polarity	Irradiation	Humidity - gm/M³
●	Positive	Ultra-violet	9.9
x	Negative	do.	9.9
□	Positive	Radium(H.V.Elect)	10.5
+	Negative	do.	11.0

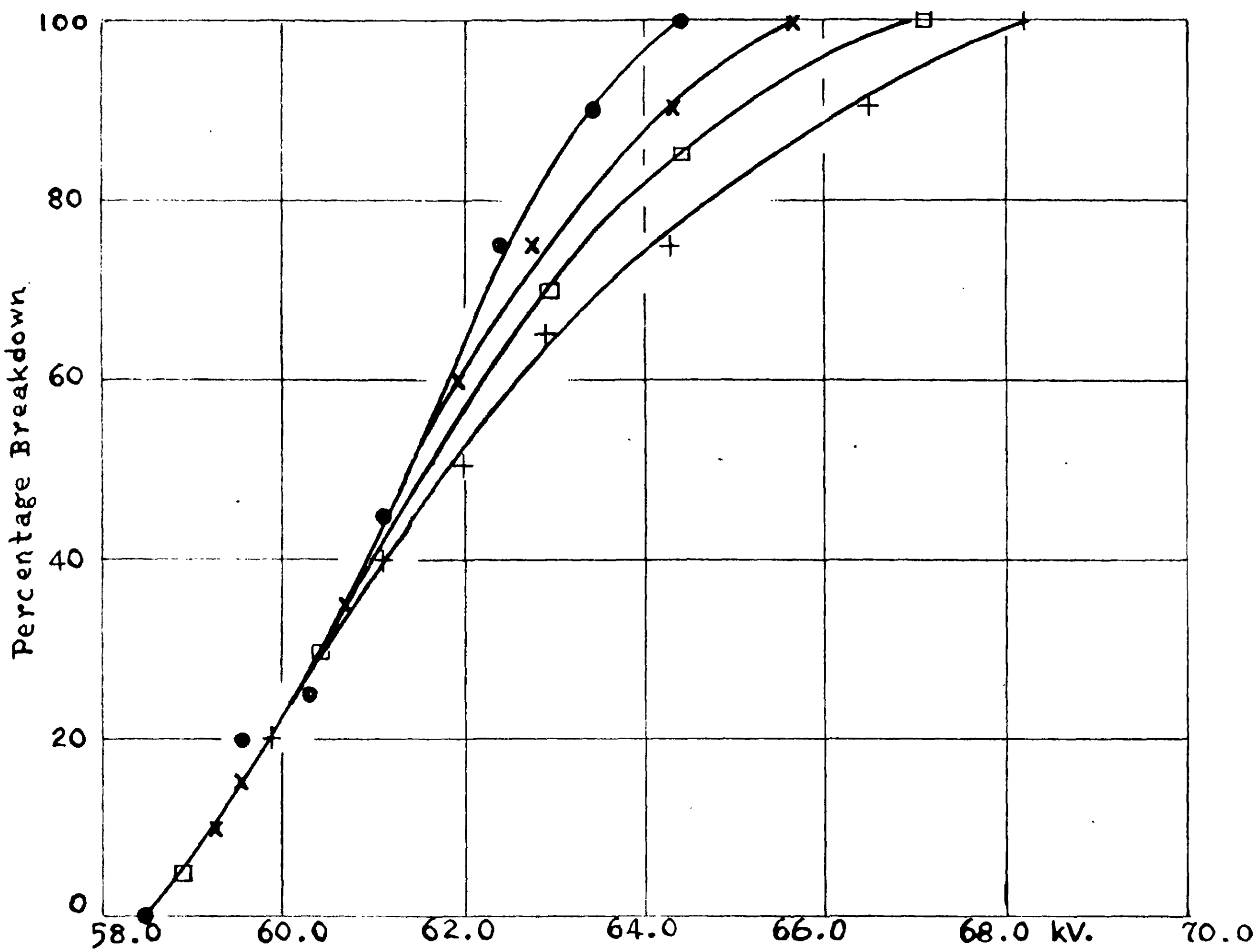


Fig. 3.11. 2cm gap between Uniform-field Electrodes.- Non-irradiated.

	Impulse Waveform.	Impulse Polarity.	Humidity. gm/M³
●	0.2/240	Positive	8.5
x	do.	Negative	8.2
□	1.2/240	Positive	8.7
+	do.	Negative	8.7

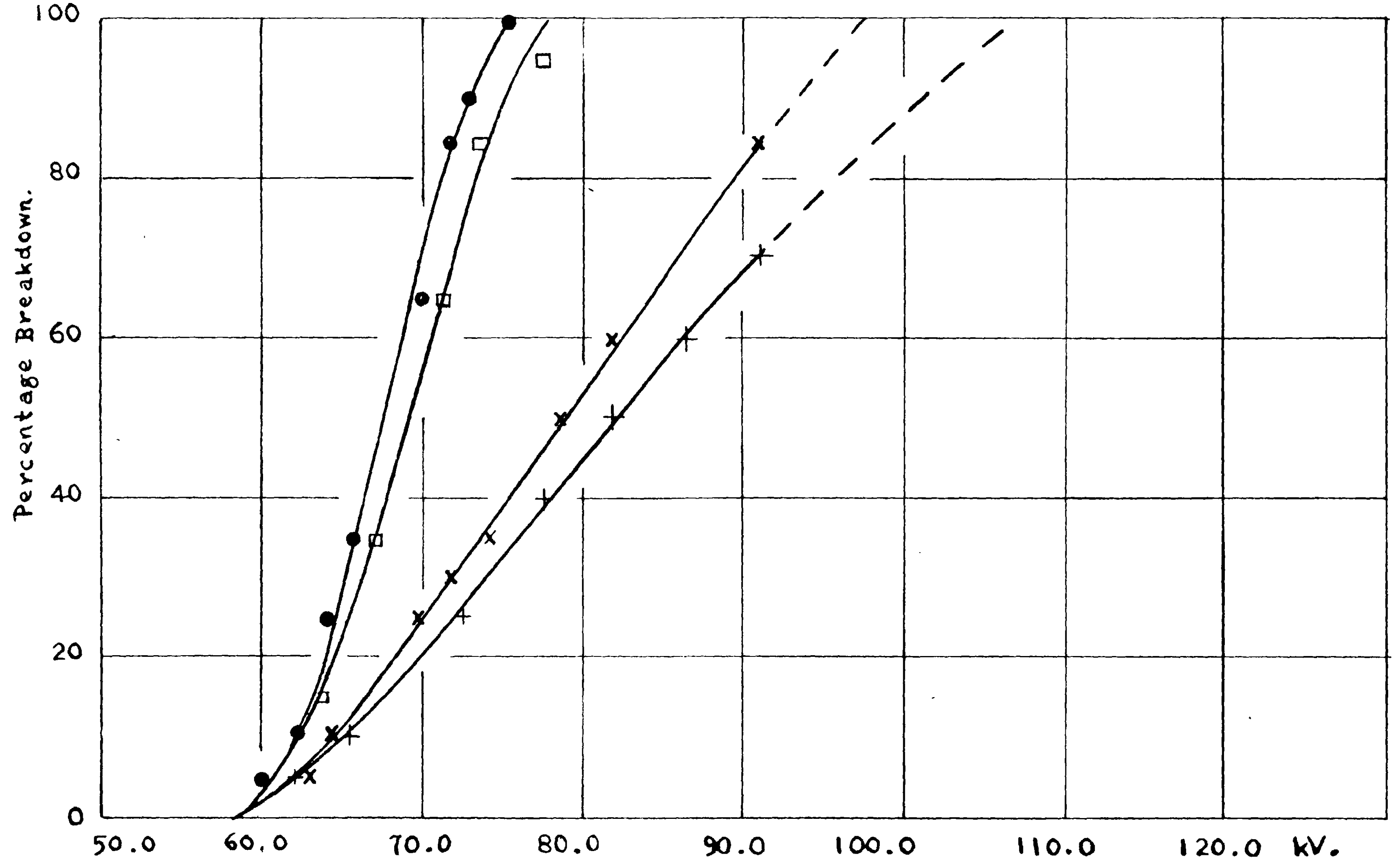
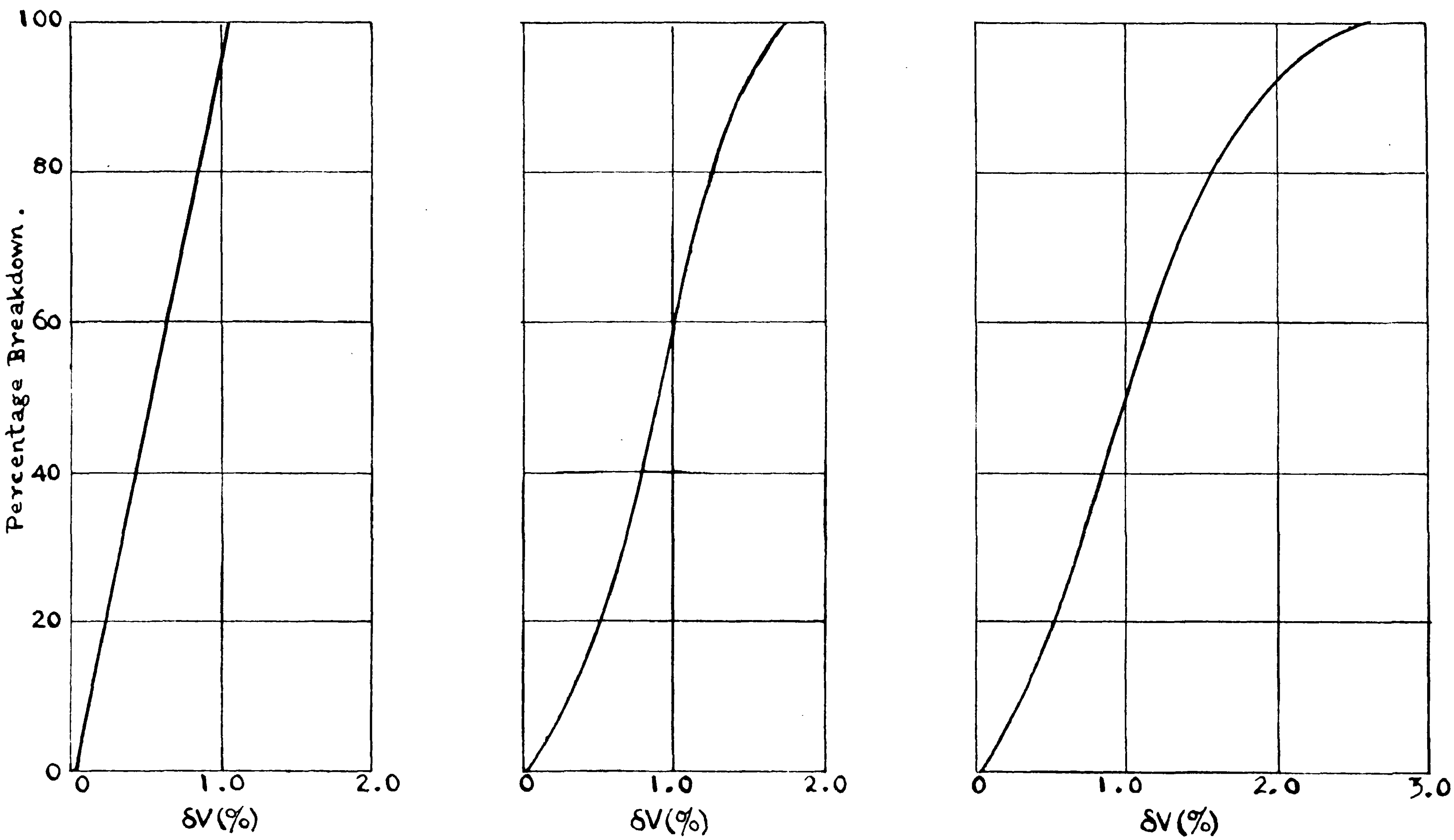


Fig. 3.12. 2cm gap between 6.25 cm diam spheres, non-irradiated.

	Impulse Waveform	Impulse Polarity.	Humidity gm/M³
●	0.2/240	Positive	9.0
x	do.	Negative	9.2
□	1.2/240	Positive	9.4
+	do.	Negative	9.6



2 cm gap between uniform-field electrodes.

Radium or Ultra-violet irradiation.

2 cm gap between 6.25 cm.dia. spheres.

Radium irradiation.

2 cm gap between 6.25 cm dia. spheres.

Ultra-violet irradiation.

Fig. 3.13. -Transition curves for 0.2/240 waveform.

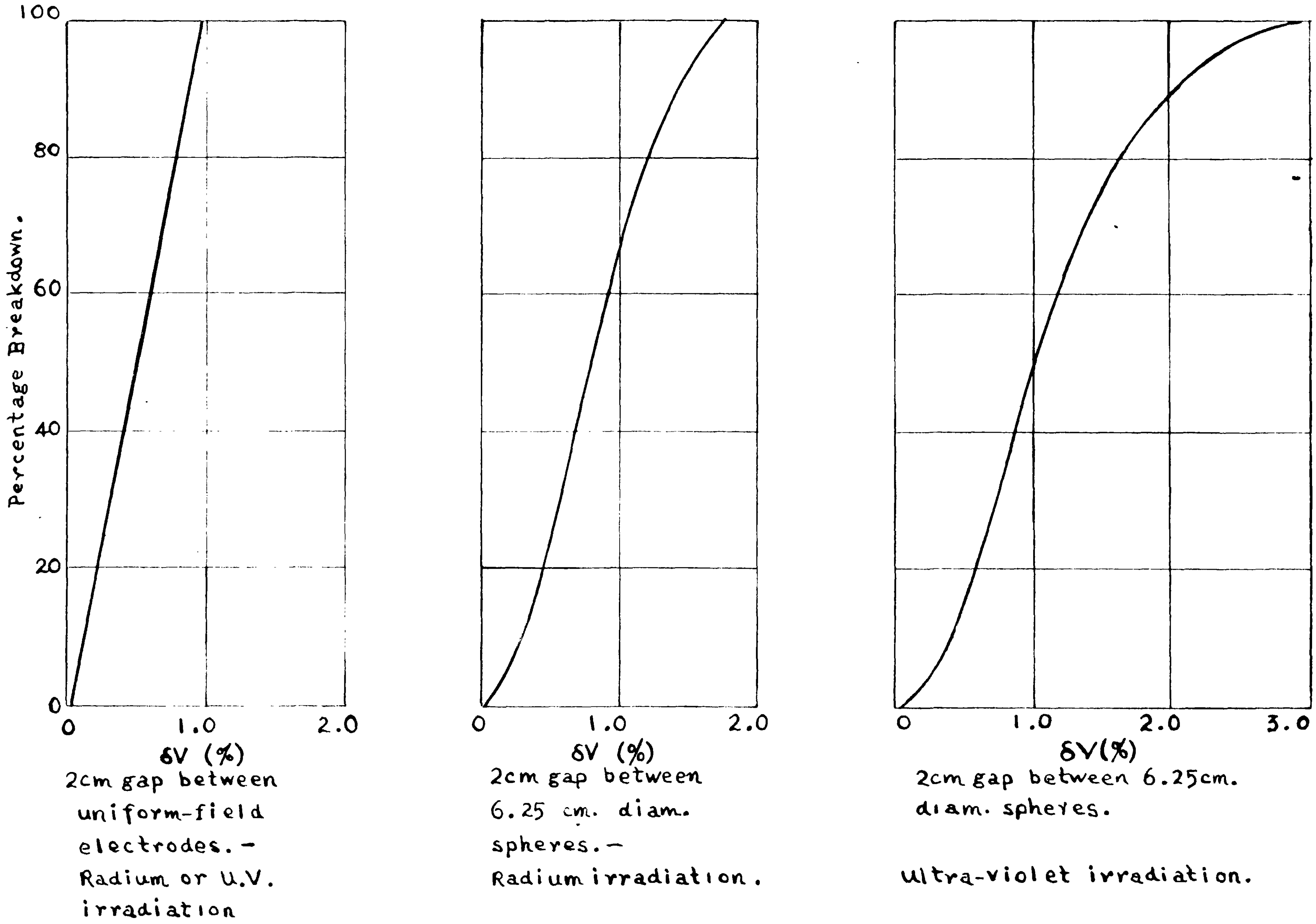


Fig. 3.14. Transition Curves for 1.2/240 waveform.

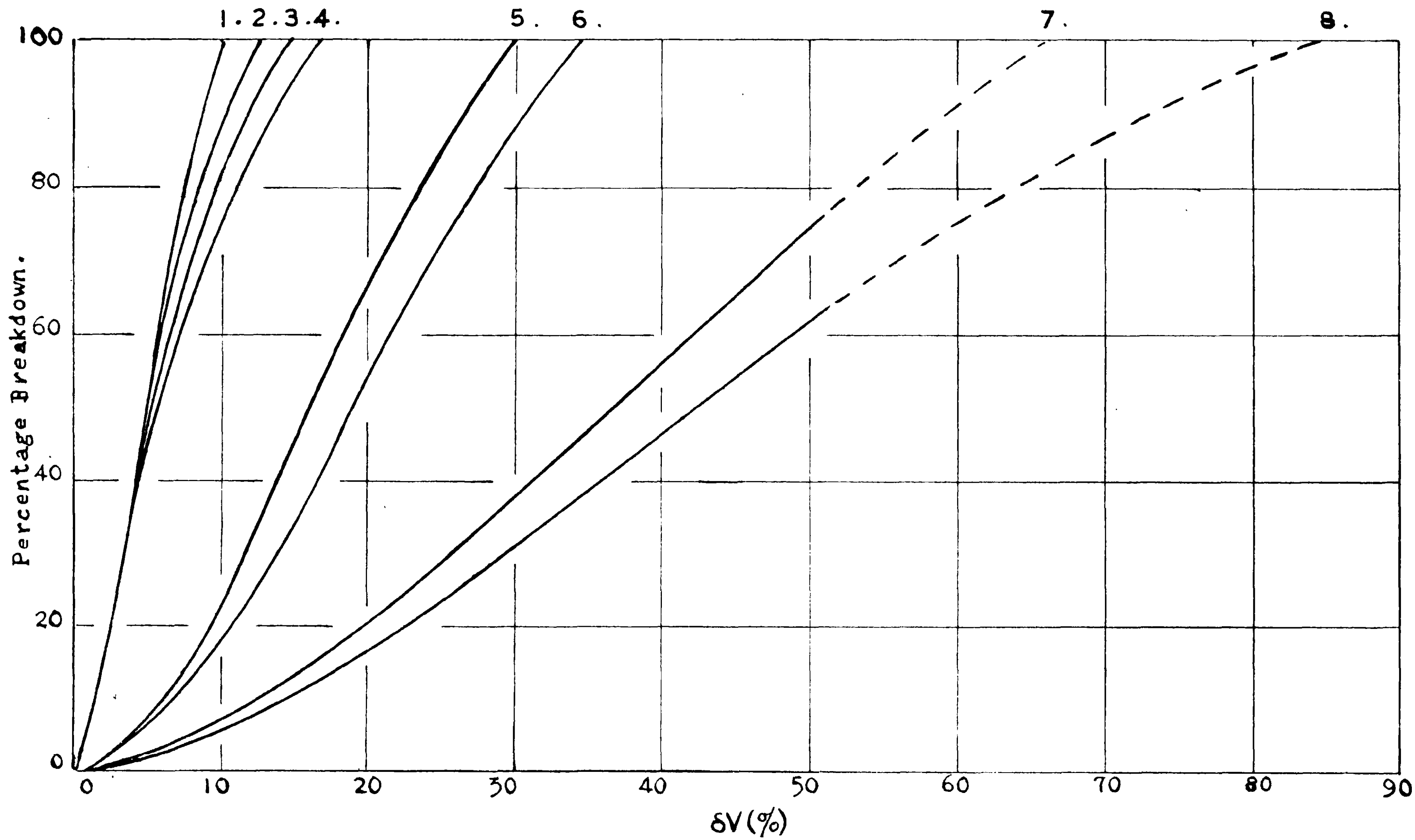


Fig. 3.15. - Transition curves for 2 cm gap, non-irradiated.

	Electrodes	Impulse Waveform	Impulse Polarity
1	Uniform field	0.2/240	Positive.
2	do.	do.	Negative
3	do.	1.2/240	Positive
4	do.	do.	Negative
5	6.25cm. spheres	0.2/240	Positive
6	do.	1.2/240	do.

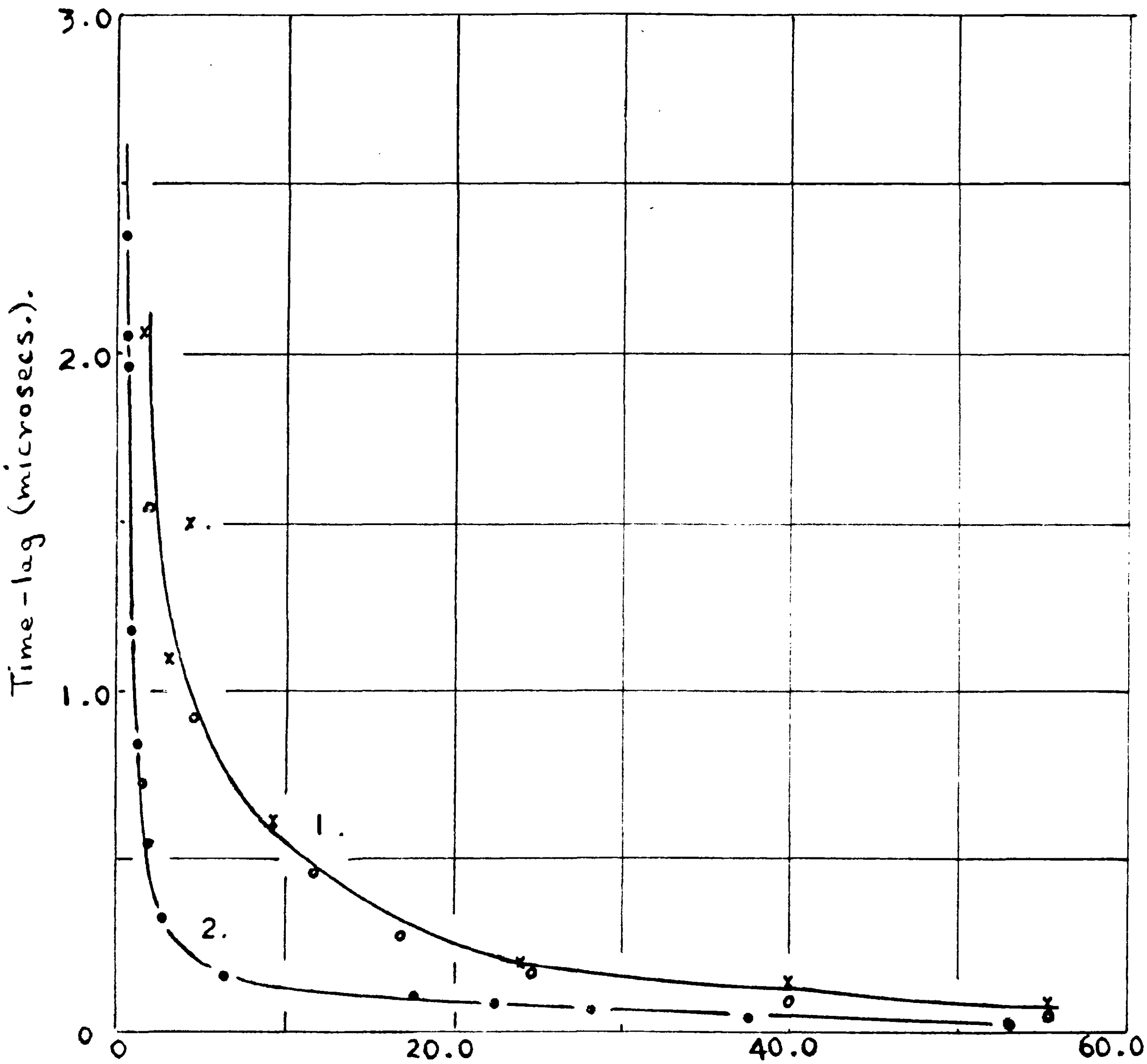


Fig. 3.16. Time-lag data for uniform-field gap (2 cm spacing) - 0.2/240 impulse waveforms applied.

1. - Non-irradiated, o = positive impulse, x = negative impulse.

2. - Irradiated - points shown only for U.V. irradiation with positive impulse applied. Other experimental conditions do not deviate from this curve.

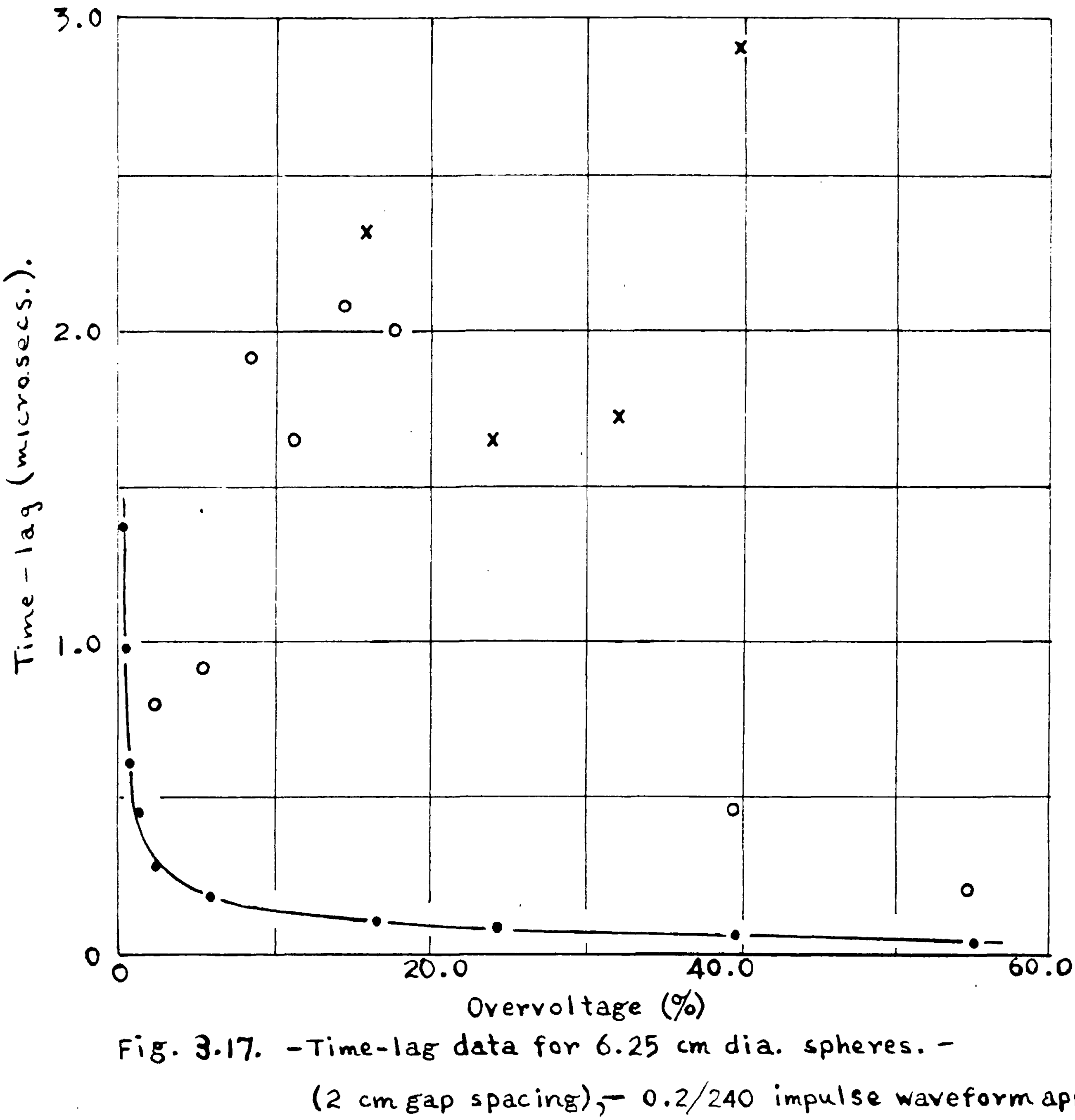


Fig. 3.17. -Time-lag data for 6.25 cm dia. spheres. - (2 cm gap spacing), - 0.2/240 impulse waveform applied.

——— = radium or ultra-violet irradiation, positive or negative impulses applied; points shown only for radium with + waves.

o = non-irradiated, positive waves;
x = non-irradiated, negative waves.

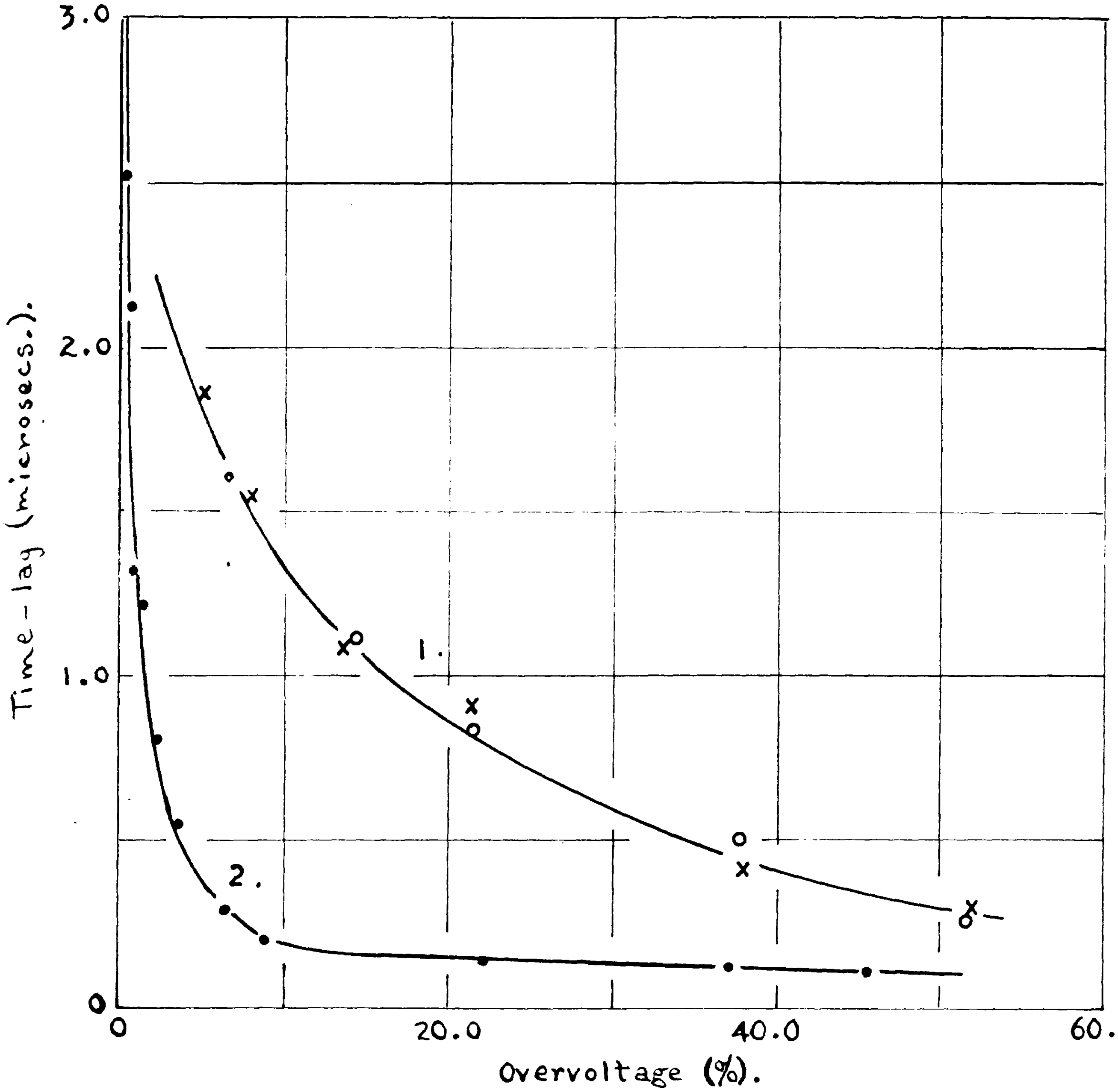


Fig. 3.18. -Time-lag data for uniform-field gap (2 cm spacing);- 1.2/240 impulse waveforms applied.

1. - Non-irradiated; o = positive impulse, x = negative impulse.

2. - radium or ultra-violet irradiation, positive or negative impulses applied; points shown only for U.V. with + waves.

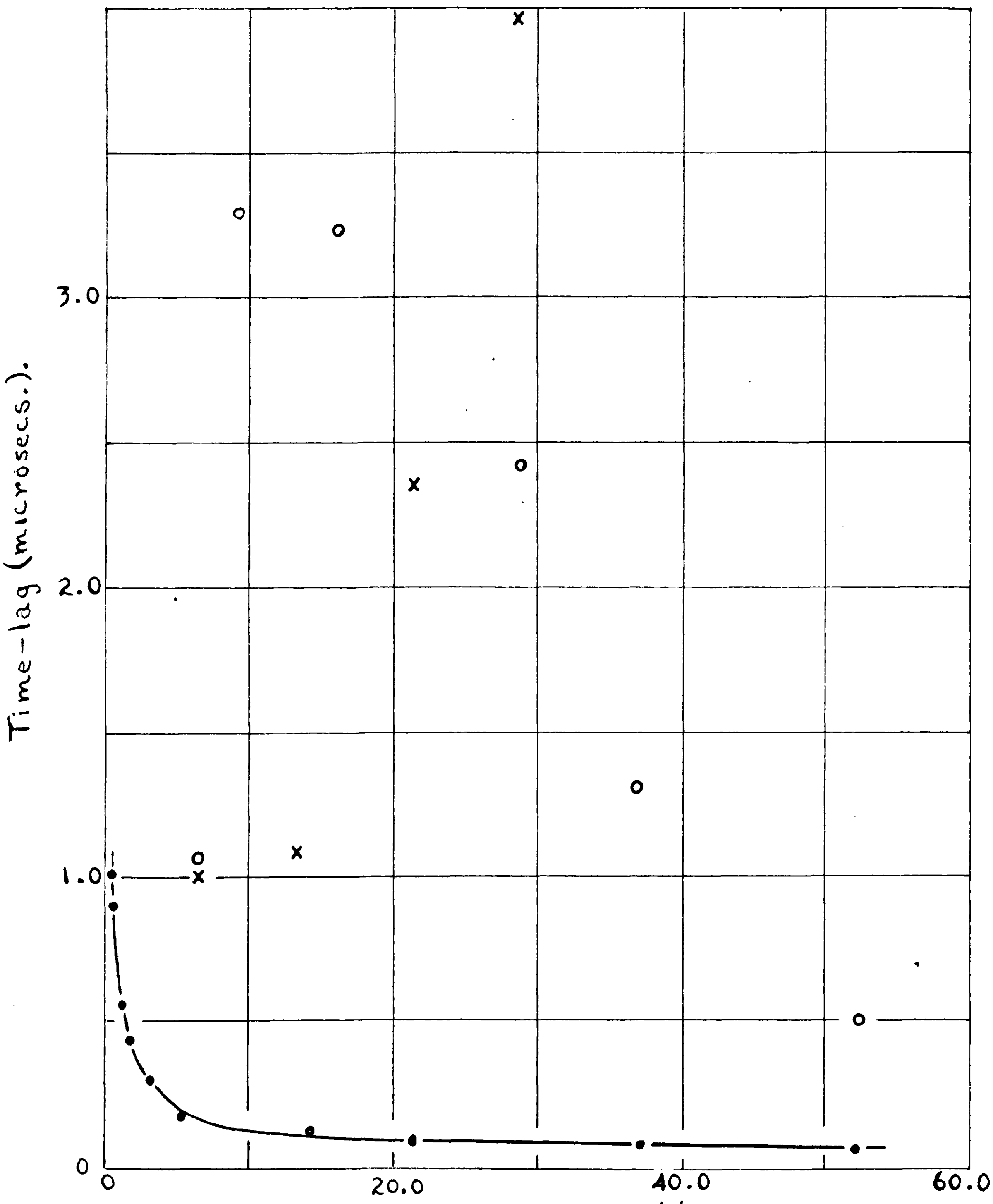


Fig. 3.19. -Time lag data for 6.25 cm. diameter spheres (2.0 cm. spacing); 1.2/240 impulse waveforms applied.

Symbols as for Fig. 3.17.

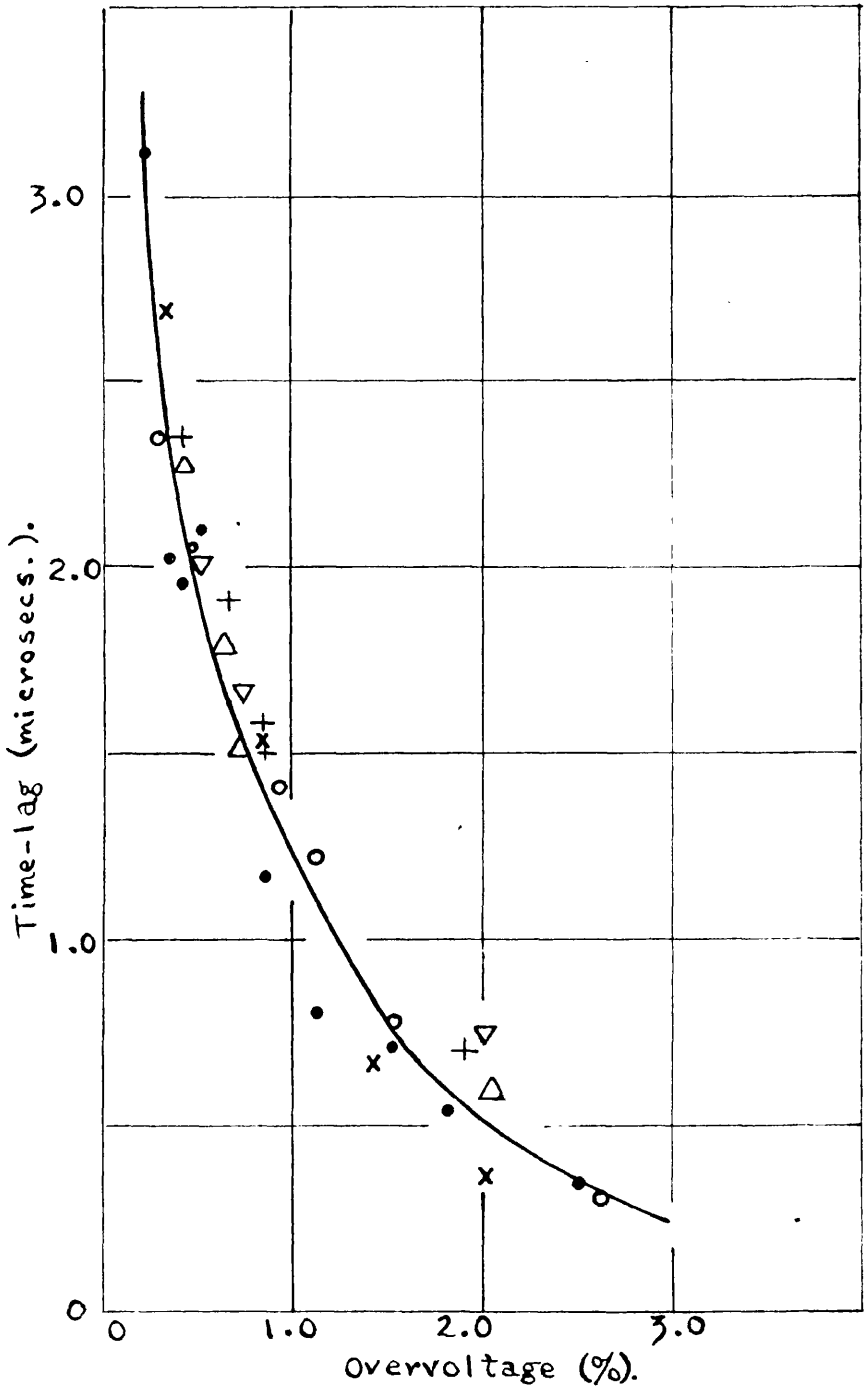


Fig. 3.20.– Detailed section of Fig. 3.16. for irradiated uniform-field gap;

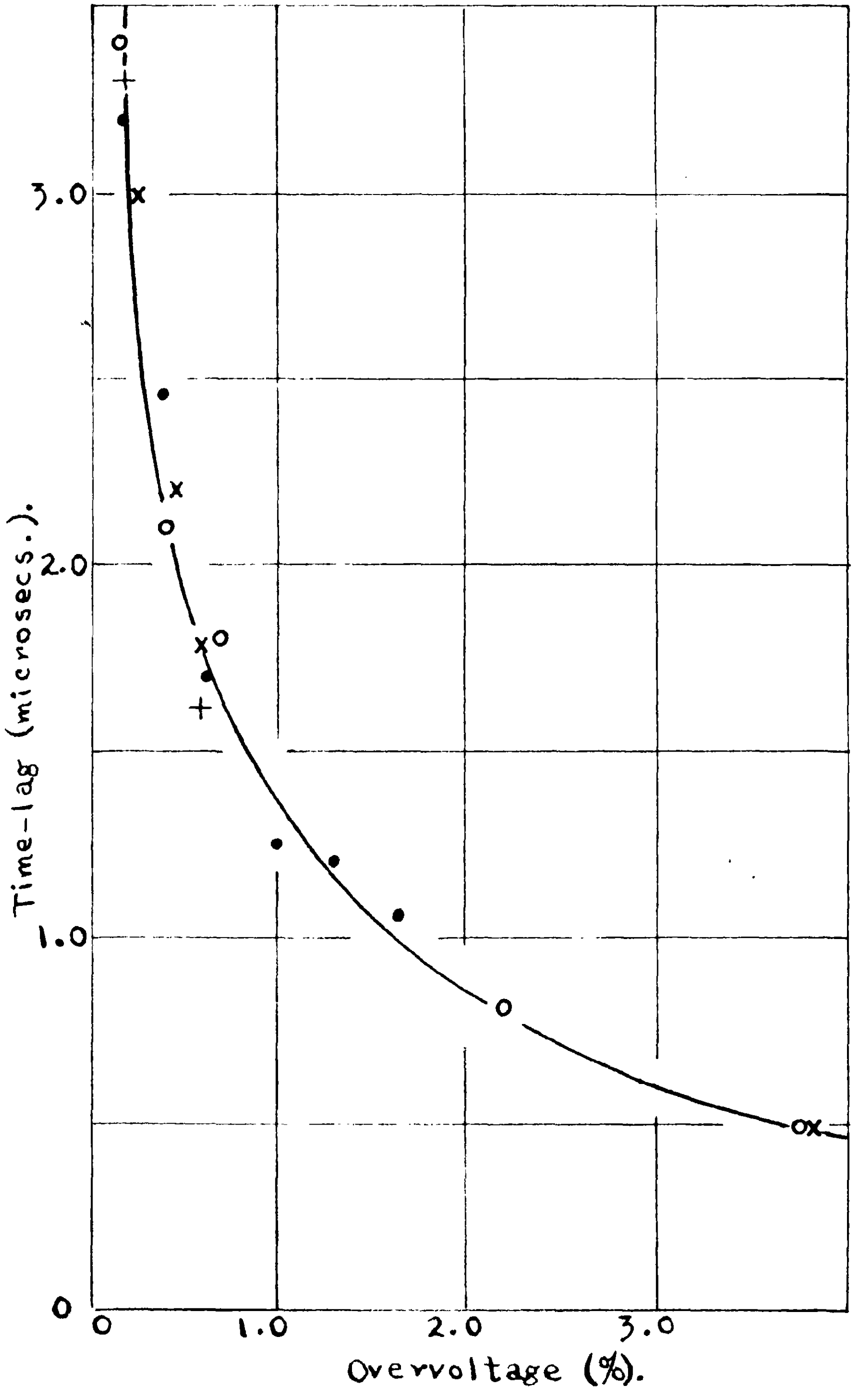


Fig. 3.21.-Detailed section of Fig. 3.18. for irradiated uniform-field gap;
• = U.V. irradiation + wave; x = – wave;

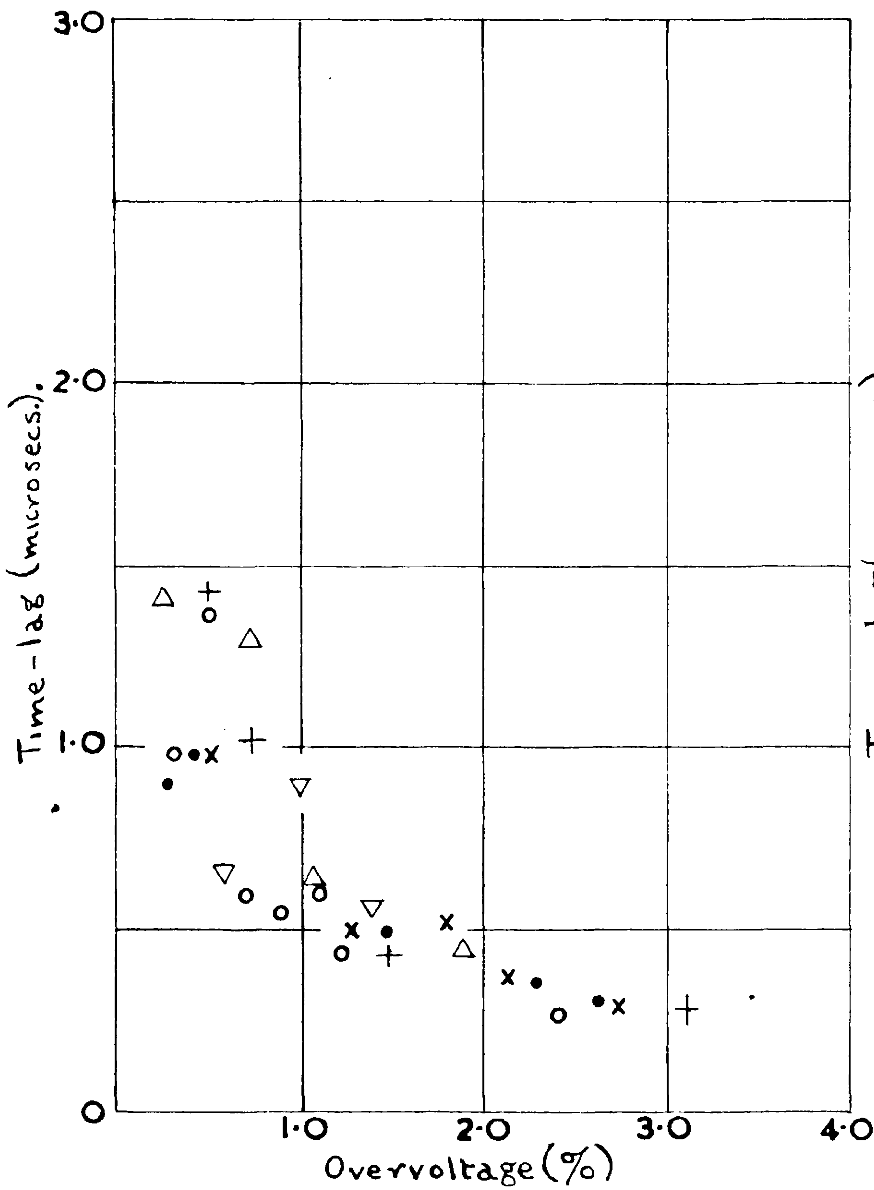


Fig. 3.22. Detailed section of Fig. 3.17. for irradiated sphere-gap; Symbols as for Fig. 3.20.

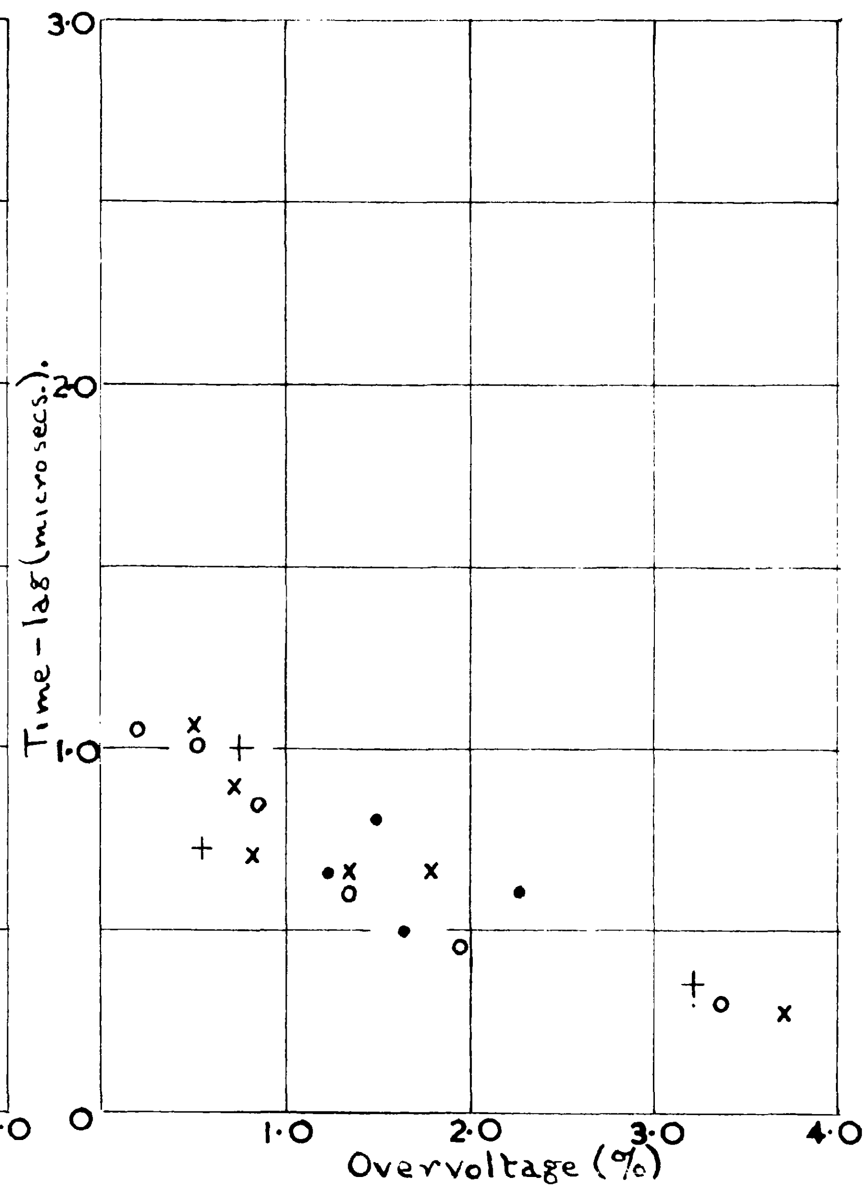


Fig. 3.23. Detailed section of Fig. 3.19. for irradiated sphere-gap. Symbols as for Fig. 3.21.

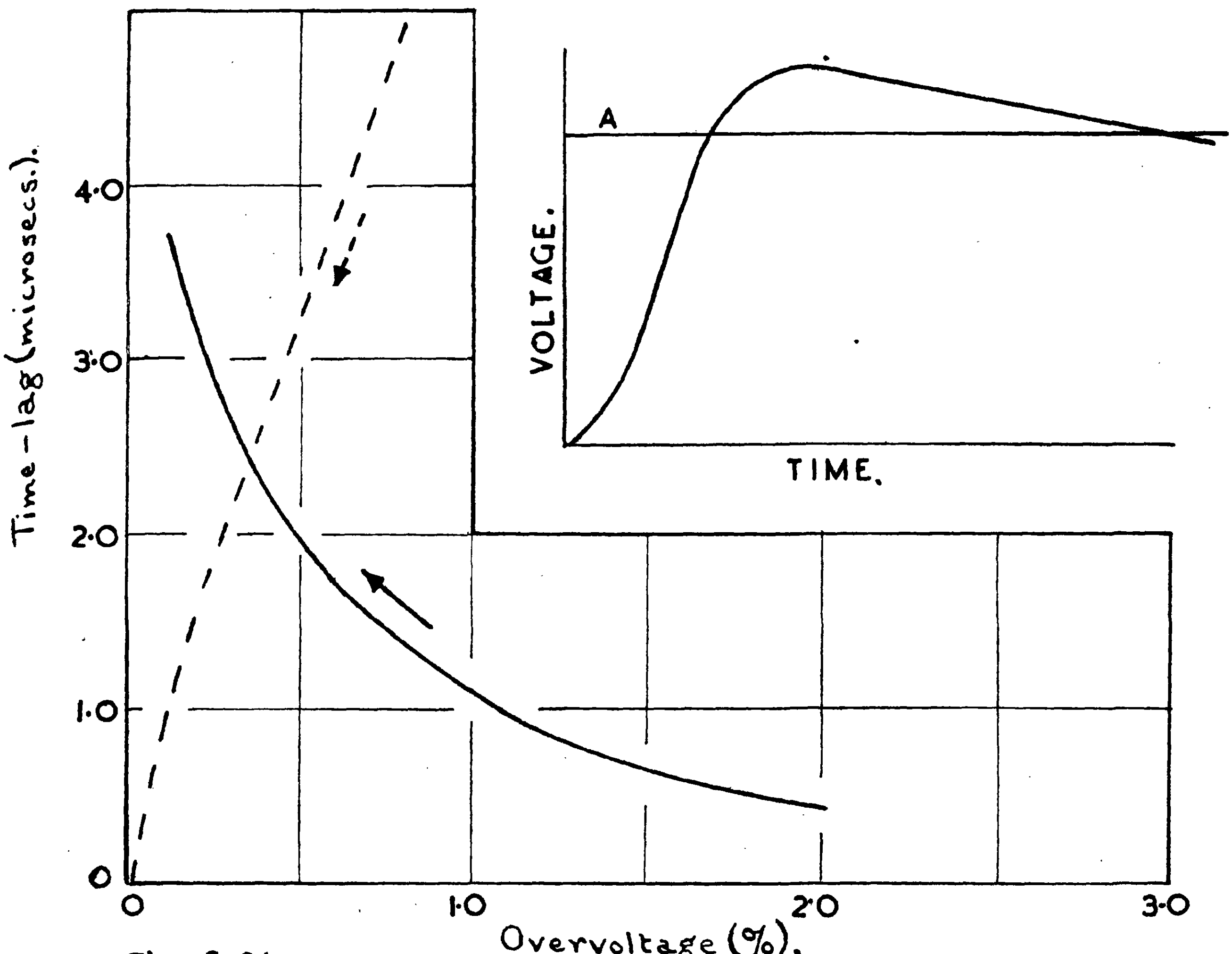


Fig. 3.24.

—— = Impulse time-lag characteristics for 0.2/240 wave (Fig.3.2
zero sparkover level 'A' taken as datum for overvoltage.

---- = duration of impulse above zero sparkover datum ('A' in inset diagram).

--→ duration decreases ; ——→ time-lag increases.

TABLE 4.1.

R_1	10MΩ	R_{11}	4MΩ	C_1	.08μF
R_2	5MΩ	R_{12}	220KΩ	C_2	.01μF
R_3	1MΩ	R_{13}	600KΩ	C_3	.08μF
R_4	10MΩ	R_{14}	9000Ω	C_4	200$\mu\mu$F
R_5	196.5MΩ	R_{15}	1800Ω	C_5	.03μF
R_6	decade	R_{16}	1000Ω	C_6	.01μF
R_7	350Ω			C_7	.25μF
R_8	18.25M			C_8	.25μF
R_9	decade			C_9	.01μF
R_{10}	2200Ω			C_{10}	500$\mu\mu$F

M - Constant voltage mains Transformer.

V - Variac transformer.

P - Potentiometer.

T_1 - Transformer 85kV. R.M.S.

T_2 - Transformer 5kV. R.M.S.

T_3 - Transformer 4.5kV. R.M.S.

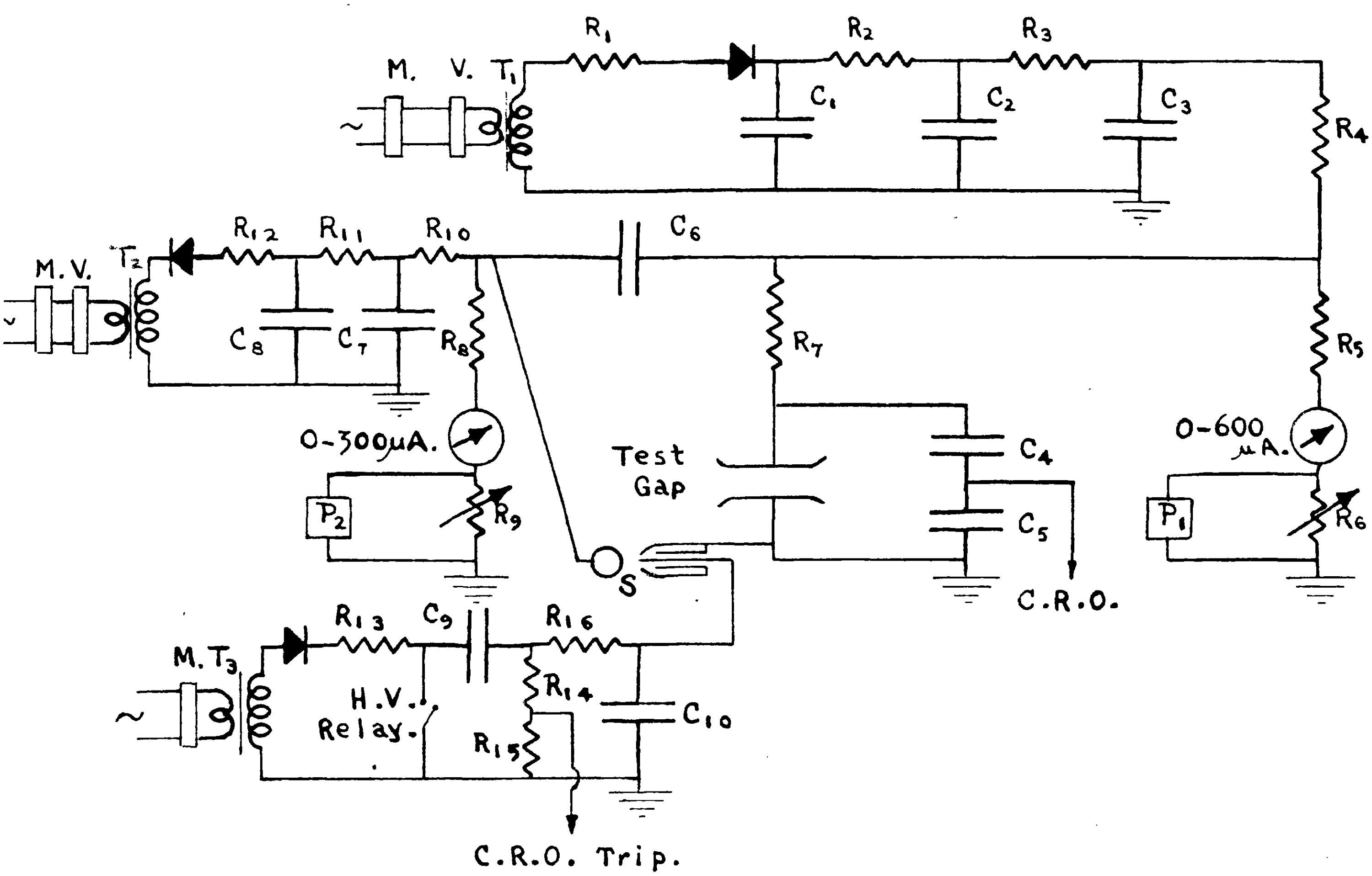


Fig. 4.1. Circuit Diagram for Static Time-lag Tests.

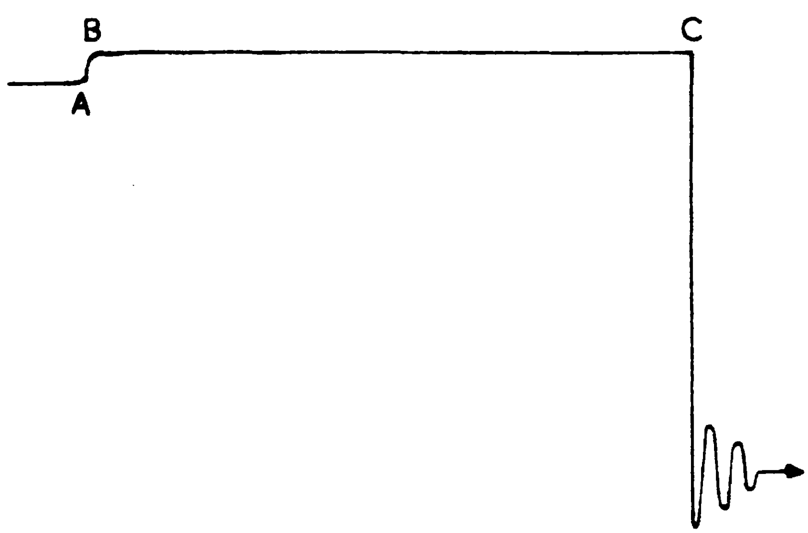


Fig. 4.2. Enlarged drawing of actual breakdown on 2.4 cm gap.

Sweep = 400 μS: A = start of pulse; C = start of spark;

BC = time-lag, here equal to 200 microseconds.

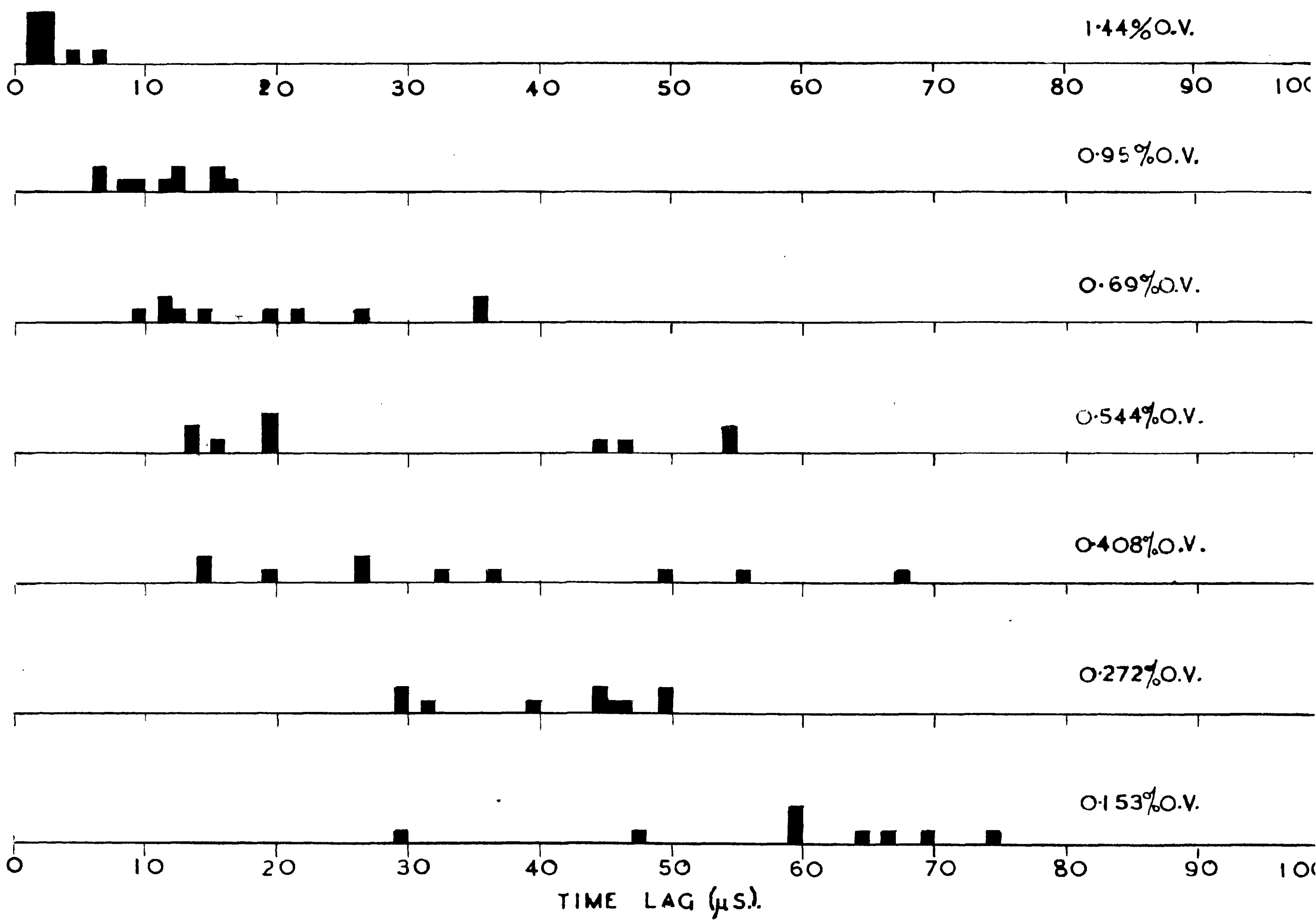


Fig. 4.3. Typical time-lag distribution for various percent-O.V., (Spacing 2·4 cm.). One square block represents one measurement.

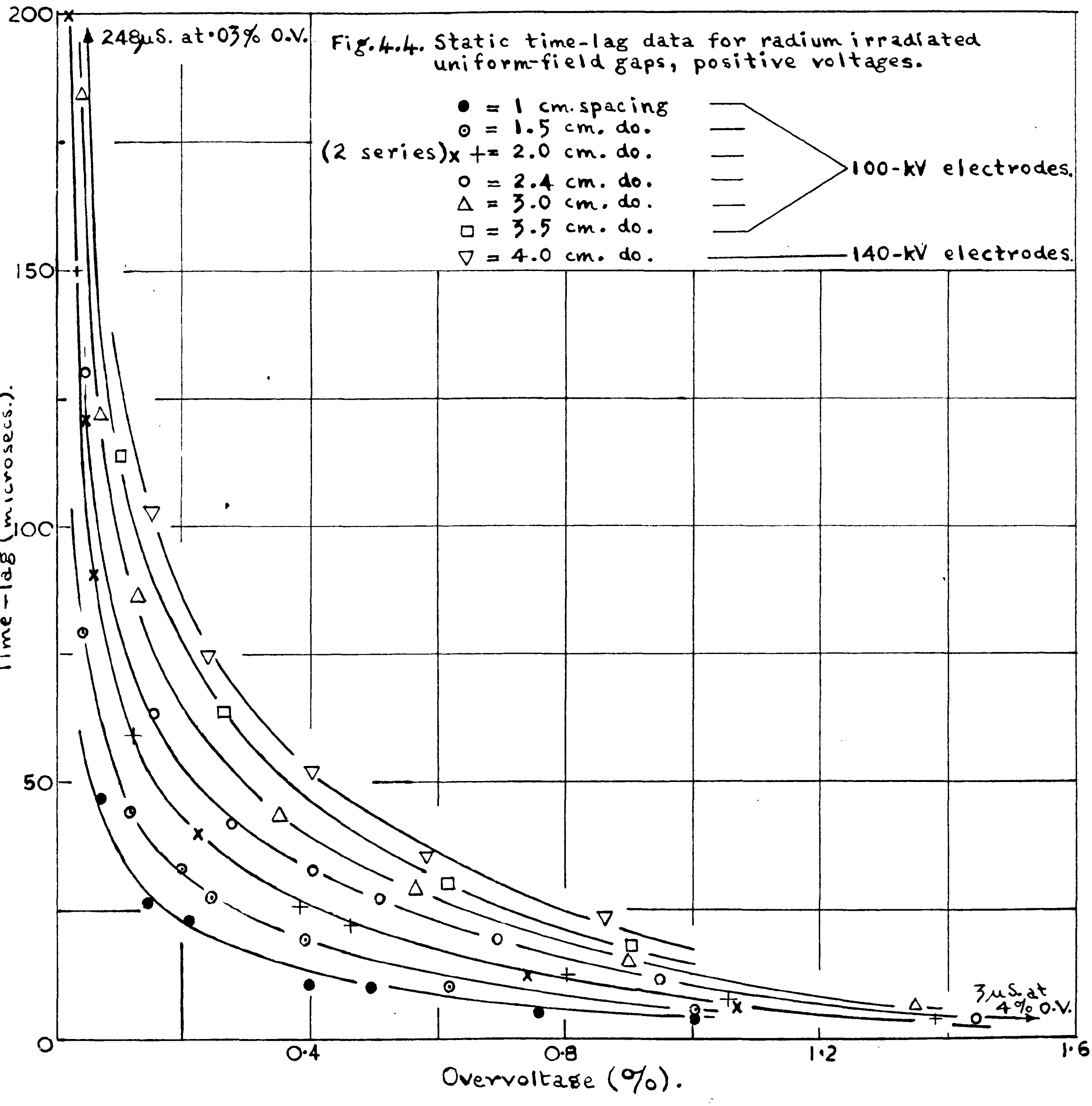
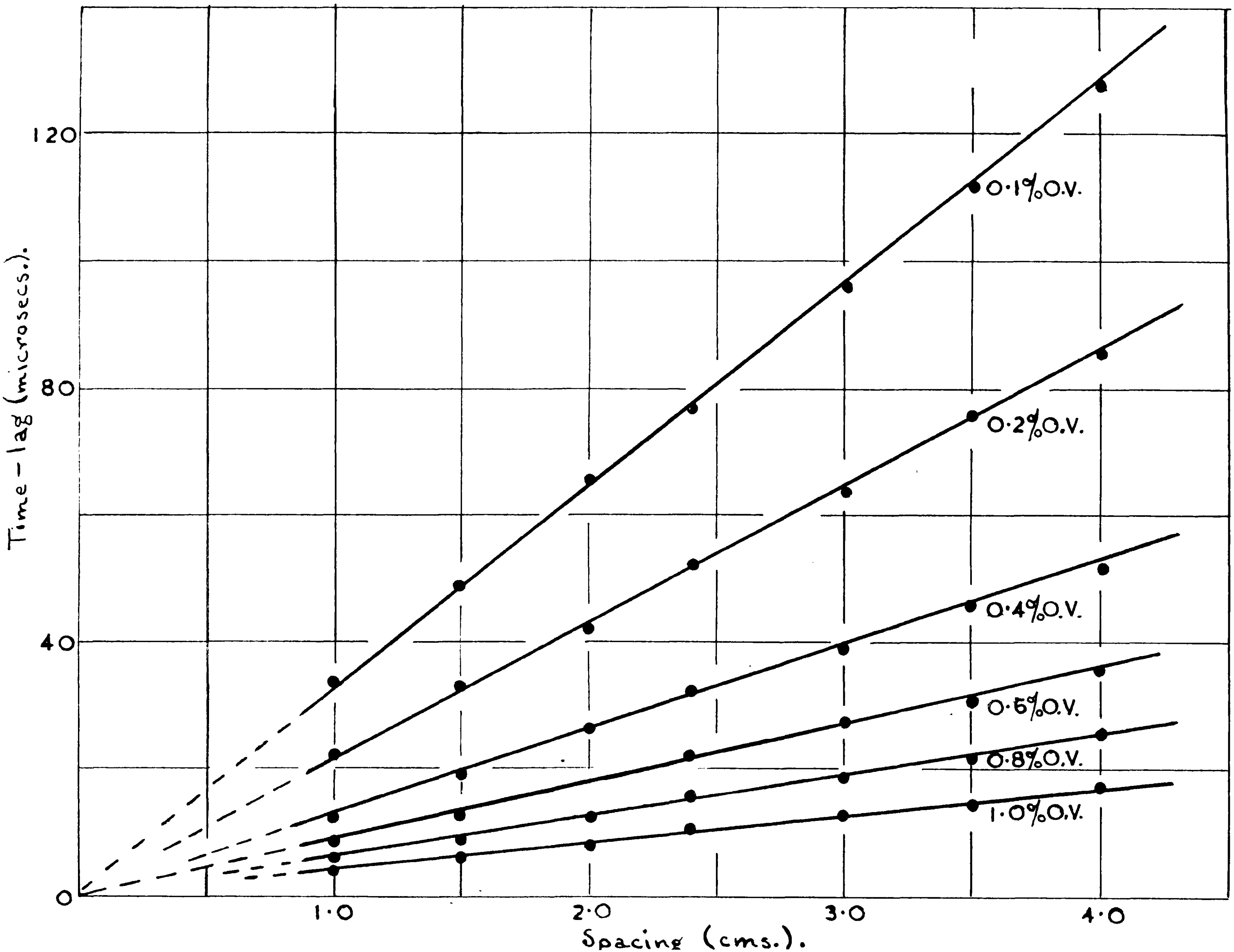


Fig. 4.4. Static time-lag data for radium irradiated uniform-field gaps, positive voltages.



Time - lag (microsecs.).
120
80
40
0
1·0
2·0
3·0
4·0
Spacing (cms.).
0·1%O.V.
0·2%O.V.
0·4%O.V.
0·6%O.V.
0·8%O.V.
1·0%O.V.

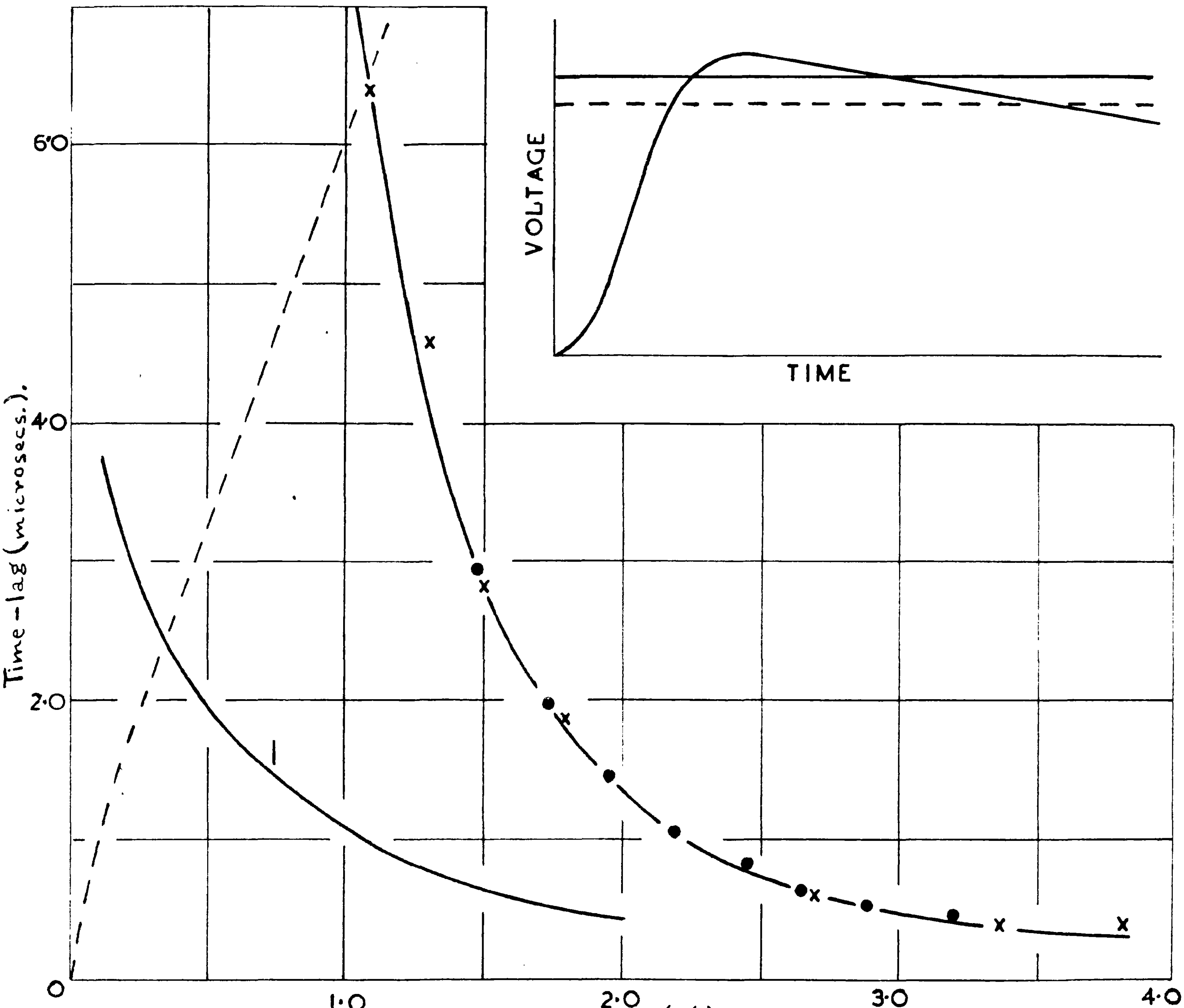


Fig. 4.6. Comparison of static and impulse time-lag data for an irradiated uniform-field gap (2 cm spacing).

I = Impulse characteristic for 0.2/240 waveform (see fig. 3.20.).

x = Observed points from static characteristic (see fig. 4.4.).

● = Points transferred from I.

---- = Duration of impulse voltage waveform.

On the inset figure, full and dotted horizontal lines illustrate relative levels for minimum sparking voltage on impulse and static voltages respectively

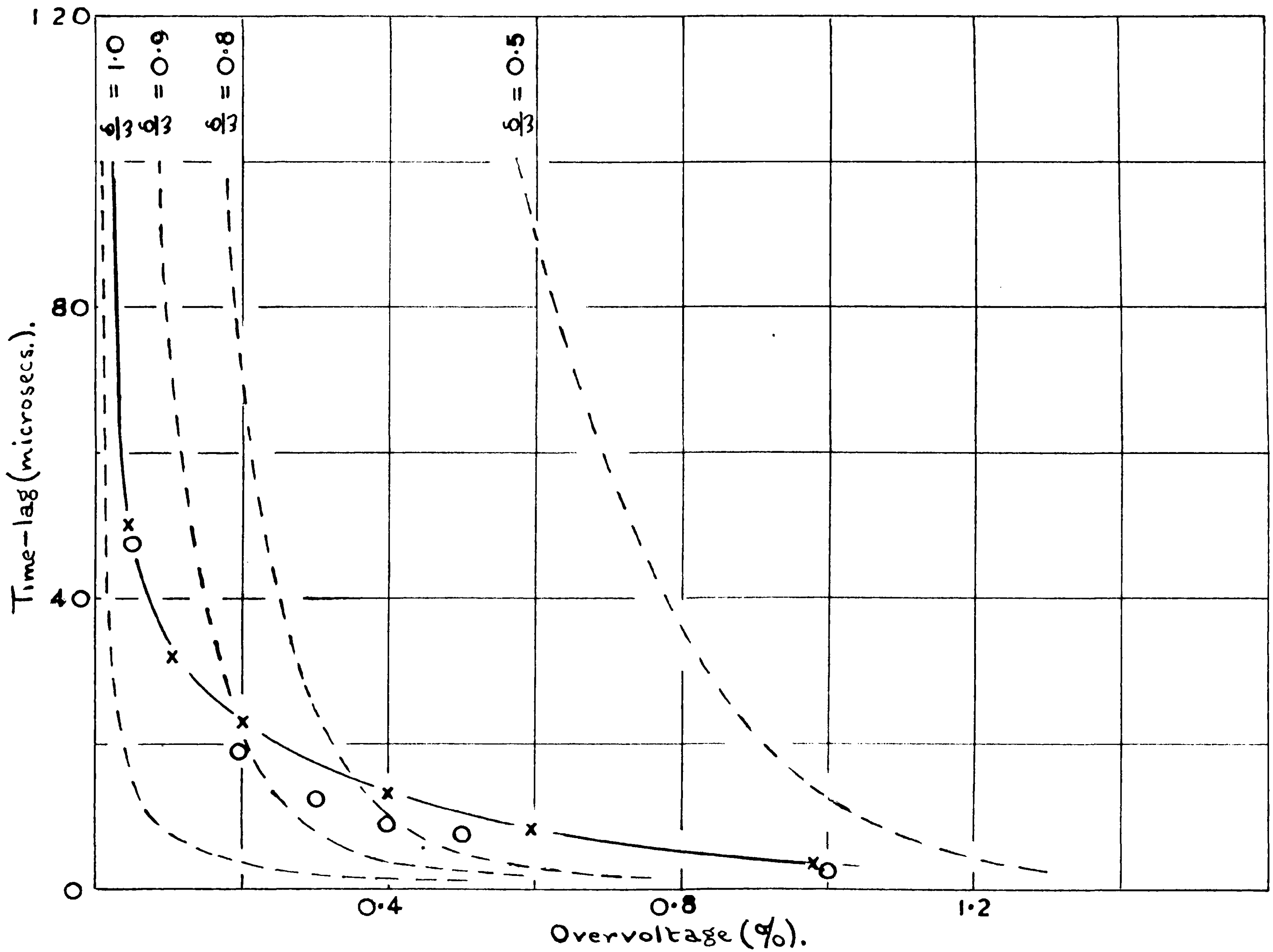


Fig. 4.7. Comparative formative time-lag data for 1 cm. gap.
—x— = Author's results; o = Fisher and Bederson's results (ref 65);

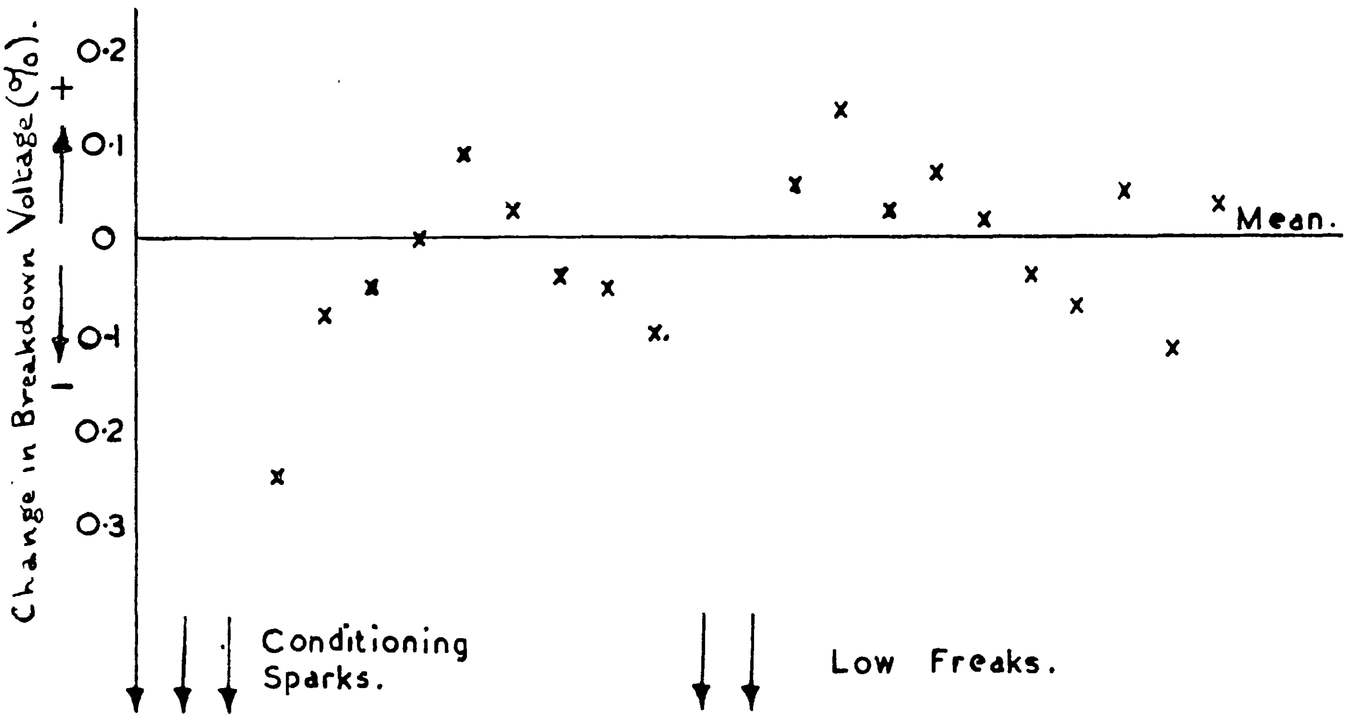


Fig. 4.8a. – Sequence diagram for 1 cm. gap, 100kV electrodes.

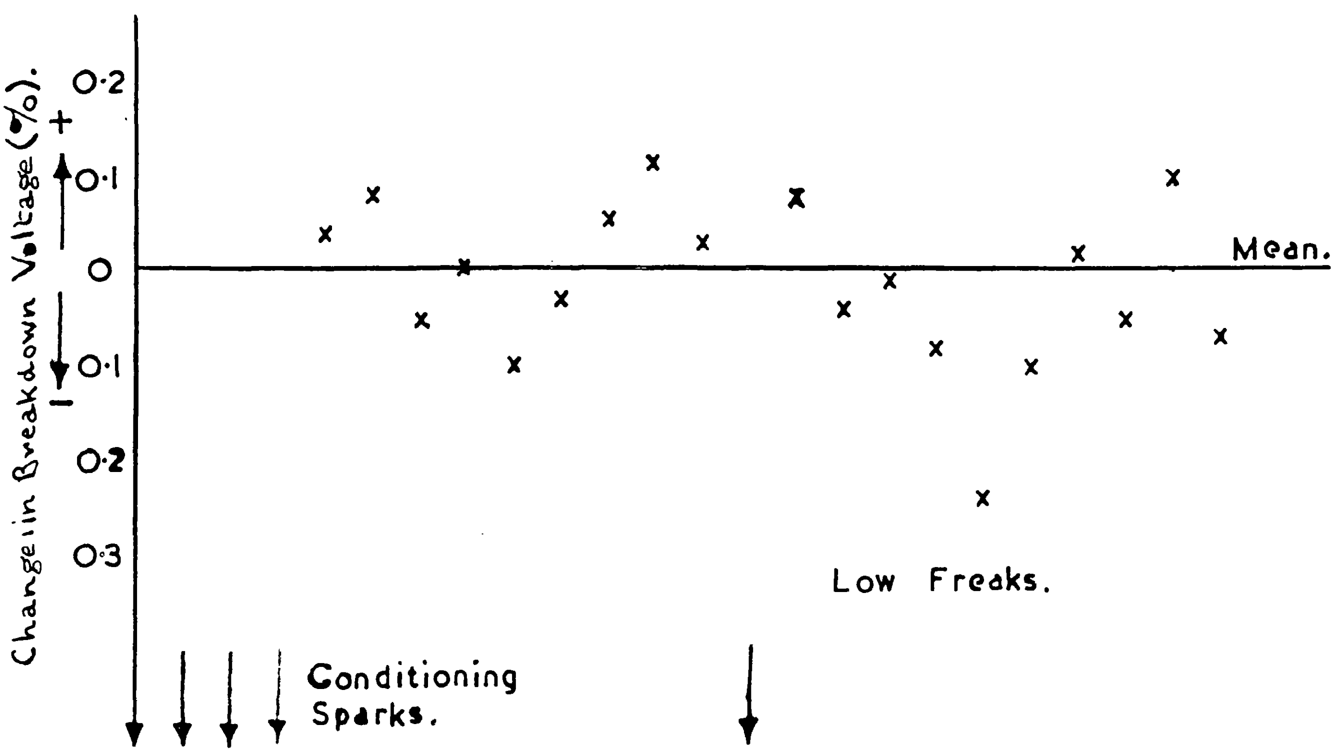


Fig. 4.8b. – Sequence diagram for 4.5 cm. gap, 140kV electrodes.

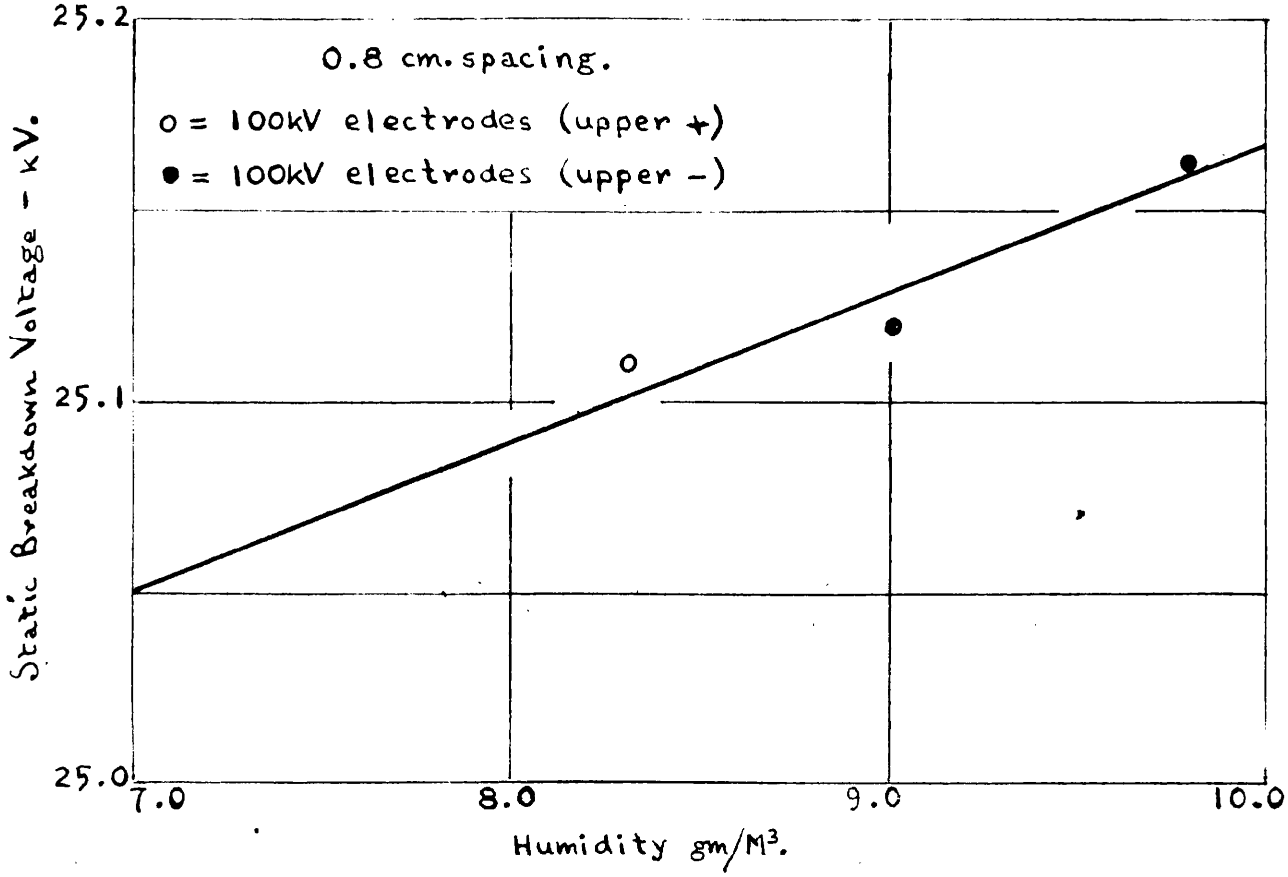


Fig. 4.9. Breakdown Voltage/Humidity Curve for Uniform-:field gap (0.8 cm. spacing).

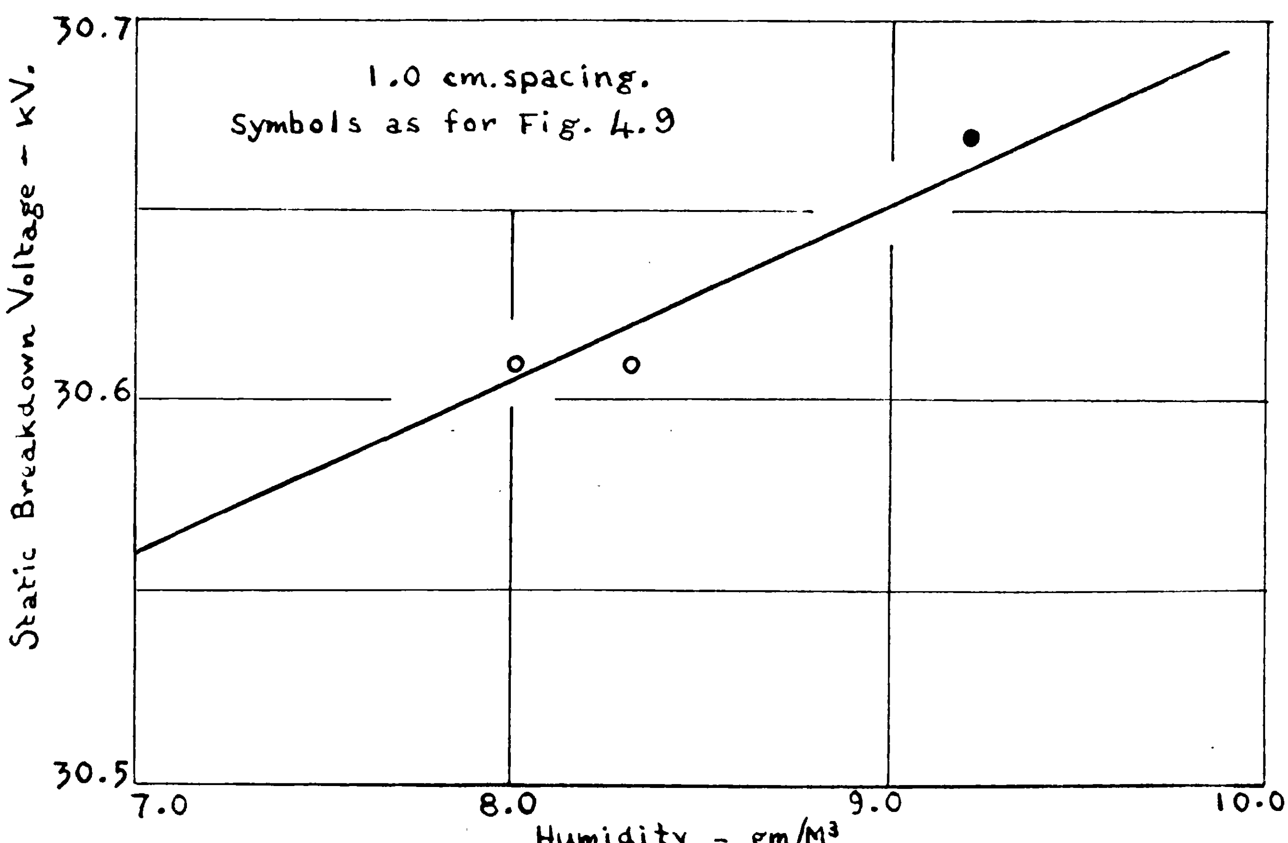


Fig. 4.10. Breakdown Voltage/Humidity Curve for Uniform-:field gap (1 cm. spacing).

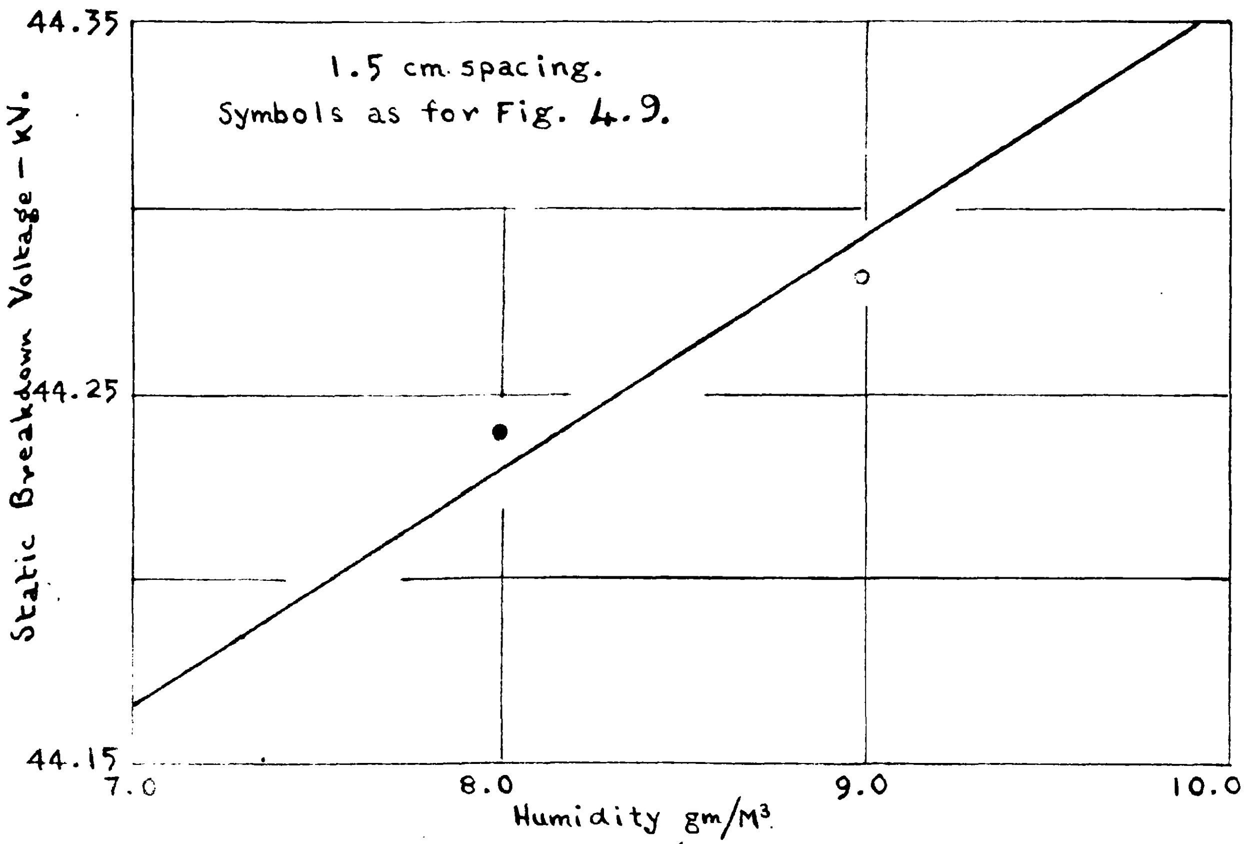


Fig. 4.11. Breakdown Voltage/Humidity Curve for Uniform-:field gap (1.5 cm spacing).

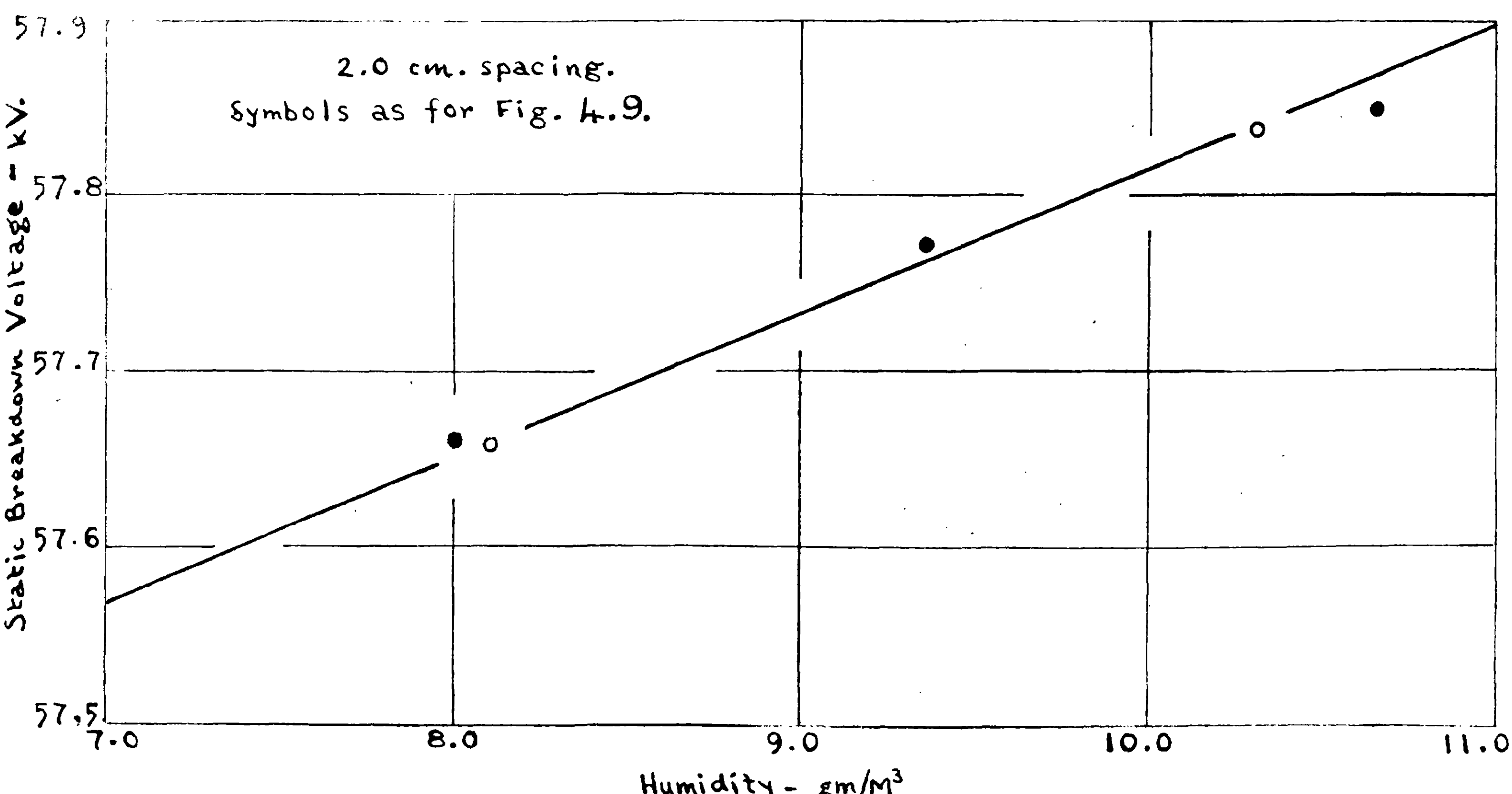


Fig. 4.12. Breakdown Voltage/Humidity Curve for Uniform-field Gap.

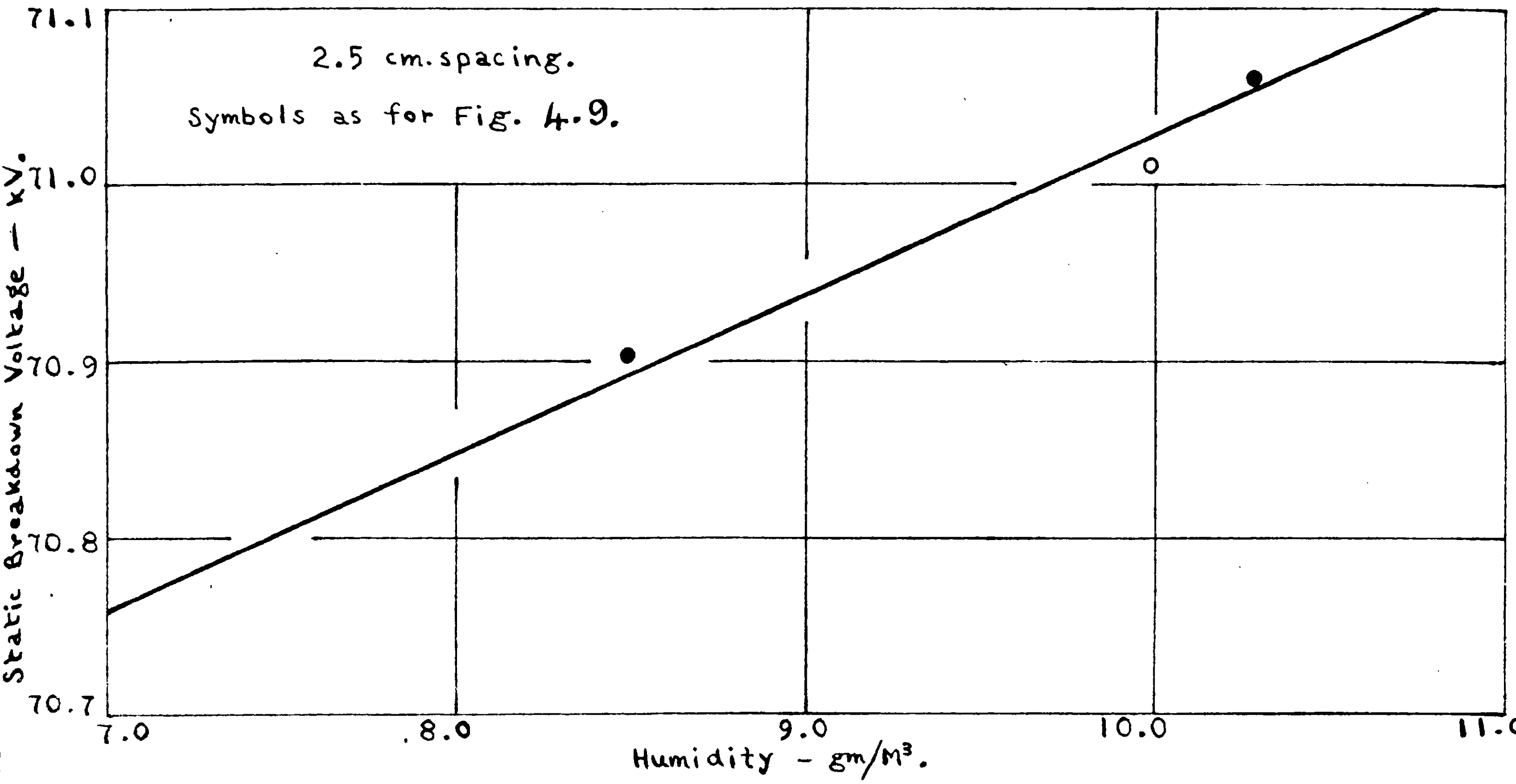


Fig. 4.13. Breakdown Voltage/Humidity Curve for Uniform-field gap.

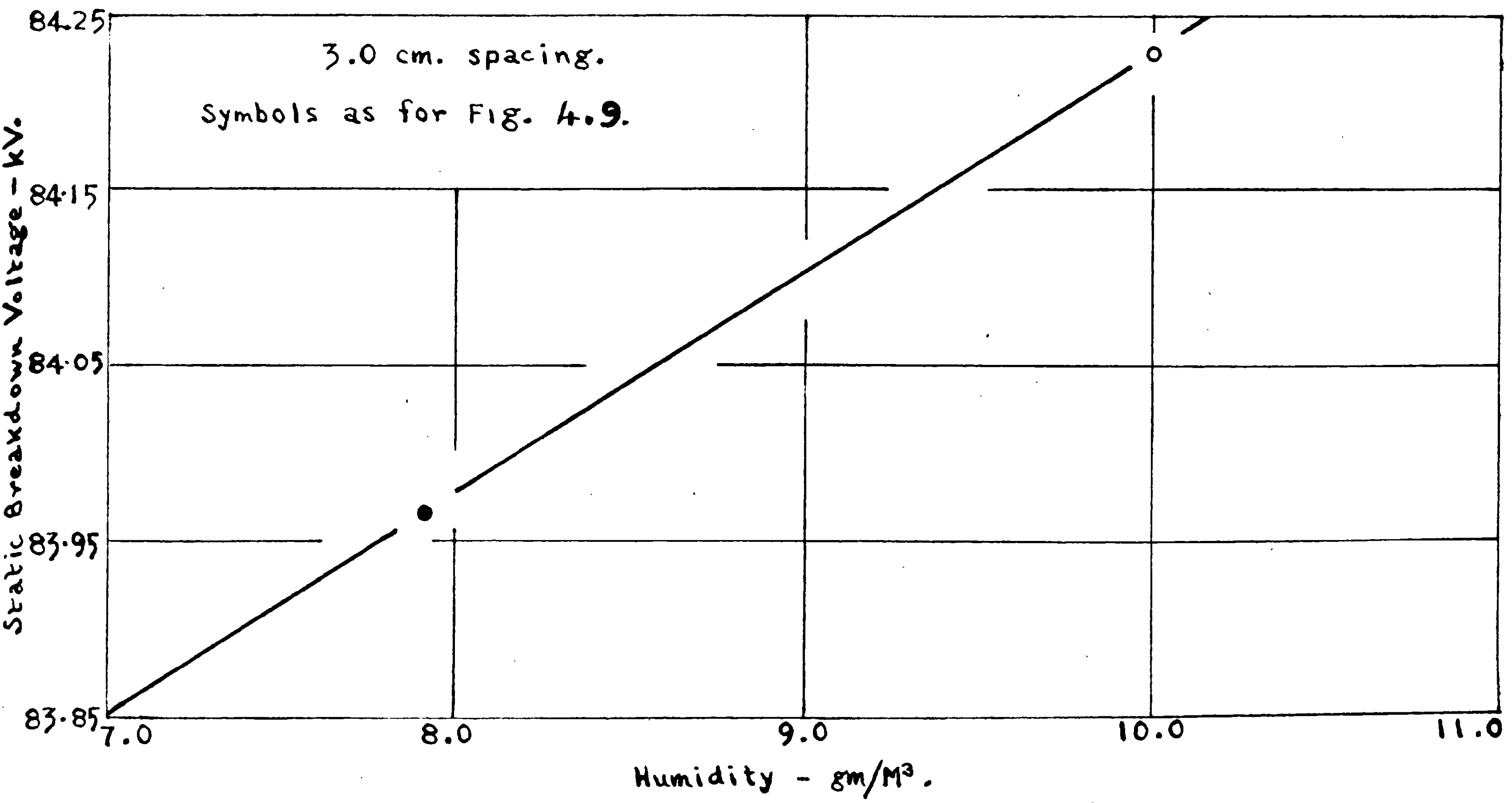


Fig. 4.14. Breakdown Voltage/Humidity Curve for Uniform-field gap.

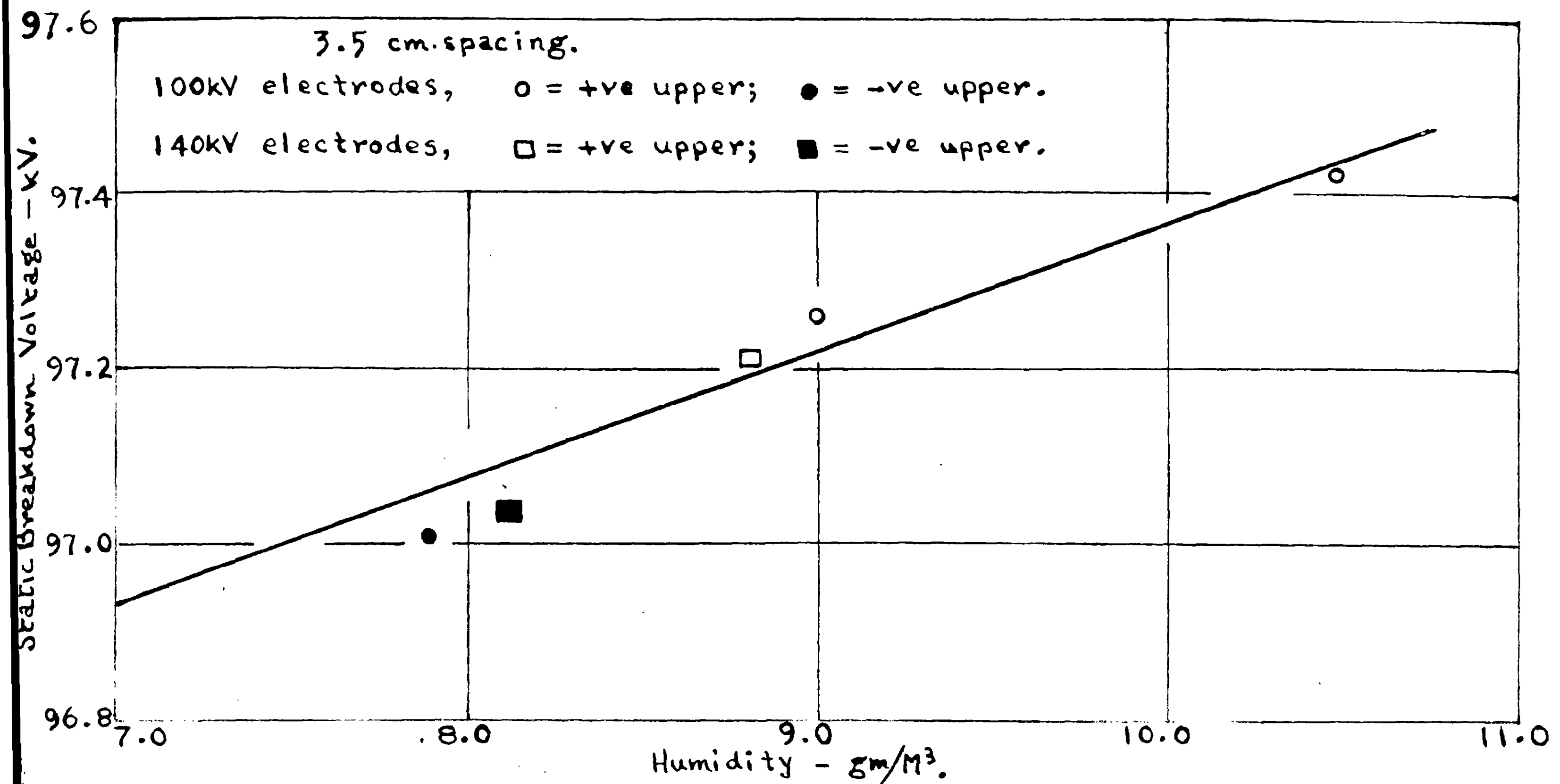


Fig. 4.15. Breakdown Voltage/Humidity Curve for Uniform-field Gap.

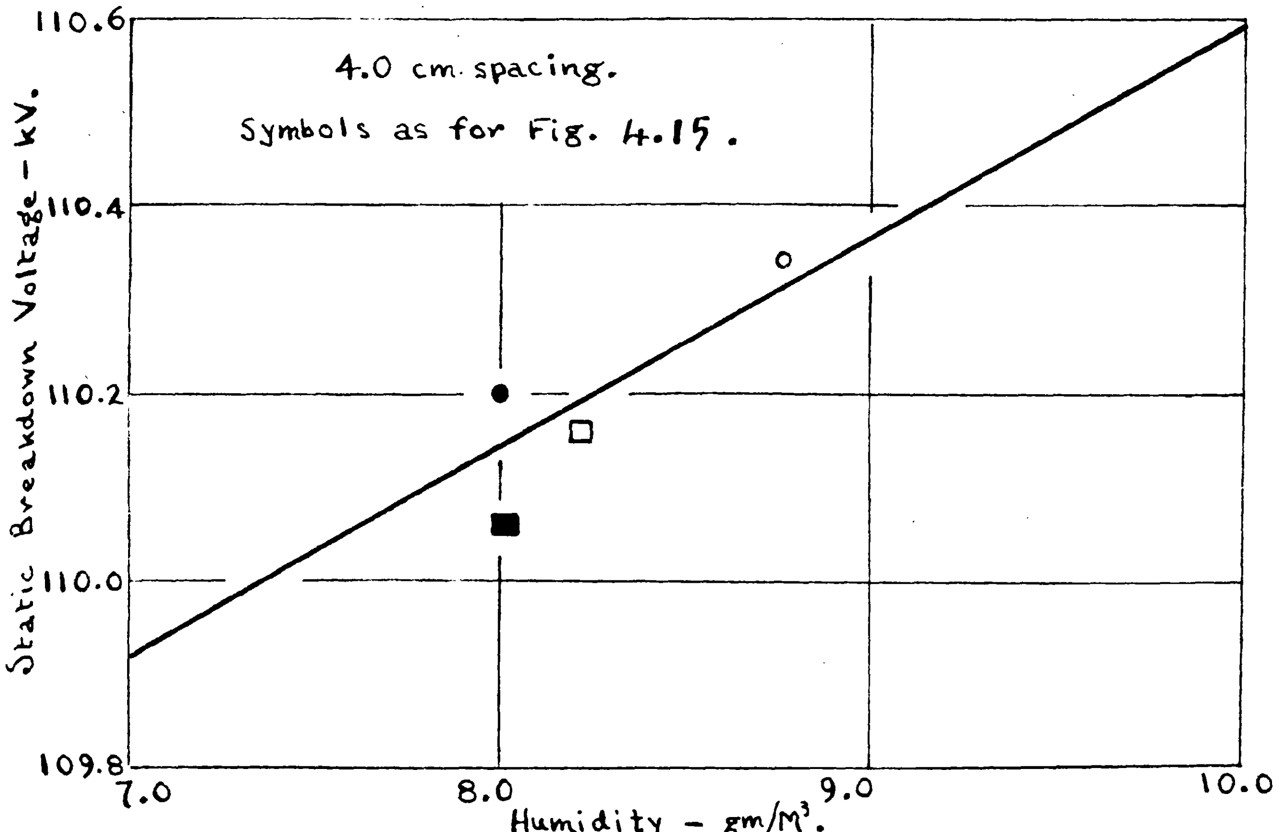
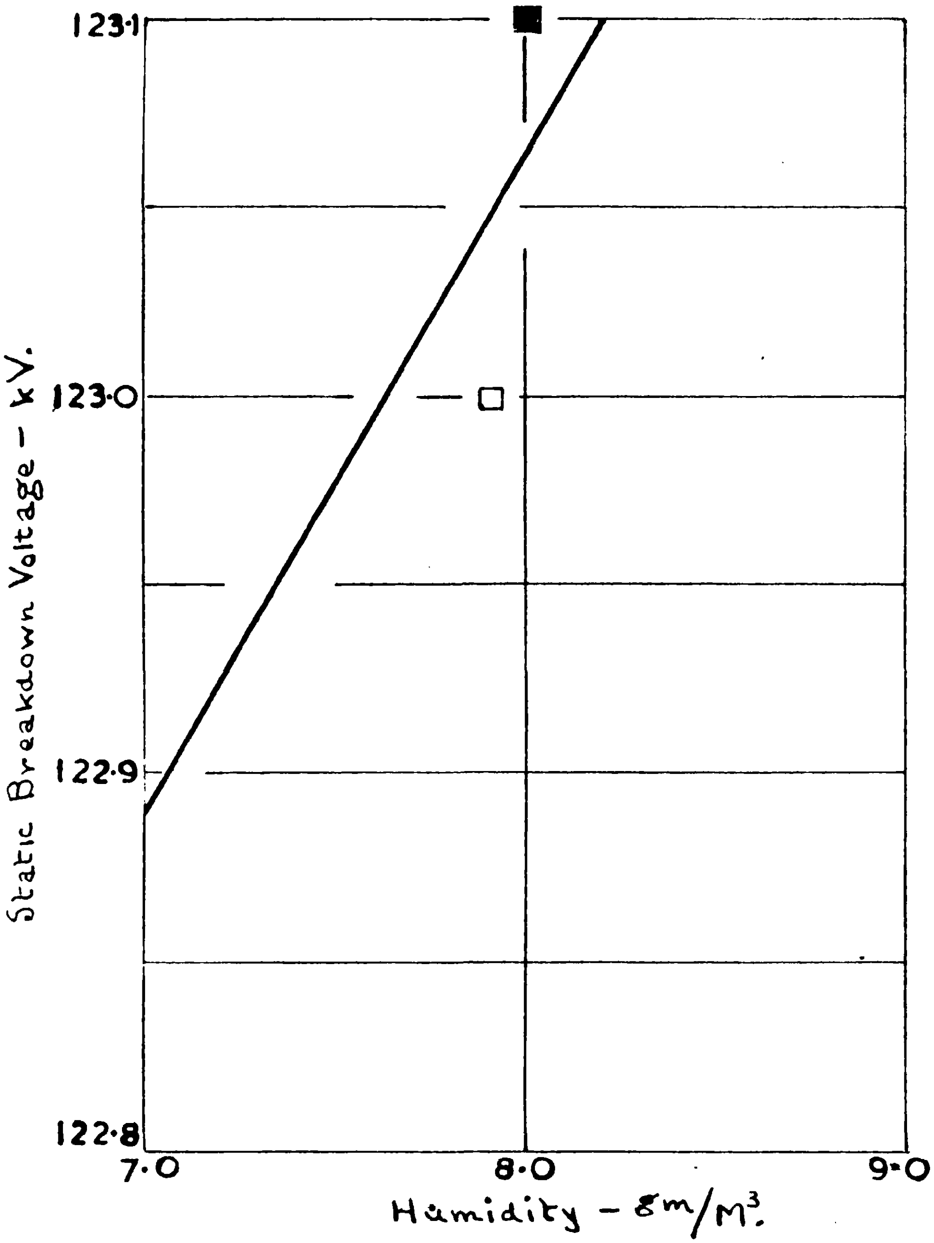


Fig. 4.16. Breakdown Voltage/Humidity Curve for Uniform-field gap.

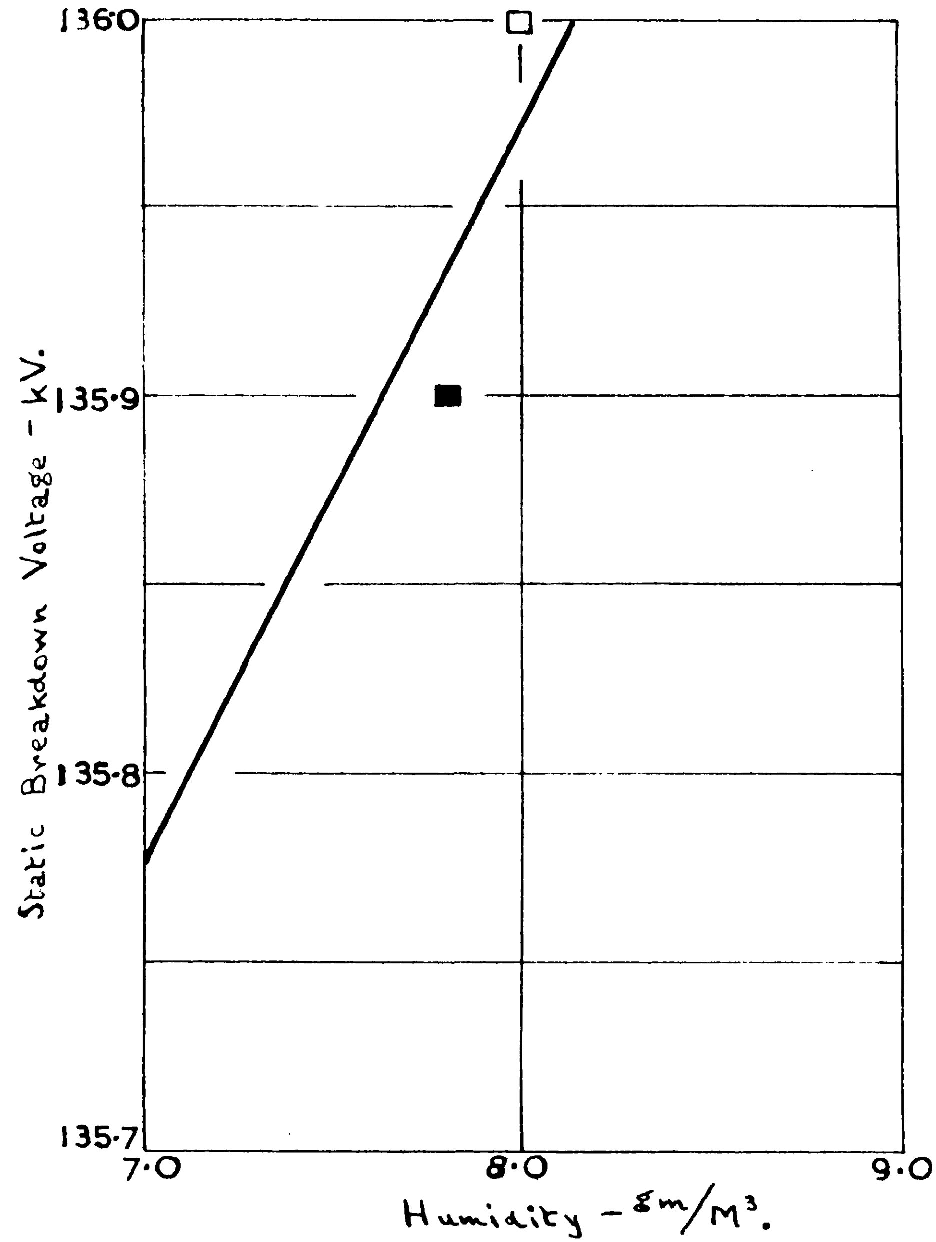
4·5 cm. spacing.

140 - kV electrodes; □ = +, ■ = − :



5·0 cm. spacing.

140 - kV electrodes ; □ = +, ■ = − :



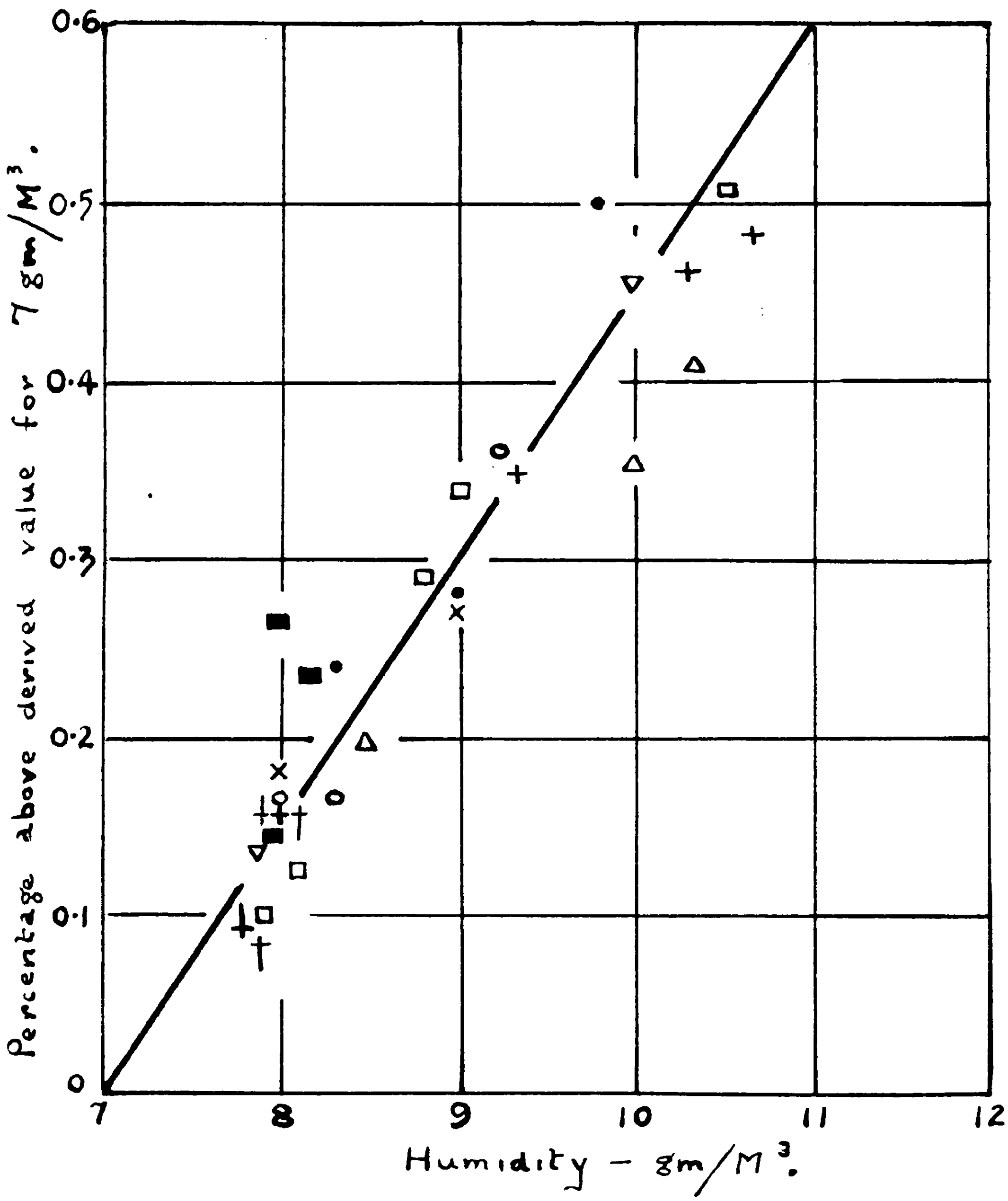


Fig. 4.19. "Breakdown voltage – Humidity" Curve.

Gap spacings: ● = 0·8 cm.; o = 1·0 cm.; x = 1·5 cm.;
+ = 2·0 cm.; Δ = 2·5 cm.; ∇ = 3·0 cm.;
□ = 3·5 cm.; ■ = 4·0 cm.; † = 4·5 cm.;
┼ = 5·0 cm.;

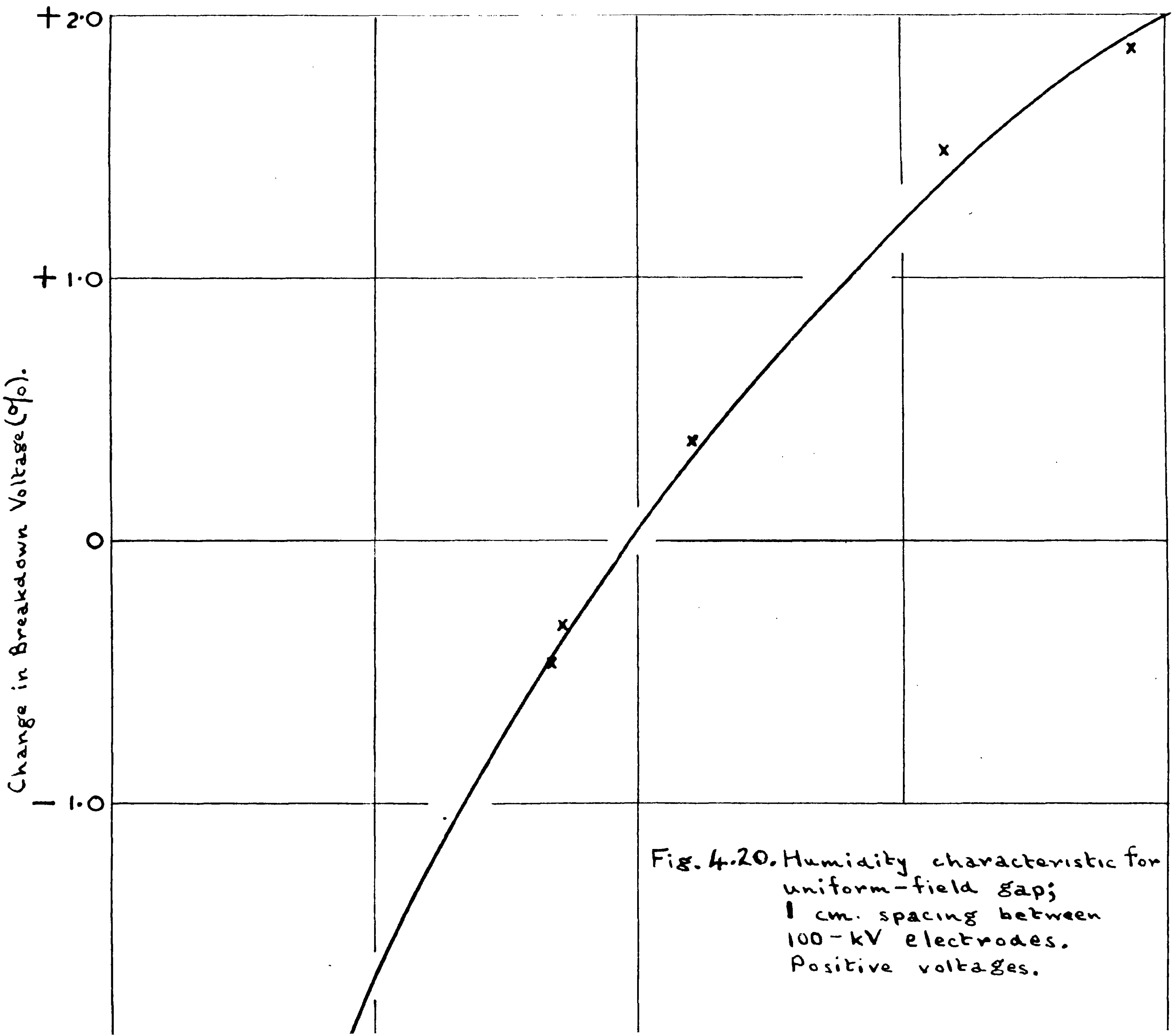


Fig. 4.20. Humidity characteristic for uniform-field gap; 1 cm. spacing between 100-kV electrodes. Positive voltages.

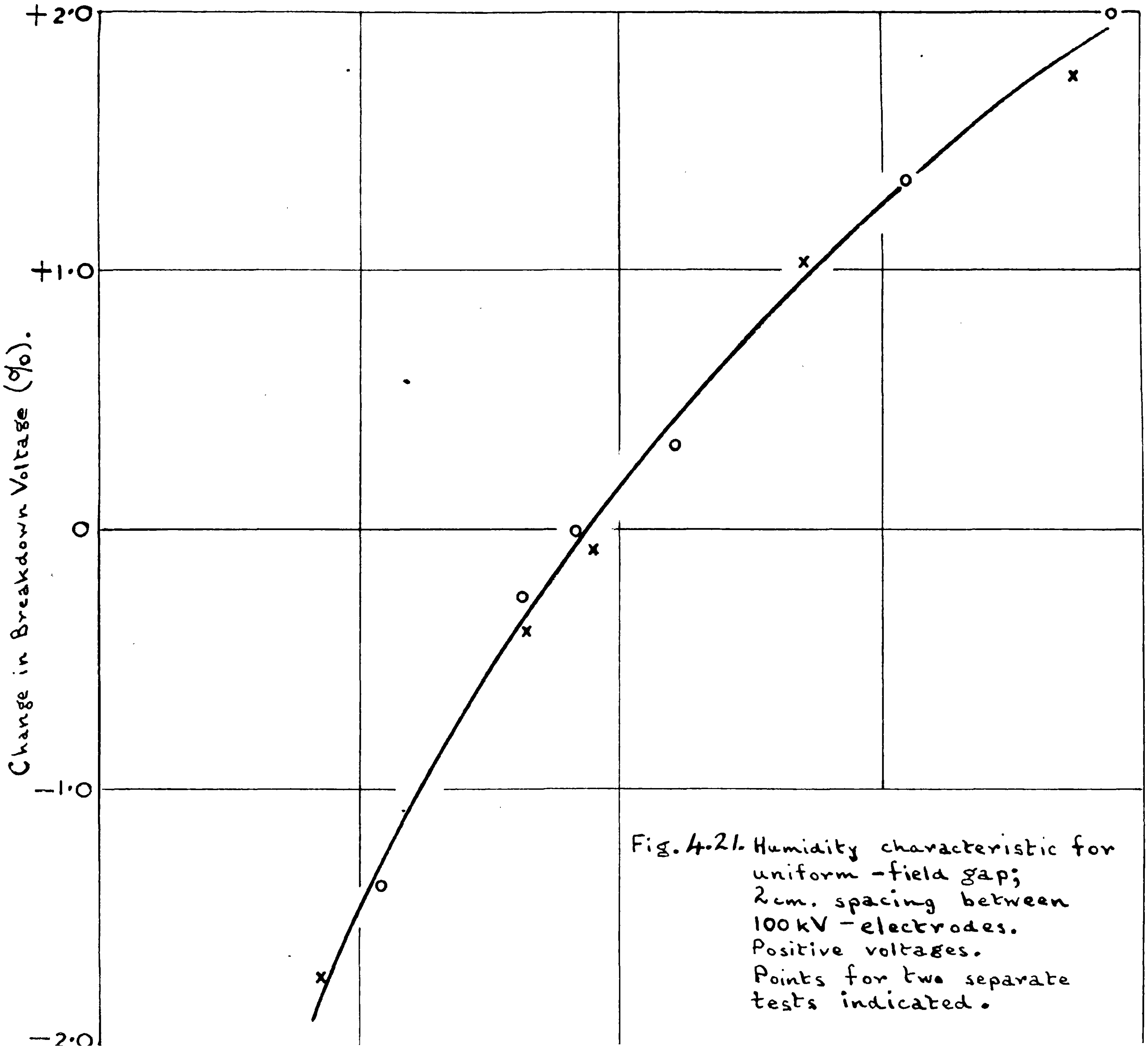


Fig. 4.21. Humidity characteristic for uniform-field gap; 2 cm. spacing between 100 kV-electrodes. Positive voltages. Points for two separate tests indicated.

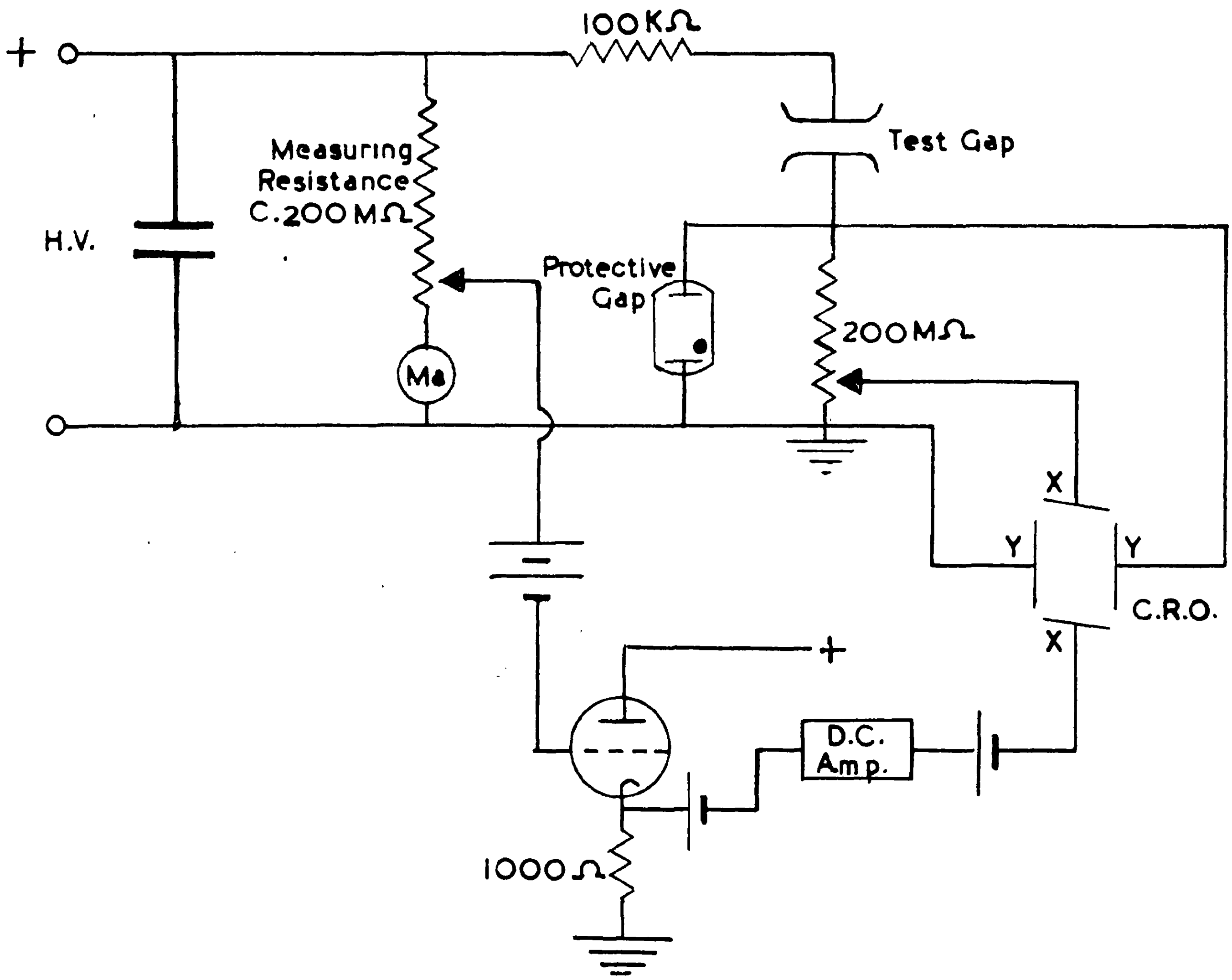


Fig. 5.1. CIRCUIT DIAGRAM

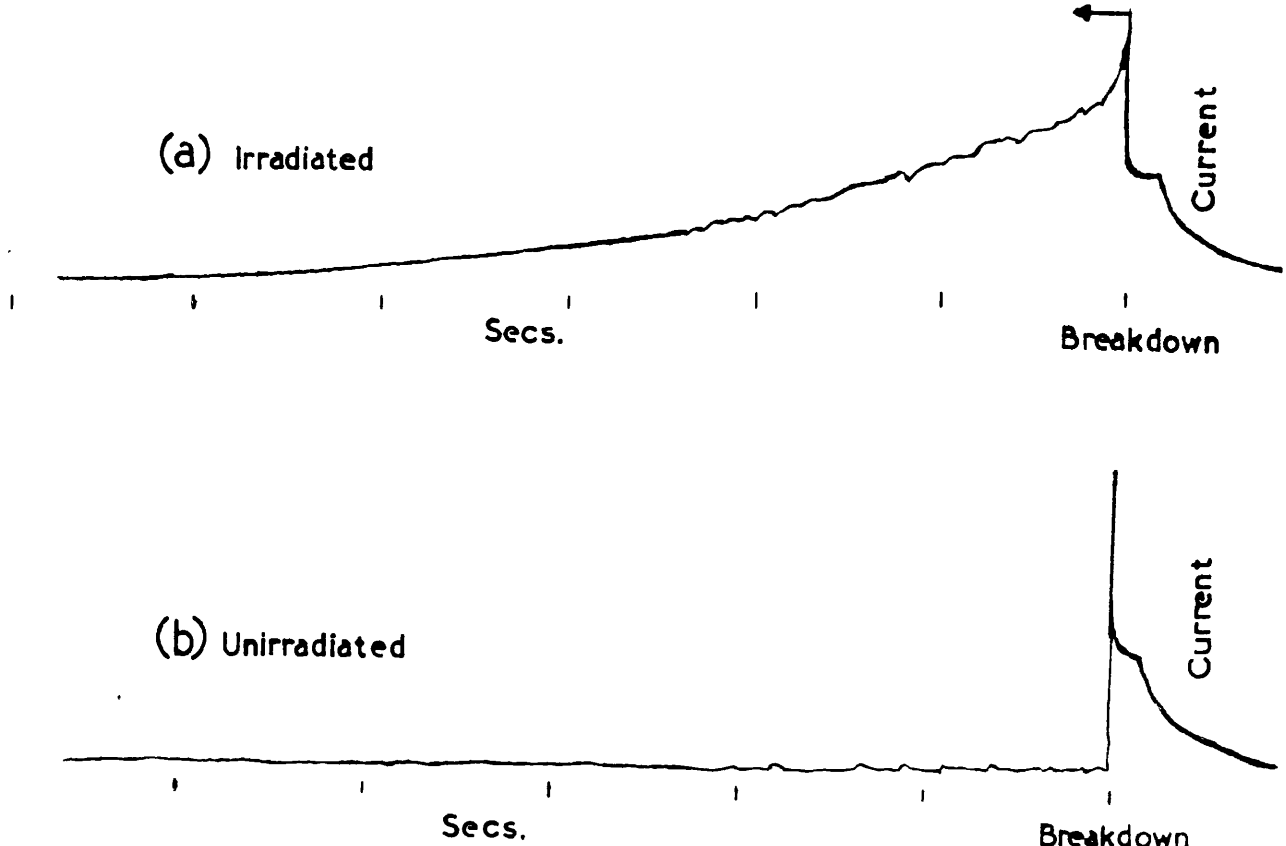


Fig. 5.2. Projection of moving film records for 2cm. gap — Film speed 1"/sec

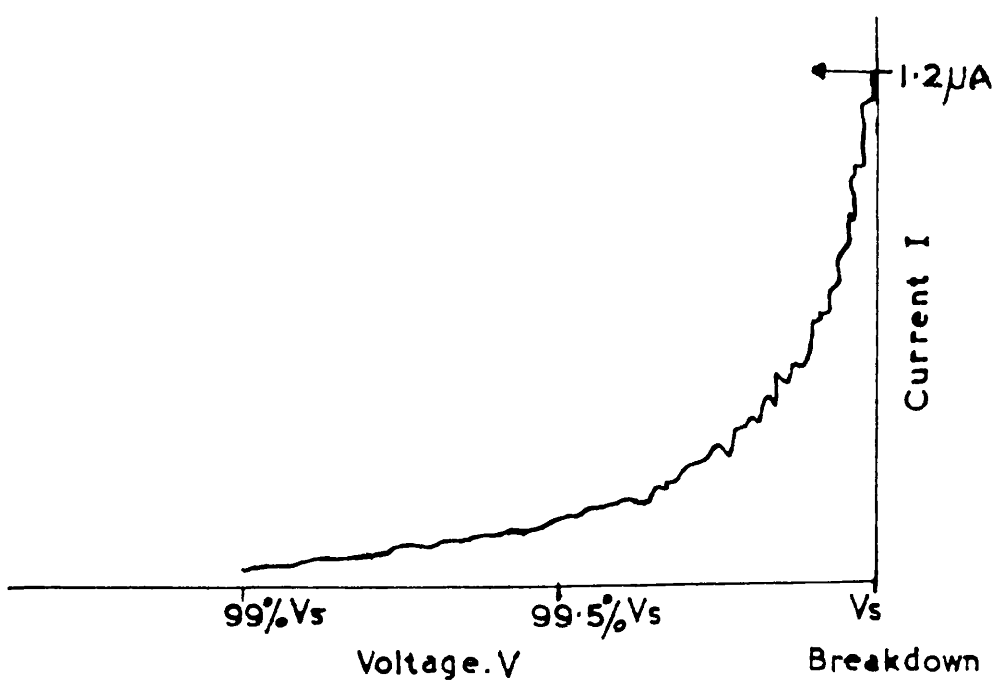


Fig. 5.3. Projection of I–V Oscillogram for 2cm gap irradiated

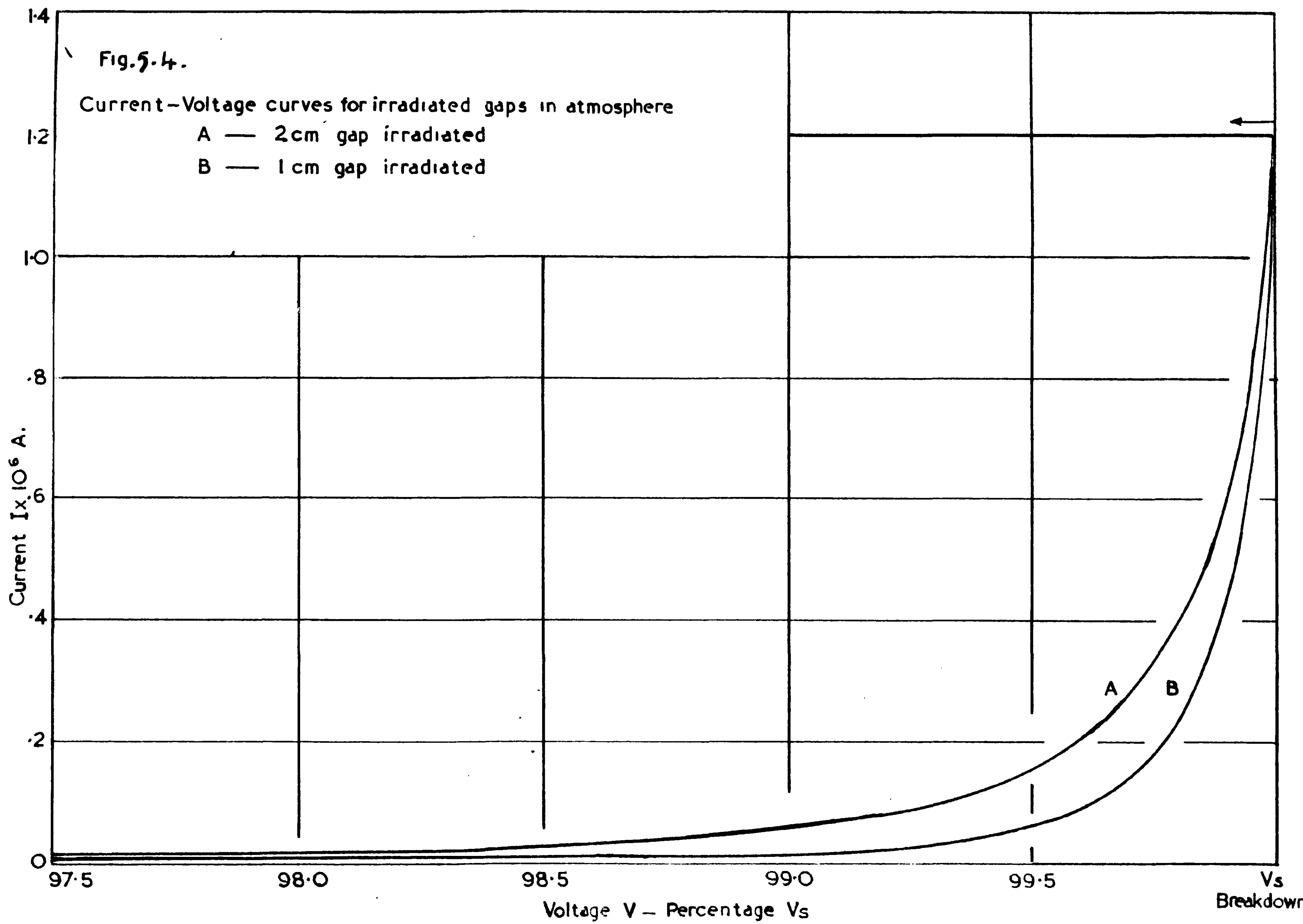


Fig.5.4.
Current-Voltage curves for irradiated gaps in atmosphere
A — 2cm gap irradiated
B — 1cm gap irradiated
1·4
1·2
1·0
·8
·6
·4
·2
0
Current I x 10⁶ A.
97·5
98·0
98·5
99·0
99·5
Vs
Breakdown
Voltage V – Percentage Vs
A
B

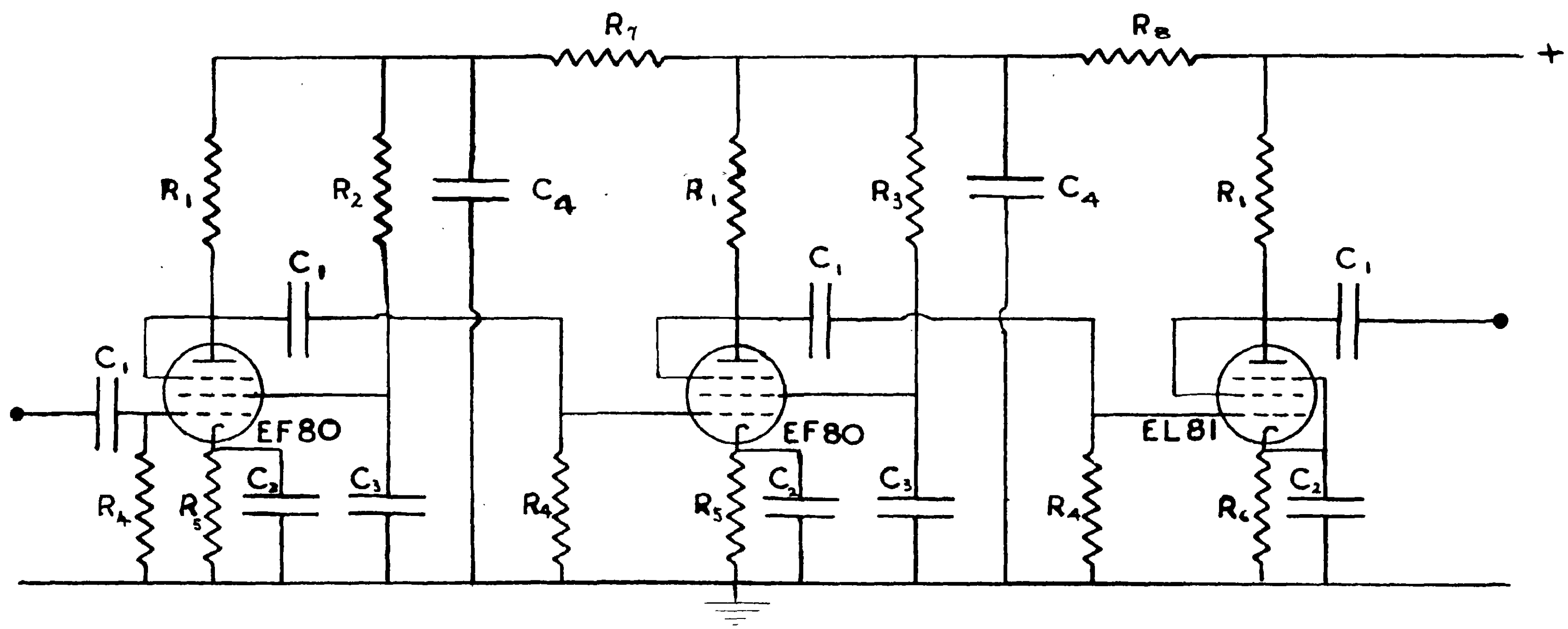


Fig. 5.5. Amplifier for pulse current measurements.

$R_1 = 3.3\,k\Omega$.	$R_5 = 200\,\Omega$.	$C_1 = 0.1\,\mu F$.
$R_2 = 14.0\,k\Omega$.	$R_6 = 1000\,\Omega$.	$C_2 = 25.0\,\mu F$.
$R_3 = 22.0\,k\Omega$.	$R_7 = 1000\,\Omega$.	$C_3 = 8.0\,\mu F$.
$R_4 = 0.5\,M\Omega$.	$R_8 = 5.5\,k\Omega$.	$C_4 = 16.0\,\mu F$.

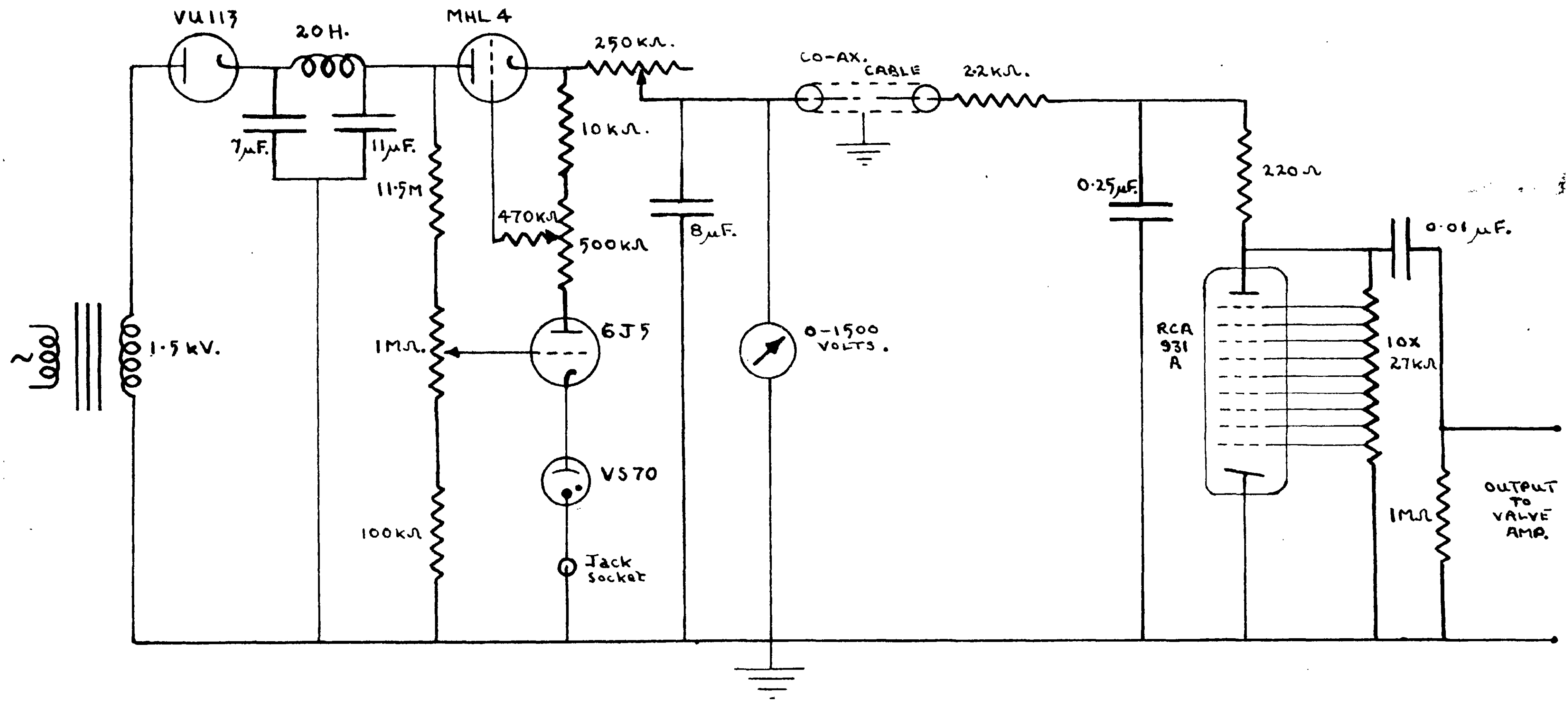


Fig. 5.6. Stabilized E.H.T. supply to photomultiplier circuit.