HIGH VOLTAGE DISCHARGE ALONG A SOLID-TRANSFORMER OIL INTERFACE

BY

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Report of Thesis Examiners

THIS IS TO CERTIFY THAT the members of the examining committee of the Master's thesis of

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have read the thesis and are unanimously agreed that it should be graded Approved.
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ABSTRACT

Flashover across the surface of specimens of polymethylmethacrylate (perspex), polyethylene and tetrafluoroethylene (Teflon), inserted between electrodes which establish an approximate uniform field in transformer oil, was investigated under standard impulse voltages. Successive breakdowns were applied across the specimen surface without restoration of initial experimental conditions, in order to establish the effect of the rate of deterioration of the sample surface on the subsequent dielectric strength. The effect of electro-conductive paint applied to the ends of cylindrical specimens were also considered in this thesis.

The present experiments showed that the flashover values fall into regions. Those corresponding to clean surfaces and those corresponding to surfaces subjected previously to breakdown. When the specimen's surface is clean, no significant difference could be observed between breakdown values for perspex, polyethylene or Teflon. After a track formation on the surface the breakdown strength for perspex remained higher than in the case of polyethylene and Teflon with Teflon giving the lowest values.

In general breakdown voltages across the sample surface with ends painted were lower than those for specimens without painted ends, as long as the surface was clean. In the latter

cases without painting the ends consecutive breakdowns followed the same tracks along the surface, but with painted ends multiple track marks were observed.

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CHAPTER I

INTRODUCTION

Most high voltage apparatus consist of solid insulating structures supporting conductors, immersed in a vacuum, gas or liqid medium. In such complex insulating systems, the weakest link is usually the interface of the solid insulator and the medium. In order to investigate this problem and establish design criteria, surface flashover across cylindrical solid dielectrics inserted between uniform field electrodes have been the subject of many investigations[1,2,3].

With the occurance of a flashover across the solid dielectric surface in any medium, changes occur in the properties of the sample surface, moisture content of the medium, and the electrode surface. These factors generally reduce the dielectric strength, unless the initial experimental conditions are provided.

In breakdown studies of composite insulating structures such as solid-gas or solid-liquid the ends of the test samples are usually coated with a conductive film. The purpose of the film is to eliminate possible discontinuities in electric field distribution which might arise in voids situated at the electrode-sample interface.

In vacuum it has been found that the paint or metal coating on sample's ends reduces the insulating strength[3].

As far as liquid insulating system is concerned, however, comparable investigations and data are limited to a few statements in books and papers which discuss surface discharges across solid-liquid interfaces using Lichtenberg Figure[4], Dust Figure[5] and high speed camera techniques[6]. The majority of these investigators dealt predominantly with simple insulations inserted between rod-plane electrode systems and did not consider the effects of the electro-conductive paint.

The present investigations were carried out with cylindrical shaped polymer samples placed between electrodes which produce an approximate uniform field, and the whole assembly was immersed in transformer oil. The deterioration rate of solid insulators and extent of reduction of flashover voltage due to successive breakdowns without restoration of initial experimental conditions were investigated. Also the effects of conductive paint on the ends of samples were compared with flashover voltage obtained when samples were not painted.

1-1 SOLID INSULATING MATERIAL IN TRANSFORMER OIL

Historically, transformer insulation consist of a composite insulation system which is mainly oil, pressed-board and craftpaper. The change from cellulose to other insulants has been mainly a question of economics and lack of reliable information of performance under heat and oil.

Polymer science has been developing rapidly, and some of the new plastics have far better dielectric characteristics in air than papers; namely power dissipation factor and tracking resistance. These plastics are finding wide application as electrical insulants. As far as insulation system in transformer is concerned, however, plastics are rarely used. This is mainly due to economical reasons and also because of lack of information concerning behaviour of composite insulation system of oil and plastics.

In general, once flashover takes place along the oil-solid interface, changes occur in the insulating system, such as moisture content of oil, the electrode surface and the solid specimen surface. These factors make it difficult to obtain consistent flashover data. In this present investigation, flashover voltages across the oil-solid interface were measured for polyethylene, perspex and Teflon specimens without controlling the above factors.

CHAPTER II

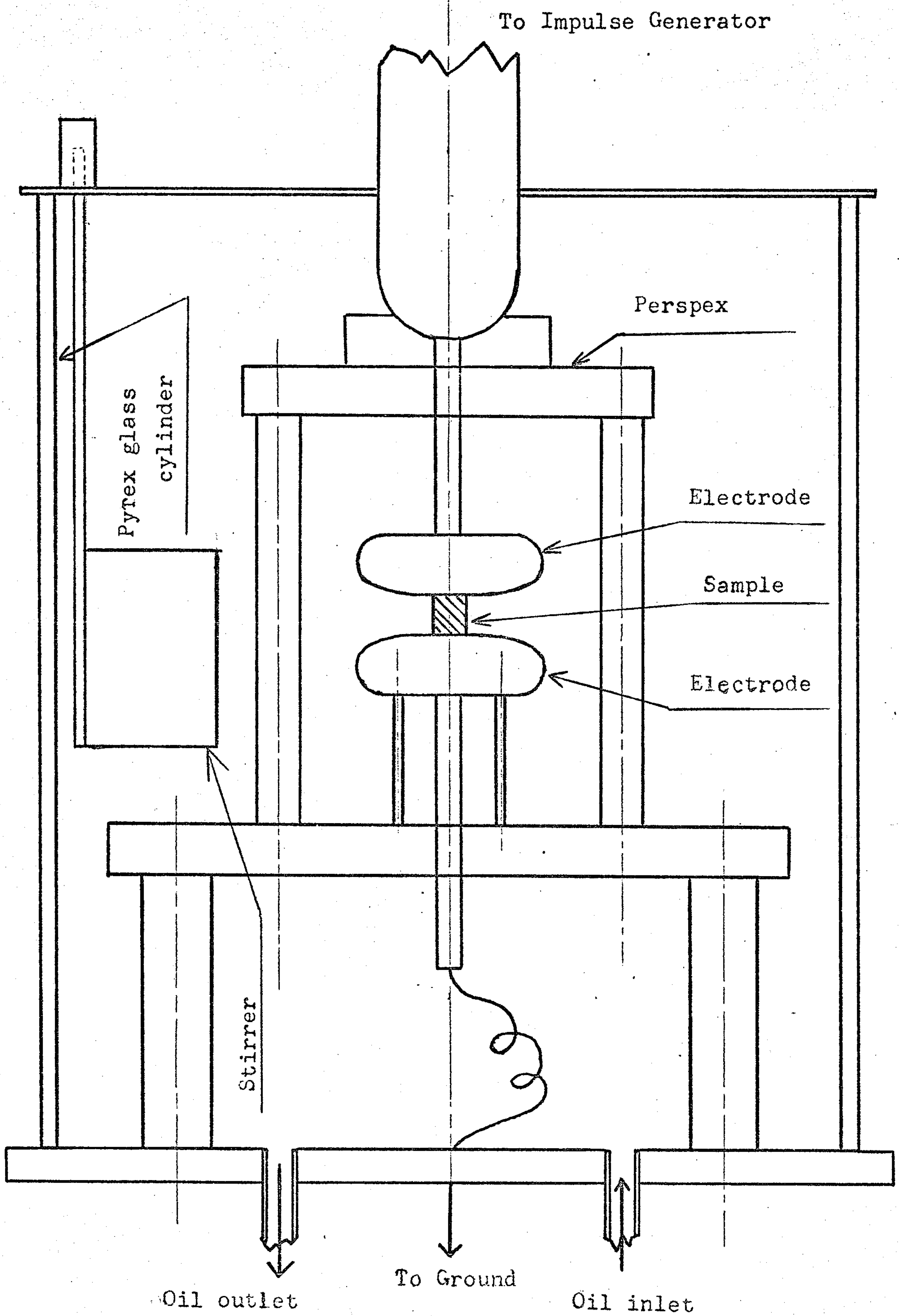
EXPERIMENTAL APPARATUS AND PROCEDURE

2-1 THE TEST CELL

The test cell is shown in Fig.2-1. It consisted of a pyrex-glass cylinder, 34.6 cm (centimeters) in height and 30 cm in inner diameter. The cell housed two nickel-coated electrodes and their holding system made of plexiglass, shown in Fig. 2-2.

The shape of electrodes is shown in Fig. 2-3 in full scale. This electrode configuration was proposed by Bruce[7] to produce a uniform field for spacings up to 2.54 cm. The upper electrode used in this work has a small projection at its centre, the purpose of which was to hold the sample inserted into the gap between the electrodes in position. At the begining of this work, neither electrodes had a projection. When flashover occured along the interface, the shock following the discharge tended to blow the sample out of the gap. If the discharge current was small enough, the sample might have remained in position, but the smaller current means the higher limiting current resistance, and thus the time constant of the high voltage circuit becomes longer and this causes error in measurement of flashover voltage. Therefore, the small projection was made at the centre of the upper electrode, as shown in Fig. 2-3. The dimension of

Fig. 2-1 Test Cell



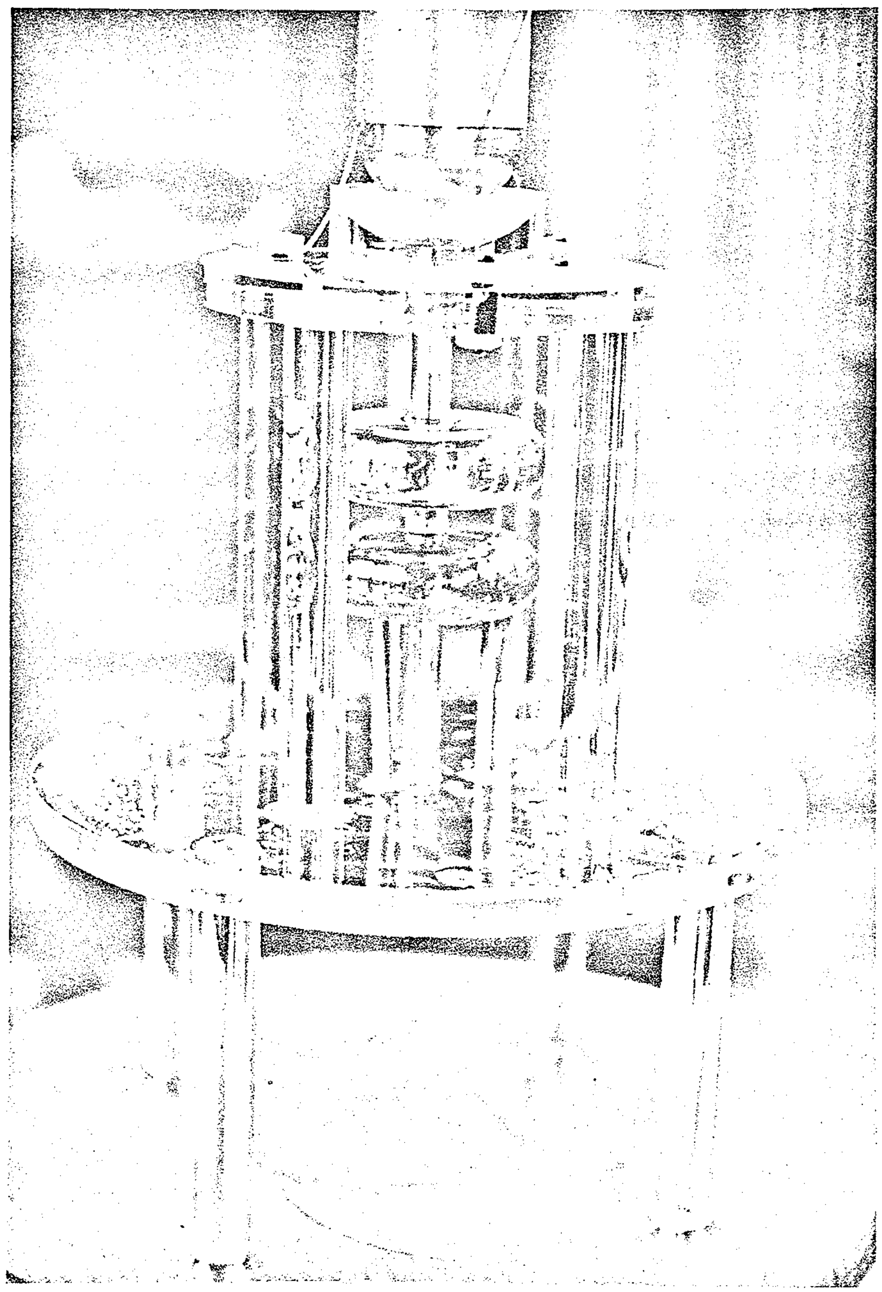


Fig. 2-2 The Electrode System

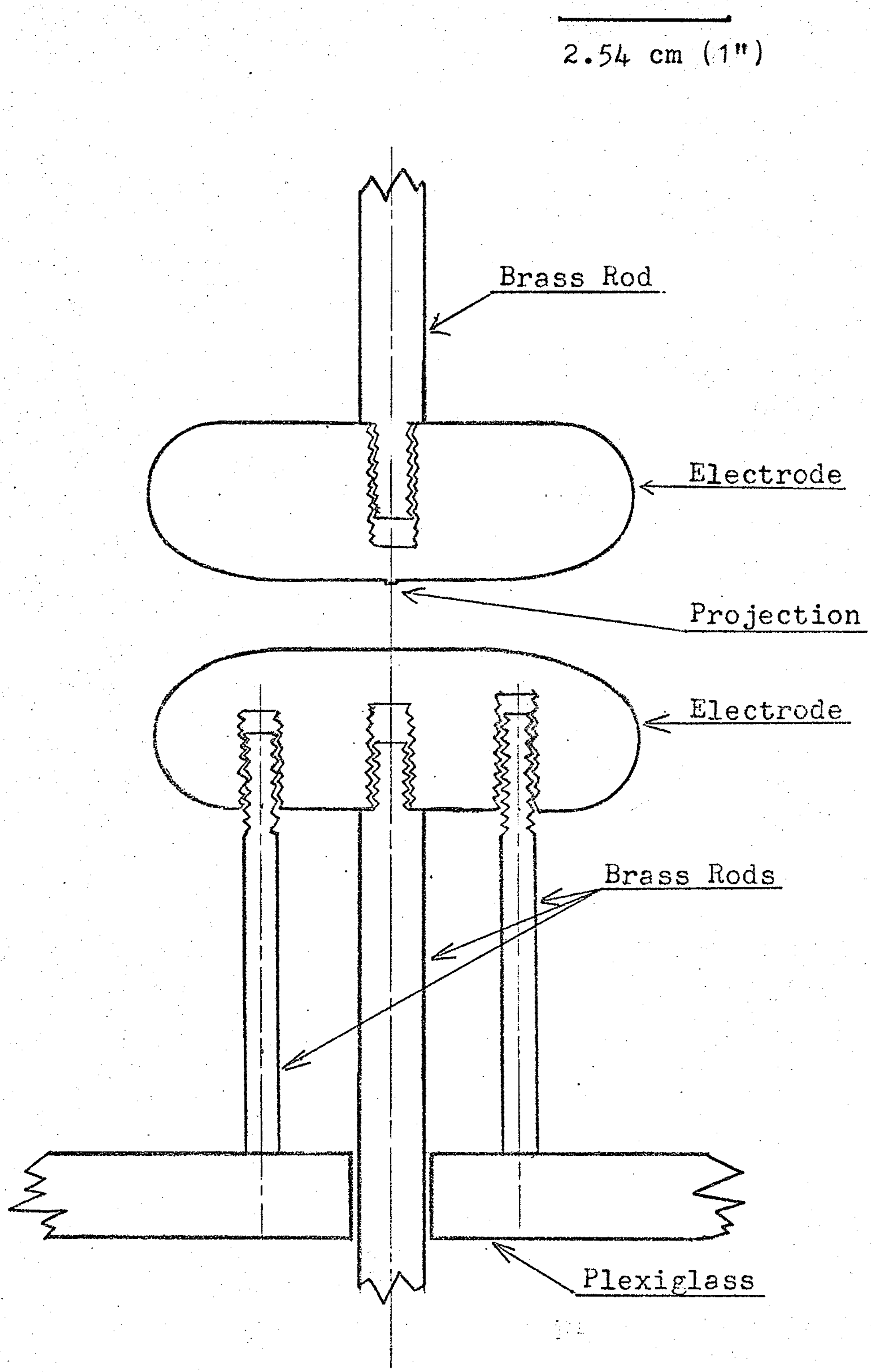


Fig. 2-3 Electrodes

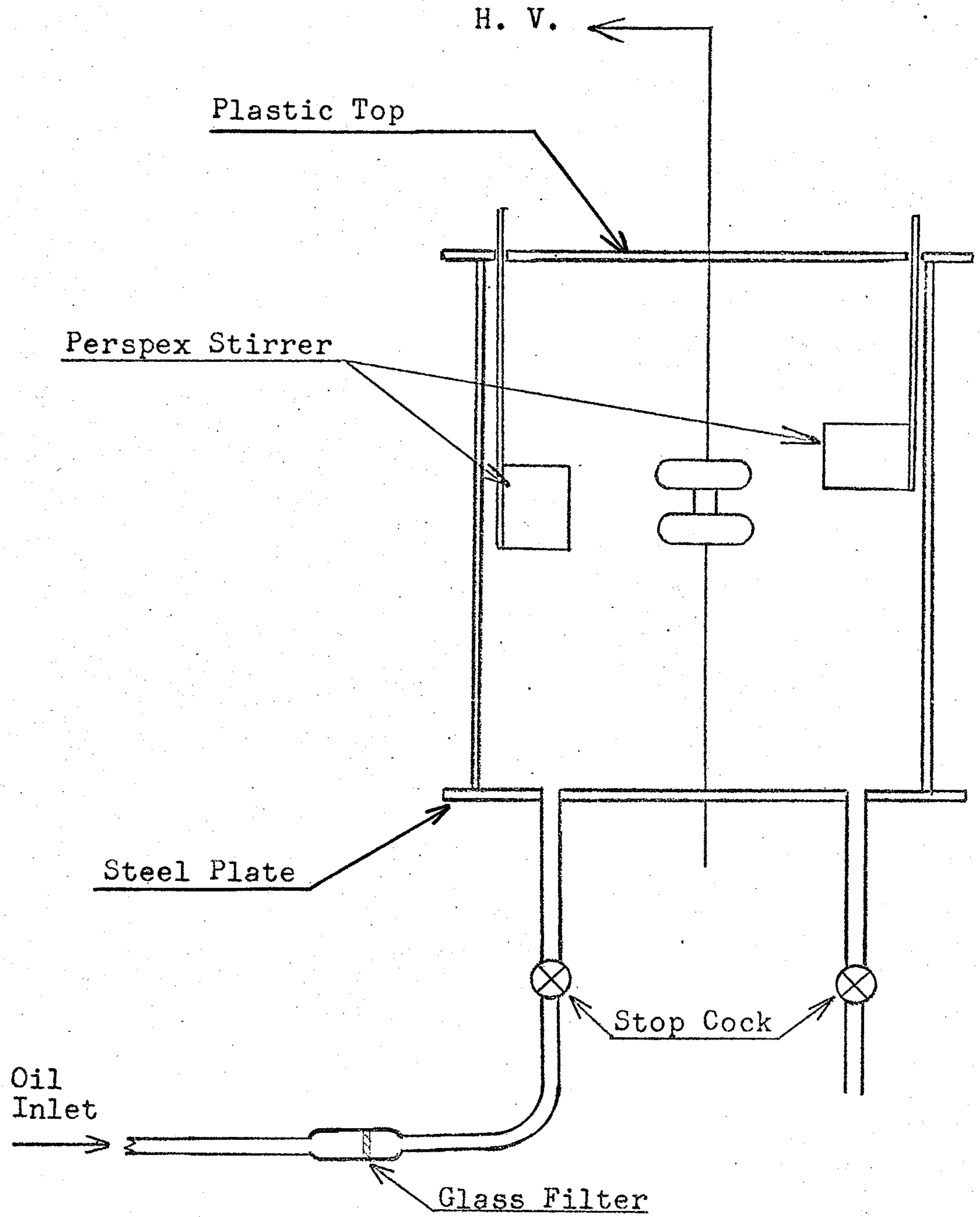


Fig. 2-4 Filling the Test Chamber

this projection is 1.5 mm (millimeters) in diameter and 0.8 mm in height, and it has round edge so that it is considered not to distort the field around the sample surface.

The cell was filled with transformer oil, Esso Voltesso 35, which passed a minimum breakdown voltage test of 30 kilovolts using ASTM method D877 and is regarded suitable for use in switchgears and transformers.

The method adopted for filling the test cell is shown in Fig. 2-4. The oil enters the cell through a 10 micron sintered glass filter at rate of approximately 1 ml (millilitre) per second. The cell was filled from the bottom to prevent the formation of air bubbles. When a solid sample was changed, oil was changed and both electrodes were polished with a metal polish liquid and cleaned with accetone.

The cell housed two stirrers but only one of them is shown in Fig. 2-1. They were made of plexiglass and were operated manually. Their function was to drive bubbles from the undersides of the electrodes after each breakdown and aid in circulating the oil in the cell.

2-2 TEST SPECIMENS

Since the diameter of the flat portion of the electrode is 2.54 cm, the sample diameter and its height must be chosen to be less than 2.54 cm such that the electrode system produces a uniform field in the gap[7]. The material for test samples used in this work were perspex, polyethylene and

Teflon supplied by Johnson Industrial Plastics Ltd., Toronto, Canada.

In the initial stage of the experiments, the sample size was 1.27 cm in diameter and 1 cm in height, and all samples had both ends painted with a conducting silver paint (G. C. No. 21.1 made by G.C.Electronics). Experiments were tried with the same size samples which were not painted, in order to check the effect of the conductive paint. But, before the impulse voltage reached the required value to cause breakdown across the sample surface, flashover occured along the outside of the test cell from the bushing to base plate. Following this observation, the sample height was reduced to 0.635 cm in order to measure the flashover voltages of the unpainted samples. Therefore, as far as 1 cm-high samples were concerned, flashover voltages were measured only for painted samples.

All samples were cut from long cylindrical rods, machined and sanded with No. 600 sandpapers so that the samples measured to 1.27 cm in diameter and 1 or 0.635 cm in height accurate to within ± 5% error, and were cleaned with Accetone. The ends of the samples were carefully painted with silver paint and dried in air, and care was taken to prevent any settlement of dust.

2-3 THE HIGH VOLTAGE SUPPLY

The experimental circuit for obtaining surge voltages is shown in Fig. 2-5. A conventional Marx type impulse

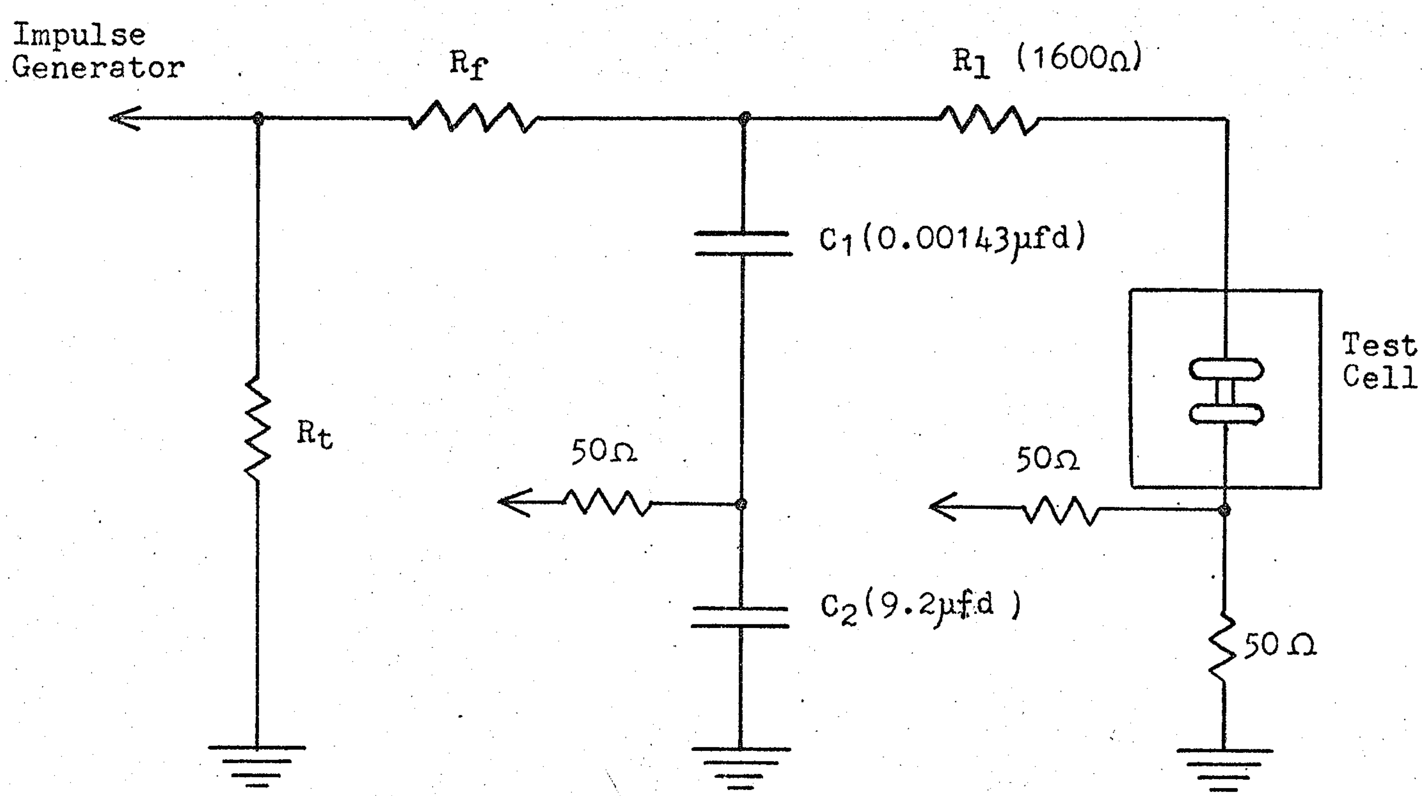


Fig. 2-5 High Voltage Circiut

generator of 24 stages with 100 KV per stage was available for the experiments, and the first 8 stages were used.

A capacitance devider of 0.00143 μfd was used for voltage measurement in all tests. The desired voltage waveshape was obtained by using appropriate external wave front and wave tail resistors (R_f and R_t). In this work, an approximate standard impulse (1.7/ 45 μsec.) was mainly used, and in this case R_f and R_t were 300 ohms and 2300 ohms, respectively. Several tests were carried out with 20/120 μsec. waveshape in addition to the standard wave, in order to compare the effect of the waveshape upon the breakdown value. For the 20/120 μsec. impulses, a 14 kilohms and a 85 kilohms resistor were used as a wavefront and a wavetail resistor, respectively.

The specimen's surface deteriorates gradually by surface flashovers. Thus the subsequent flashover occurs under different circumstances from the previous surface condition. As the surface condition changes from breakdown to breakdown, neither the 50% breakdown values nor the average values are significant. Therefore the normal breakdown technique was adopted as the method of applying a high voltage impulse. The normal technique consists of estimating or determining by trial the approximate surface breakdown strength of the sample and then applying a sequence of impulses, starting at a level well below the anticipated breakdown value, and successively increasing the voltage level with constant increments. In this work the constant increments in voltage level were 10 kilovolts.

An important factor to consider is the time interval allowed between successive impulse applications. In deciding upon what time interval is to be accepted two factors must be taken into account; the effect of discharge products caused by previous breakdown upon the subsequent breakdown and the charging time for the impulse generator.

After each breakdown, it was necessary to shut the generator off and then sweep away the bubbles produced on the undersides of the electrodes. This was accomplished by manually turning the stirrers in the test cell. In many cases this took a considerable period of time as many of the bubbles were very small and had a tendency to jump off the plate into the body of the liquid when stirred and then slowly rise to the undersides of the electrodes again. Once all the bubbles were removed, the oil was vigorously stirred and allowed to settle for ten minutes. The oil was not stirred after an impulse application which failed to produce a breakdown as preliminary investigations showed that no noticeable bubbles were formed by voltage applications, and the time period between impulses was one and half minutes which was required for the charging of the generator.

CHAPTER III

EXPERIMENTAL RESULTS AND DISCUSSIONS

Flashover voltages across the oil-polymer interface were measured with perspex, polyethylene and Teflon specimens, using a standard wave. Several experiments were performed on a 20/120 μsec. surge in addition to the standard wave.

As mentioned earlier it was not possible to obtain a flashover across the oil-sample interface when the ends of the samples (1 cm in height, 1.27 cm in diameter) in contact with the electrodes were left unpainted. Therefore later tests were performed with 0.635 cm high samples which had painted or unpainted ends.

3-1 EXPERIMENTAL RESULTS

Most of the results obtained using the standard wave are shown in Figures 3-3 to 3-32, with the exception of those obtained with a 20/120 μsec. surge which are included in Appendix I. All results shown in Figures 3-4 to 3-32 relate to 0.635 cm high and 1.27 cm diameter samples, excepting Fig. 3-3 which relates to 1 cm high samples.

Fig. 3-3 shows flashover voltages across the surfaces of 5 perspex samples with silver painted ends. From this figure, it can be seen that as long as the sample surface is clean flashover voltages obtained for new samples are usually higher than those obtained after deterioration was produced across the surface and also the results are widely scattered.

3-2 FLASHOVER VOLTAGES ACROSS PERSPEX SPECIMENS' SURFACE

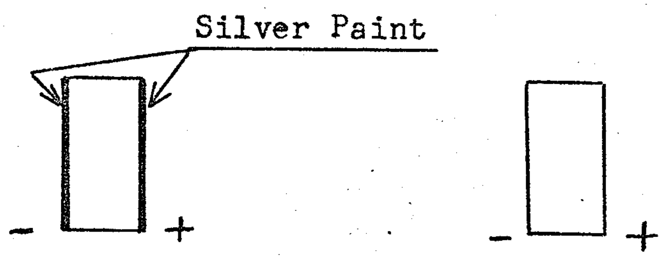
Figures 3-4 to 3-9 show results obtained using standard impulse voltages for 6 perspex samples of 1.27 cm diameter and 0.635 cm high. The results relate to specimens with ends painted as well as to those without painting the ends. In the same figures are shown diagramatically the progressive formations of tracks with number of applied impulses as observed visually after flashover. The heavy lines drawn along the sample ends such as those in Fig. 3-1 represent the silver paint.

The shape of the sample was cylindrical, and it was inserted into the gap between electrodes as shown in Fig. 3-2.

Upon examination of Figures 3-4 to 3-9 the following comments may be made. First, the initial flashover voltages of painted samples (about 160 KV) tends to be lower than those (about 200 KV) for the case of unpainted ones. This can be seen in spite of the scatter present. Second, as far as unpainted samples are concerned the first few breakdown values are considerably high (about 200 KV) until the complete track is formed, and then breakdown voltages decrease to lower values (70 - 170 KV) as soon as the track is formed.

When using unpainted samples, the failure always resulted in a single track. Thereafter successive breakdowns took place along the same path. In the case of painted samples, however, several tracks originate, one of them eventually leading to flashover. Furthermore successive breakdowns do not necessarily start at the same locations nor are the patterns exactly the same. It appears that this difference is mainly due to the irregularities at terminations of the painting layers which must have come about in spite of the precautions taken to ensure the contrary.

In the case of painted samples it may be considered that a flashover starts from one of the irregularities which subsequently is burned off. The next breakdown depends on the field strength along the path of the eroded track produced by the previous breakdown and on the local field concentrated at another irregularity. If the former field strength is lower than the latter, the path of the next flashover is initiated at a different place from the previous one. Therefore, several tracks were produced after many successive breakdowns in the case of painted samples.



(a) Painted Sample (b) Unpainted Sample

Fig. 3-1 Samples (cylindrical)

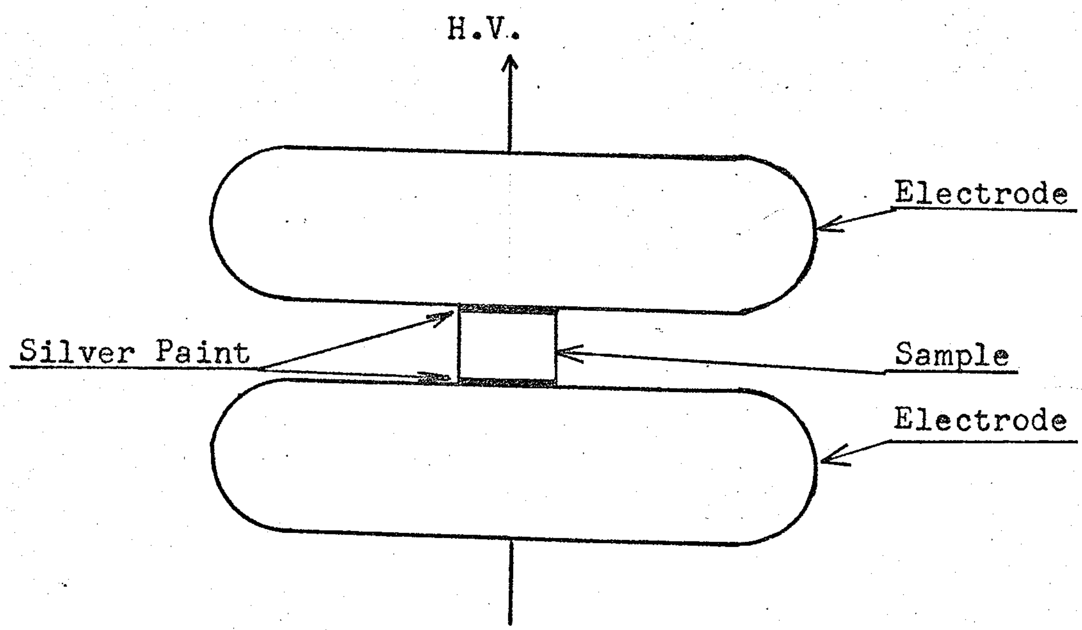


Fig. 3-2 Sample Inserted into Gap between Electrodes

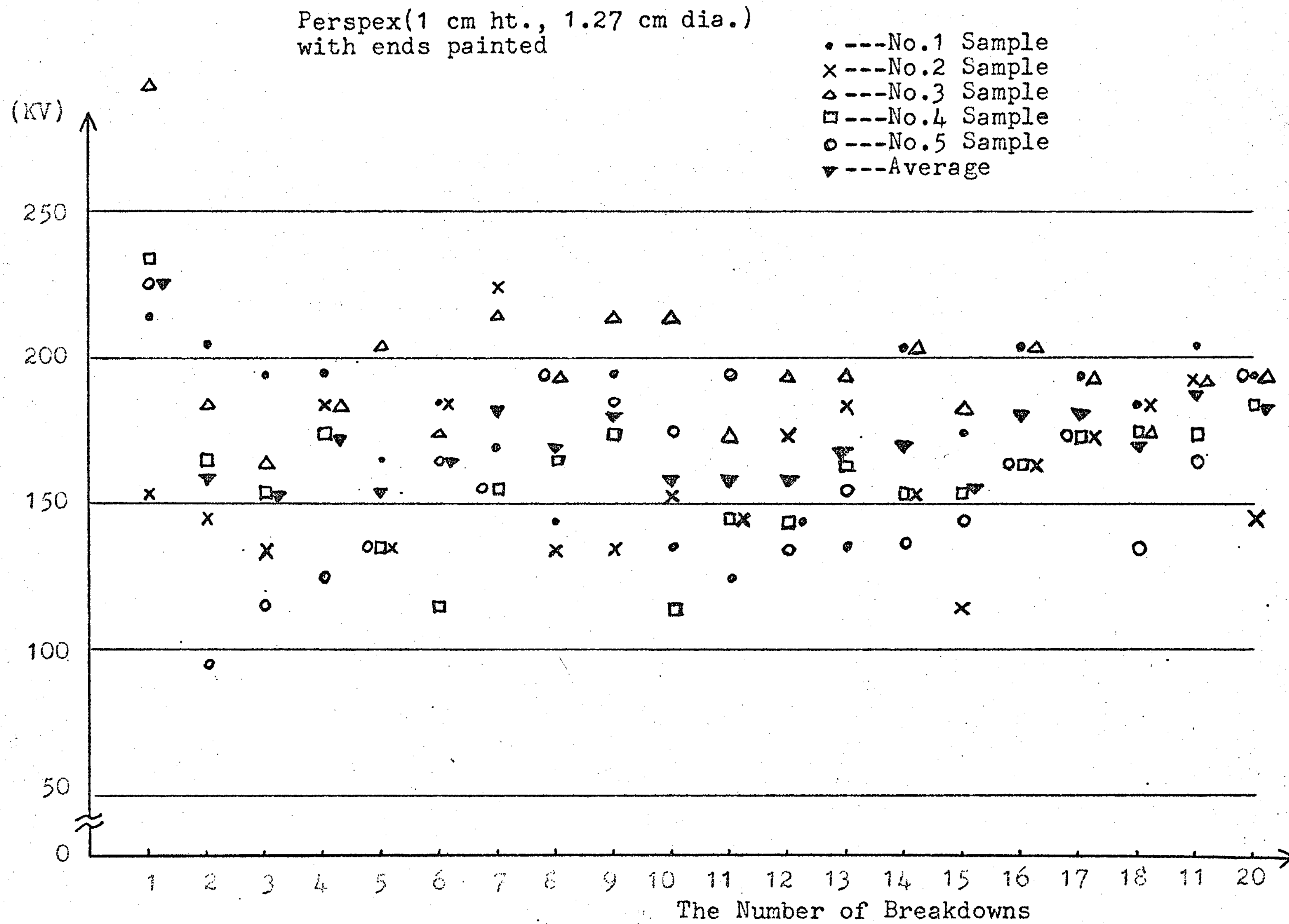


Fig. 3-3 Breakdown Voltage across Perspex Surfase

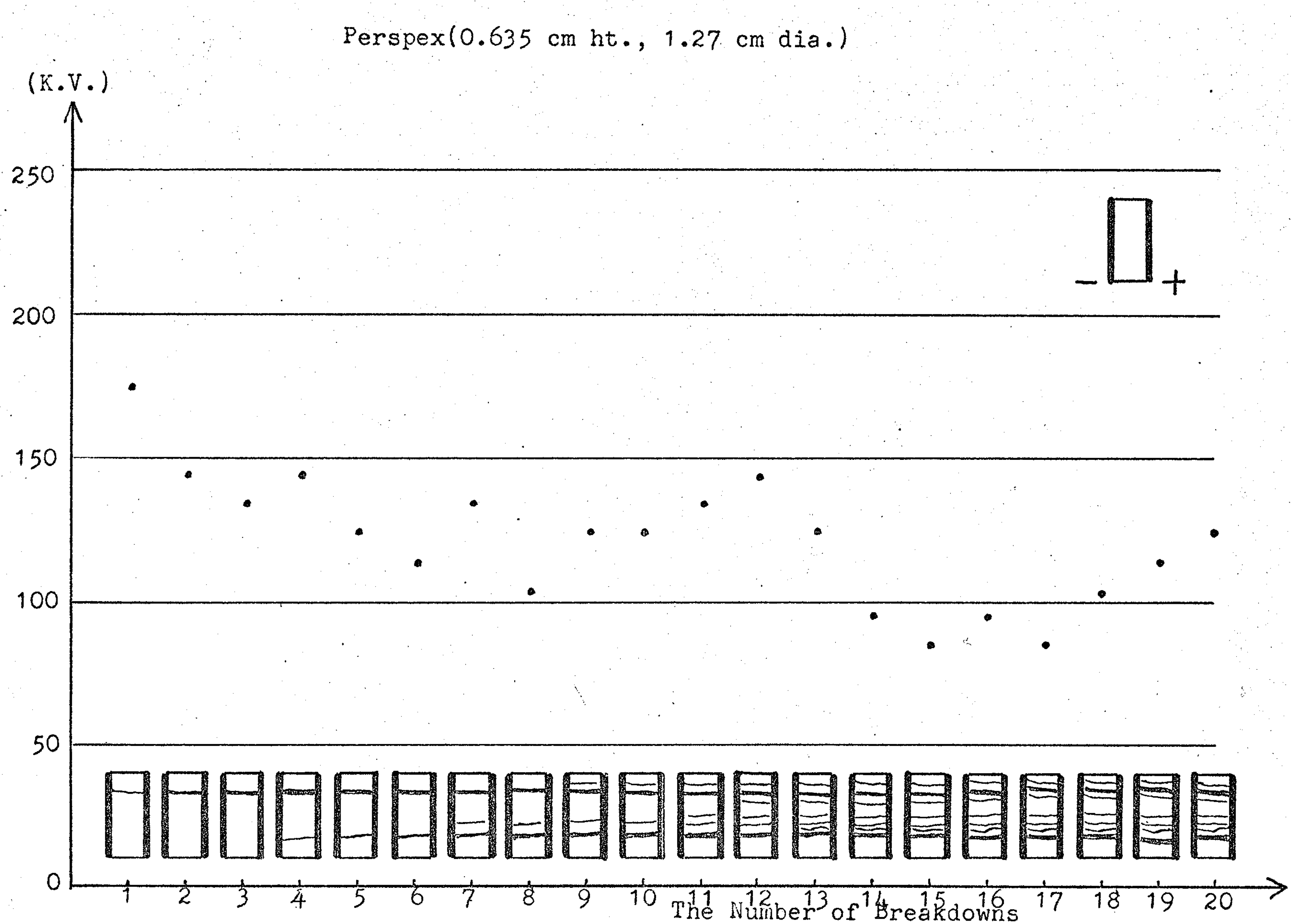


Fig. 3-4 Breakdown Voltage across Perspex Surface

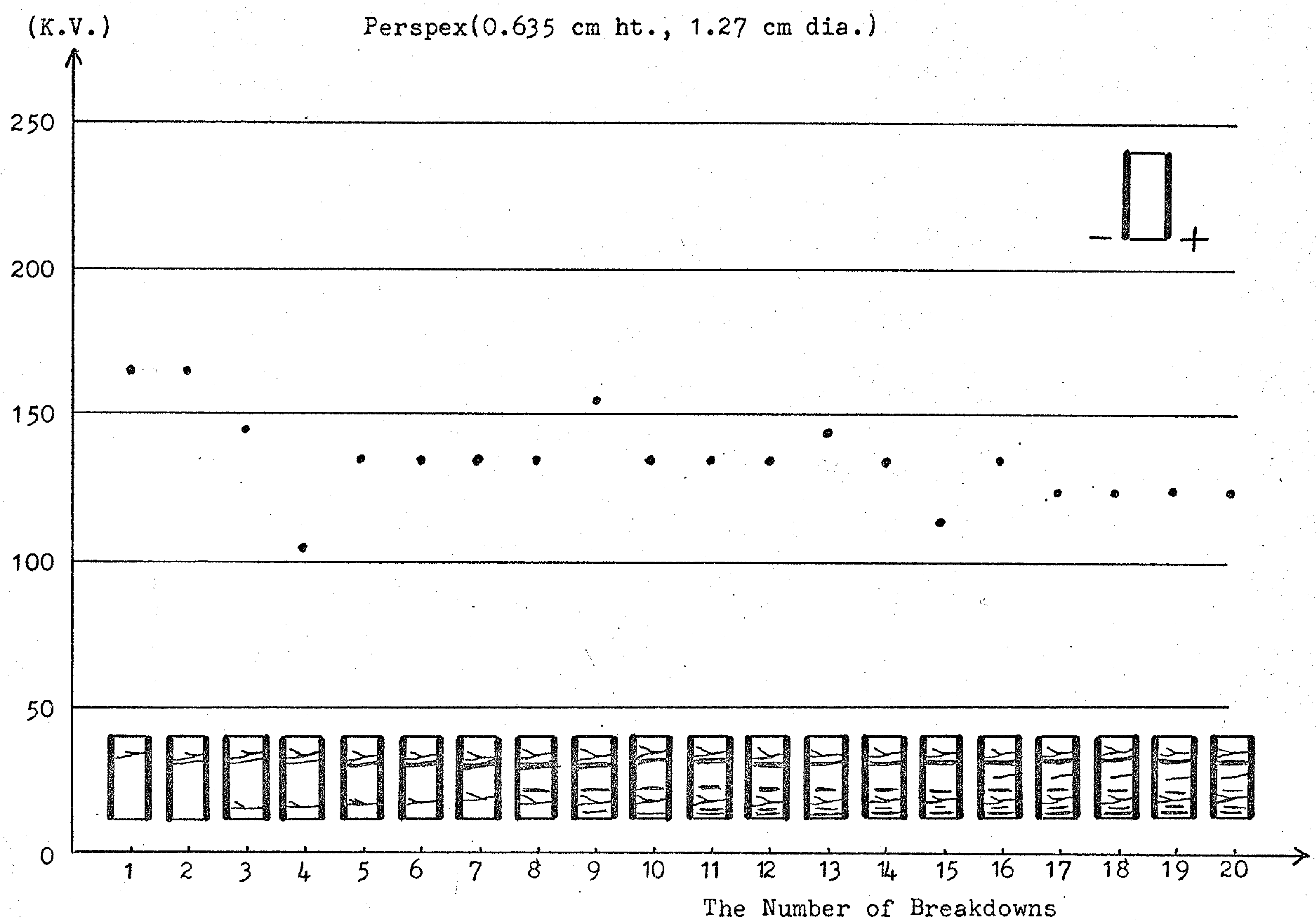


Fig. 3-5 Breakdown Voltage across Perspex Surface

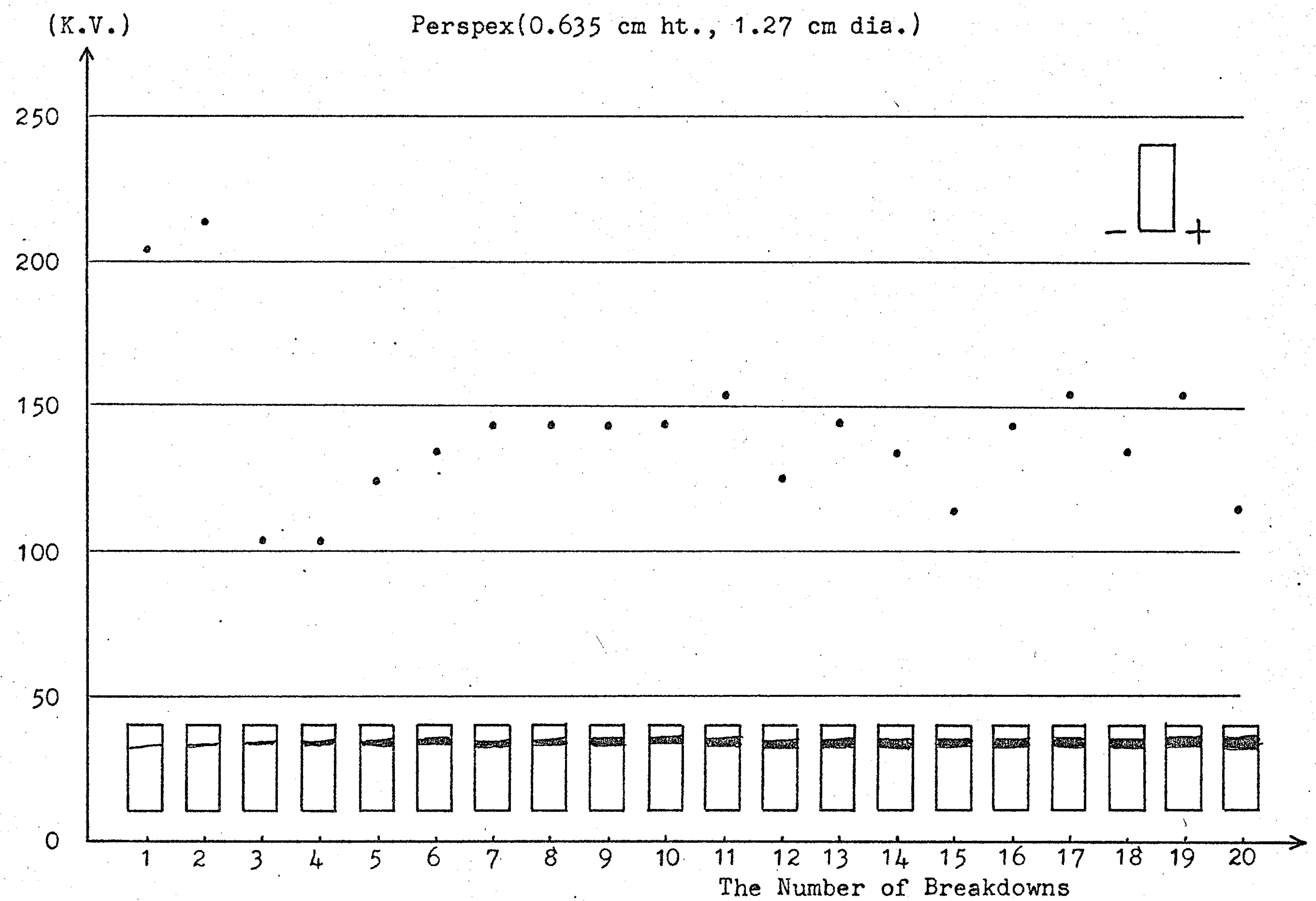


Fig. 3-6 Breakdown Voltage across Perspex Surface

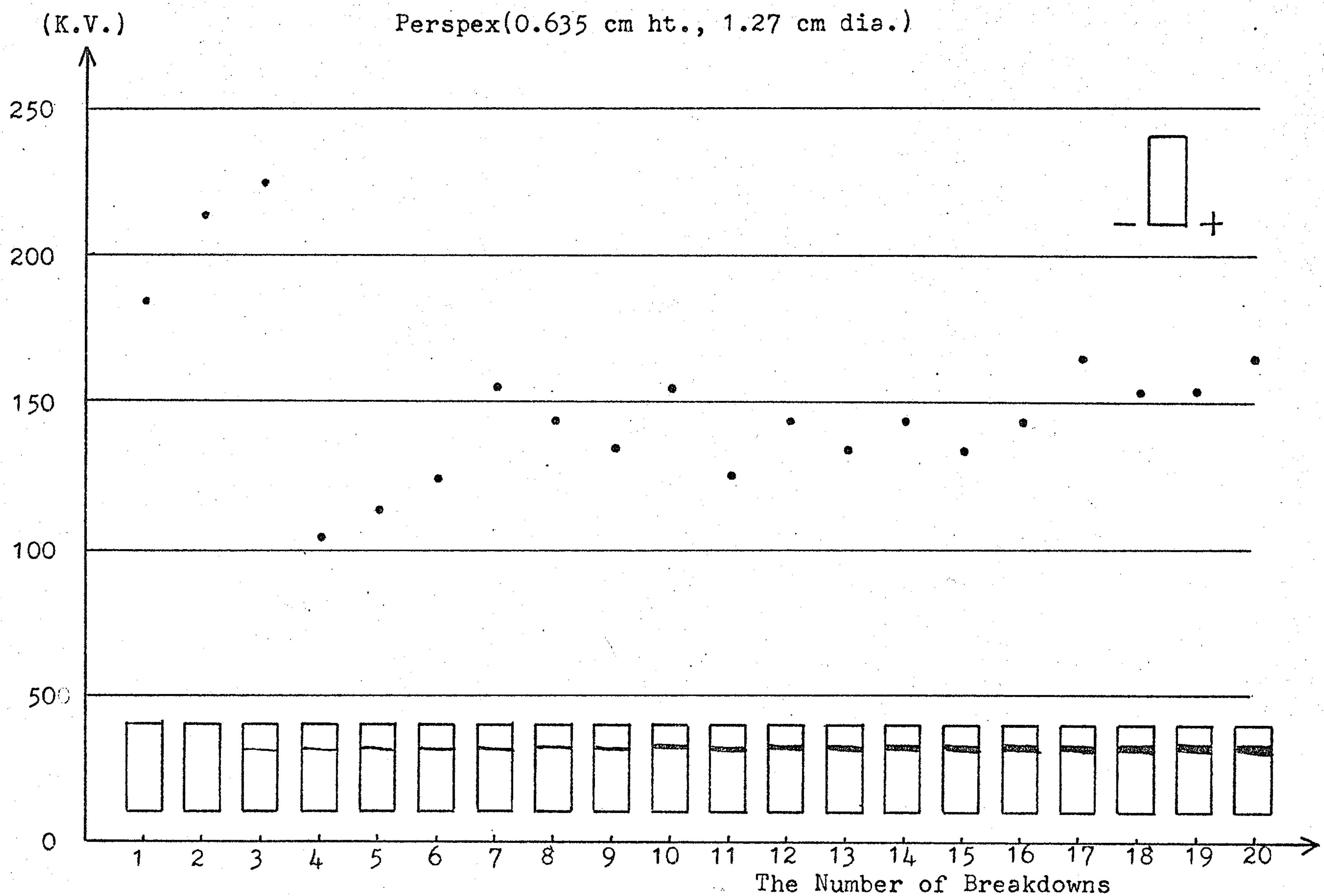


Fig. 3-7 Breakdown Voltage across Perspex Surface

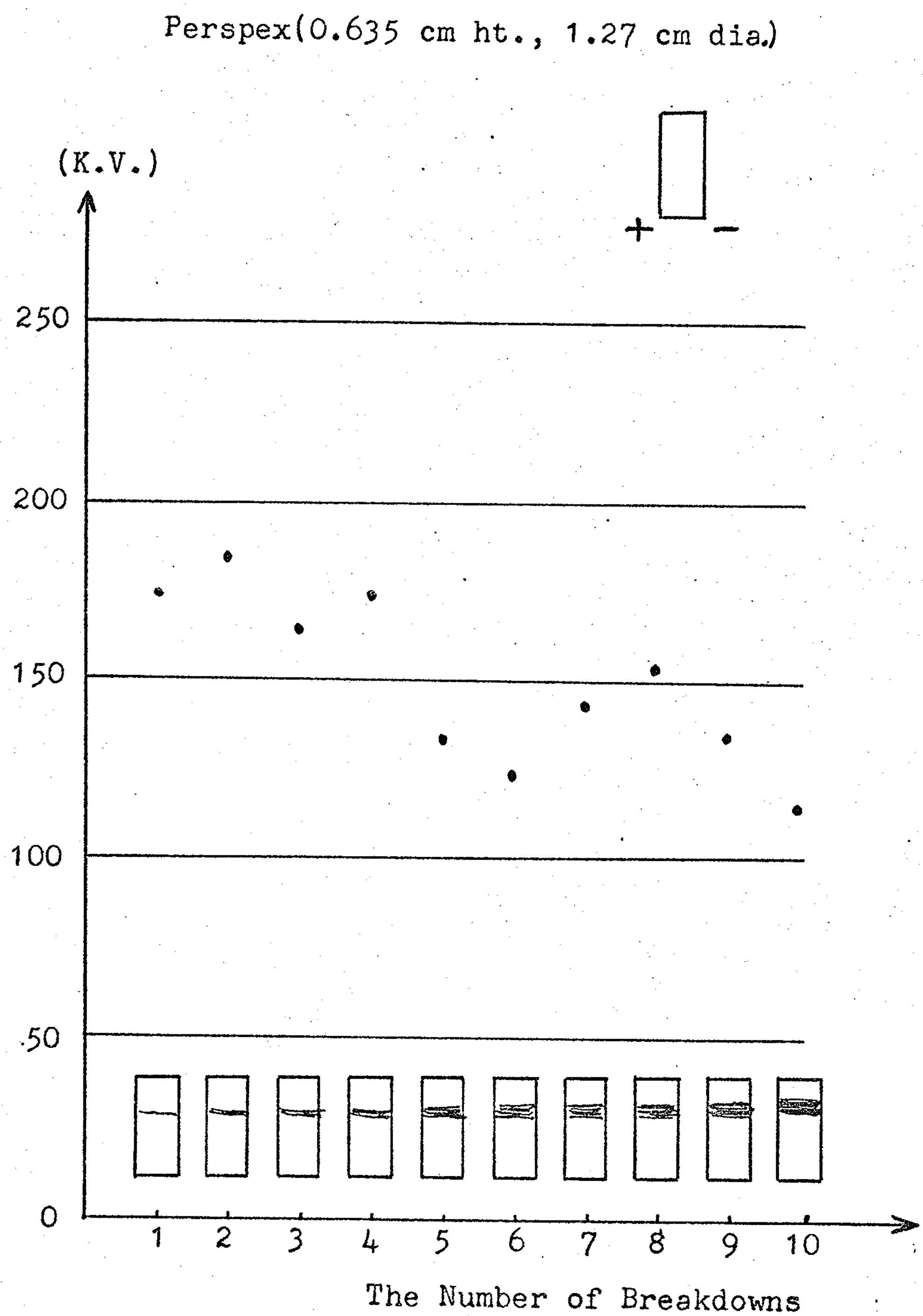


Fig. 3-8 Breakdown Voltage across Perspex Surface

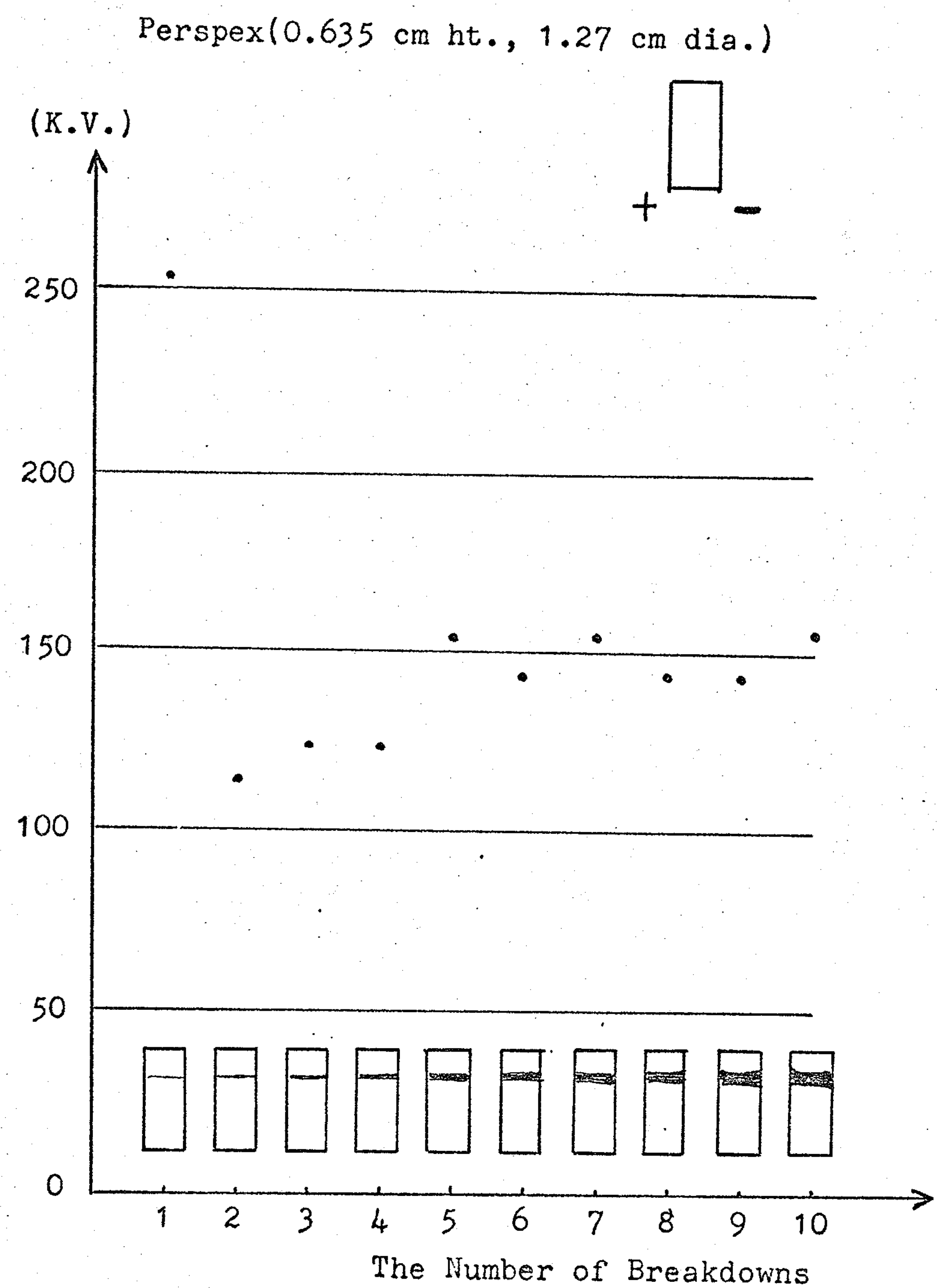


Fig. 3-9 Breakdown Voltage across Perspex Surface

3-3 FLASHOVER VOLTAGES ACROSS POLYETHYLELE SPECIMENS' SURFACE

Figures 3-10 and 3-11 show results obtained with the use of standard wave impulses and painted polyethylene samples of 0.635 cm high and 1.27 cm in diameter. Figures 3-12 to 3-16 show results obtained using the same impulses and unpainted samples of the same size as the above.

From these figures, it is seen that the results for polyethylene are more scattered than those for perpex, but no significant difference in flashover voltages for polyethylene could be observed between the samples with painted and the unpainted ends.

As far as the painted samples are concerned the first few breakdown voltages range from 140 to 180 kilovolts approximately; subsequent breakdown values range from 70 to 130 kilovolts because of track formation on the sample surface. For the same reason breakdown values for unpainted samples are as low as 80 - 150 kilovolts after the first few breakdowns which are around 200 kilovolts. The tendency of the decrease in breakdown value as mentioned above was also observed for perpex samples, but the rate of the reduction of breakdown values was not as great in the case of the painted perspex samples as was observed with the painted polyethylene samples.

From the Figures 3-10 to 3-16, it can be seen that the manner of deterioration is different from that of perspex samples; i.e. even for unpainted polyethylene samples some multiple track marks could be observed. Another significant observation was a deep erosion (about 1 mm deep from the sample surface) which was produced by some breakdowns applied since the surface deteriorated, and the subsequent breakdown voltages drop to 60 kilovolts approximately as soon as the deep erosion formed. In the case of perspex samples the depth of erosion was so small that it was not measurable. Trace marks of the deep erosion are represented by dotted lines in the Figures.

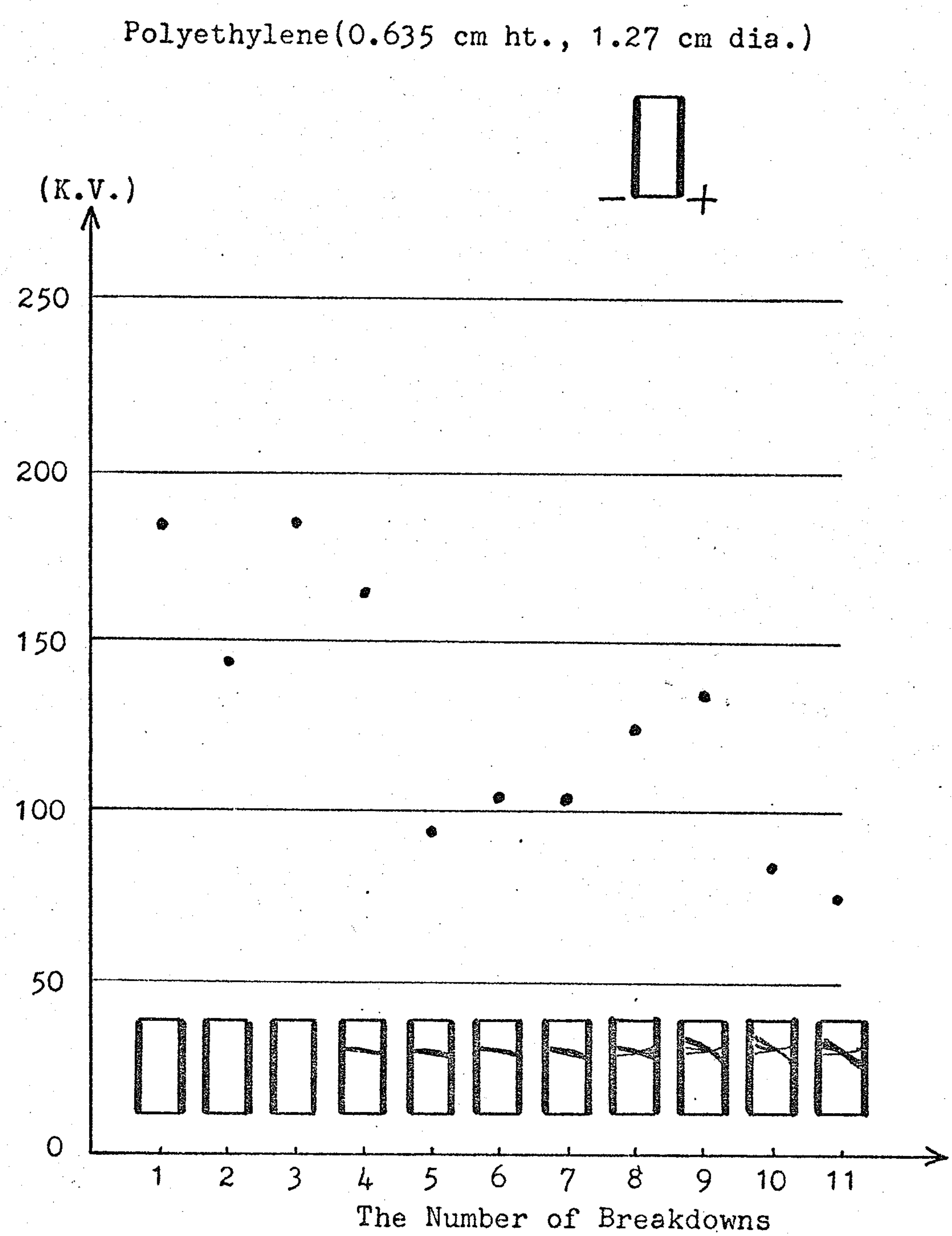


Fig. 3-10 Breakdown Voltage across Polyethylene Surface

Polyethylene(0.635 cm ht., 1.27 cm dia.)

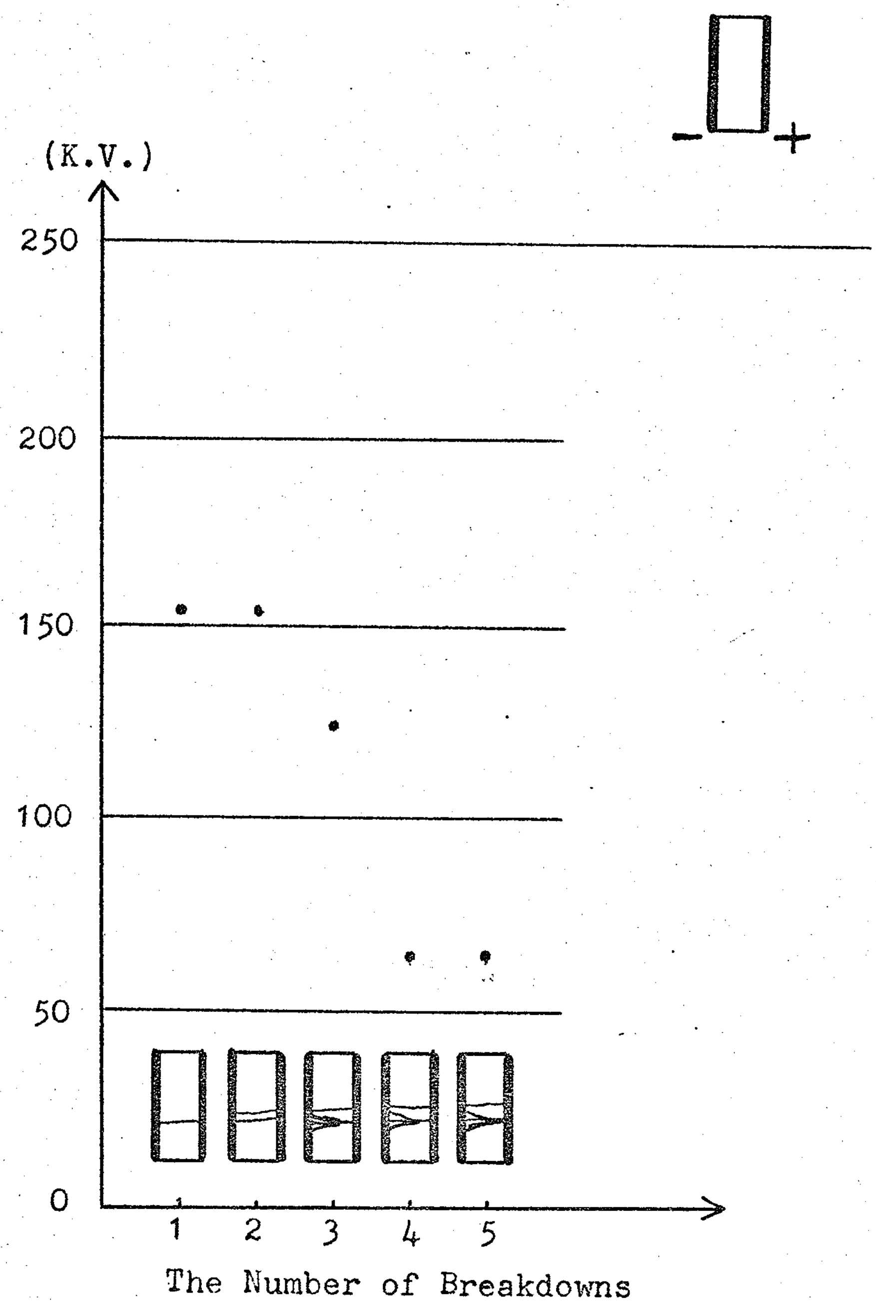


Fig. 3-11 Breakdown Voltage across Polyethylene Surface

Polyethylene(0.635 cm ht., 1.27cm dia.)

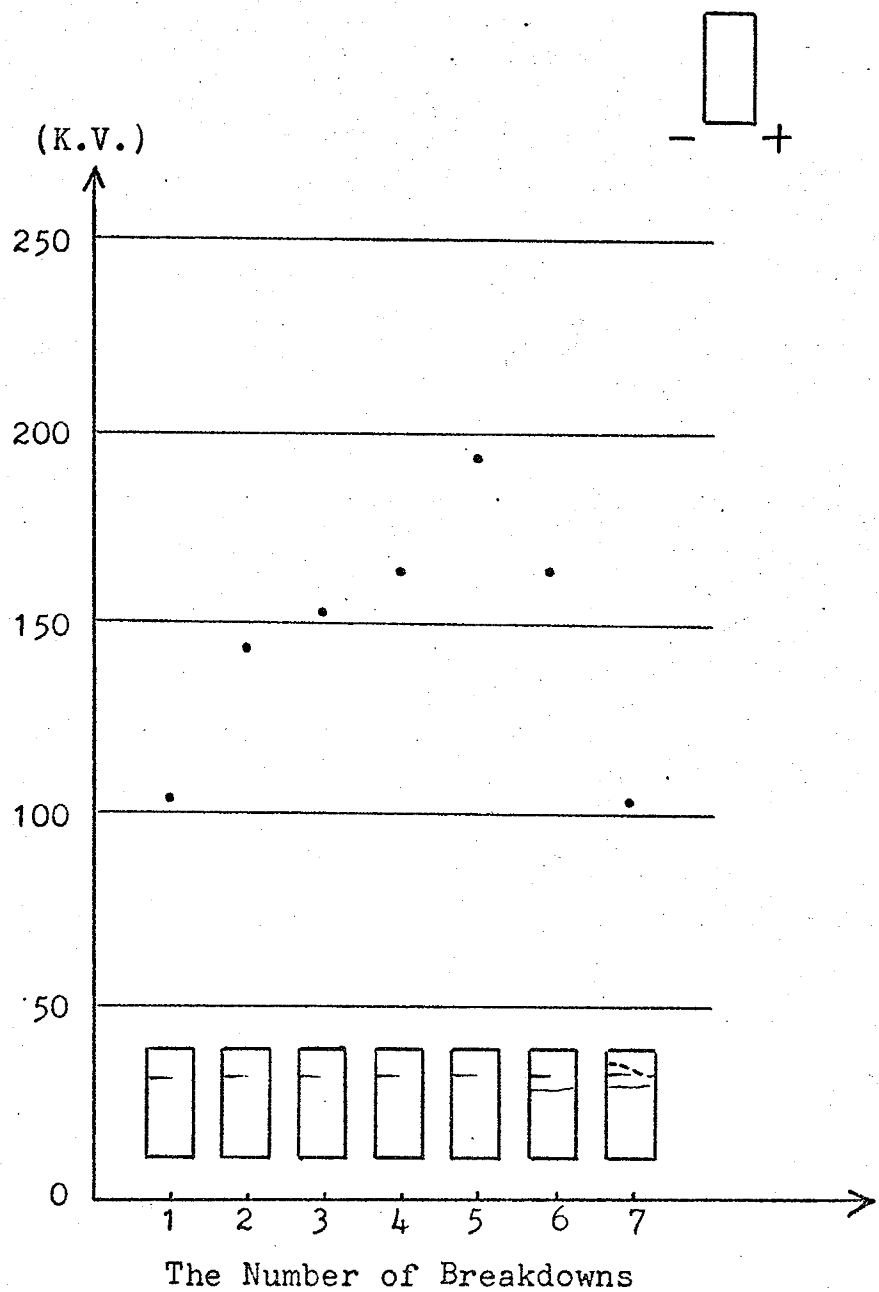


Fig. 3-12 Breakdown Voltage across Polyethylene Surface

Polyethylene(0.635 cm ht., 1.27 cm dia.)

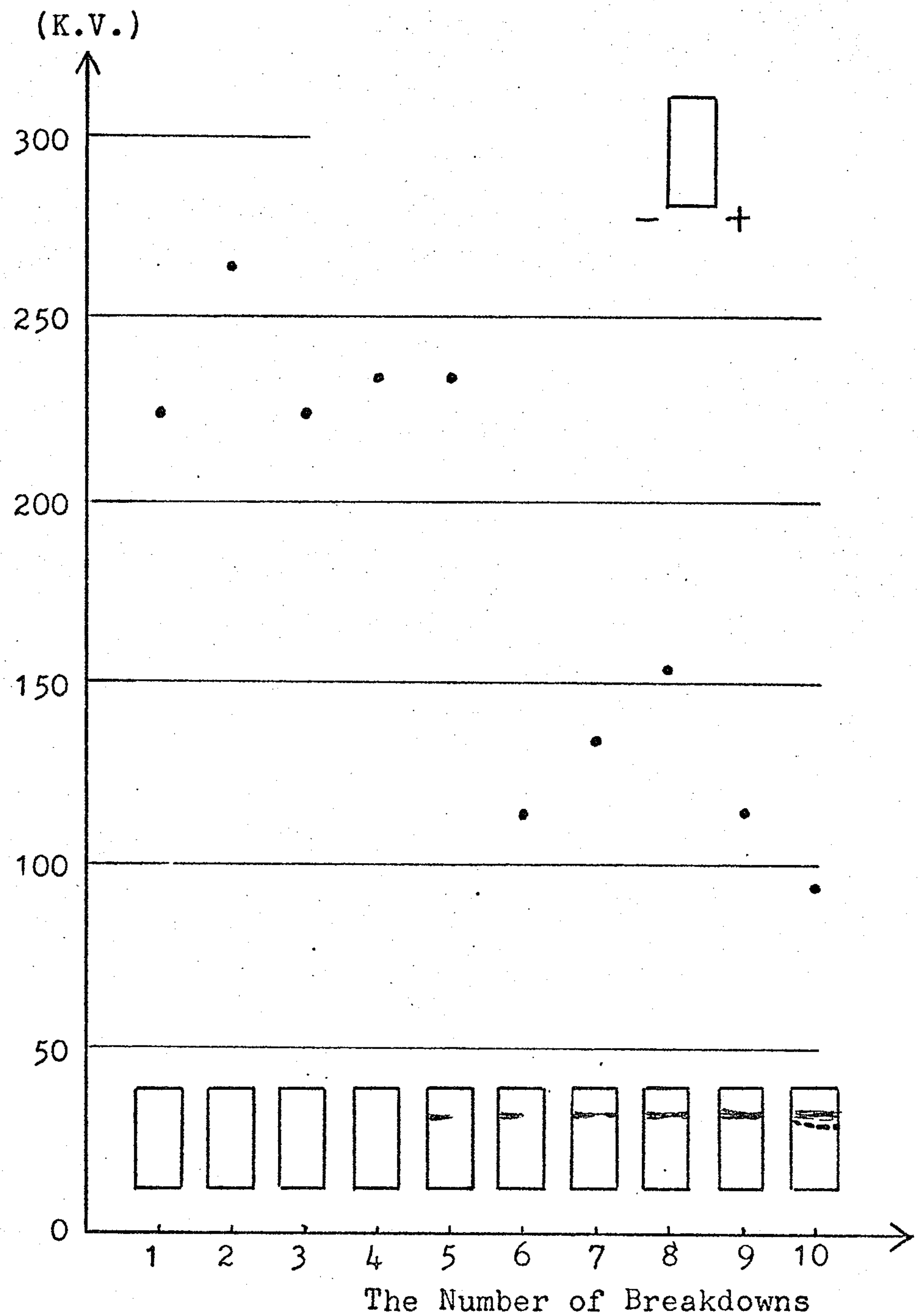


Fig. 3-13 Breakdown Voltage across Polyethylene Surface

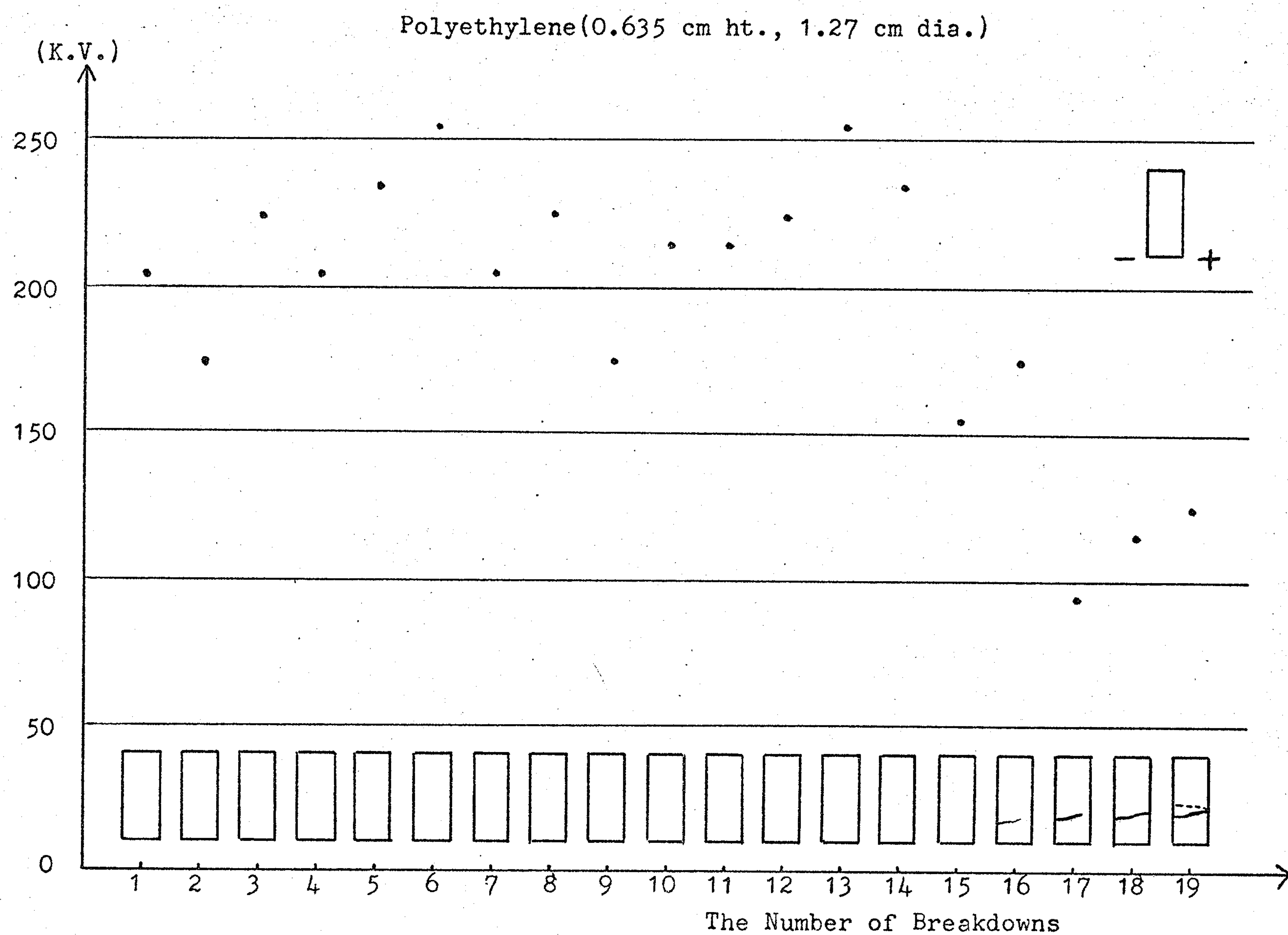


Fig. 3-14 Breakdown Voltage across Polyethylene Surface

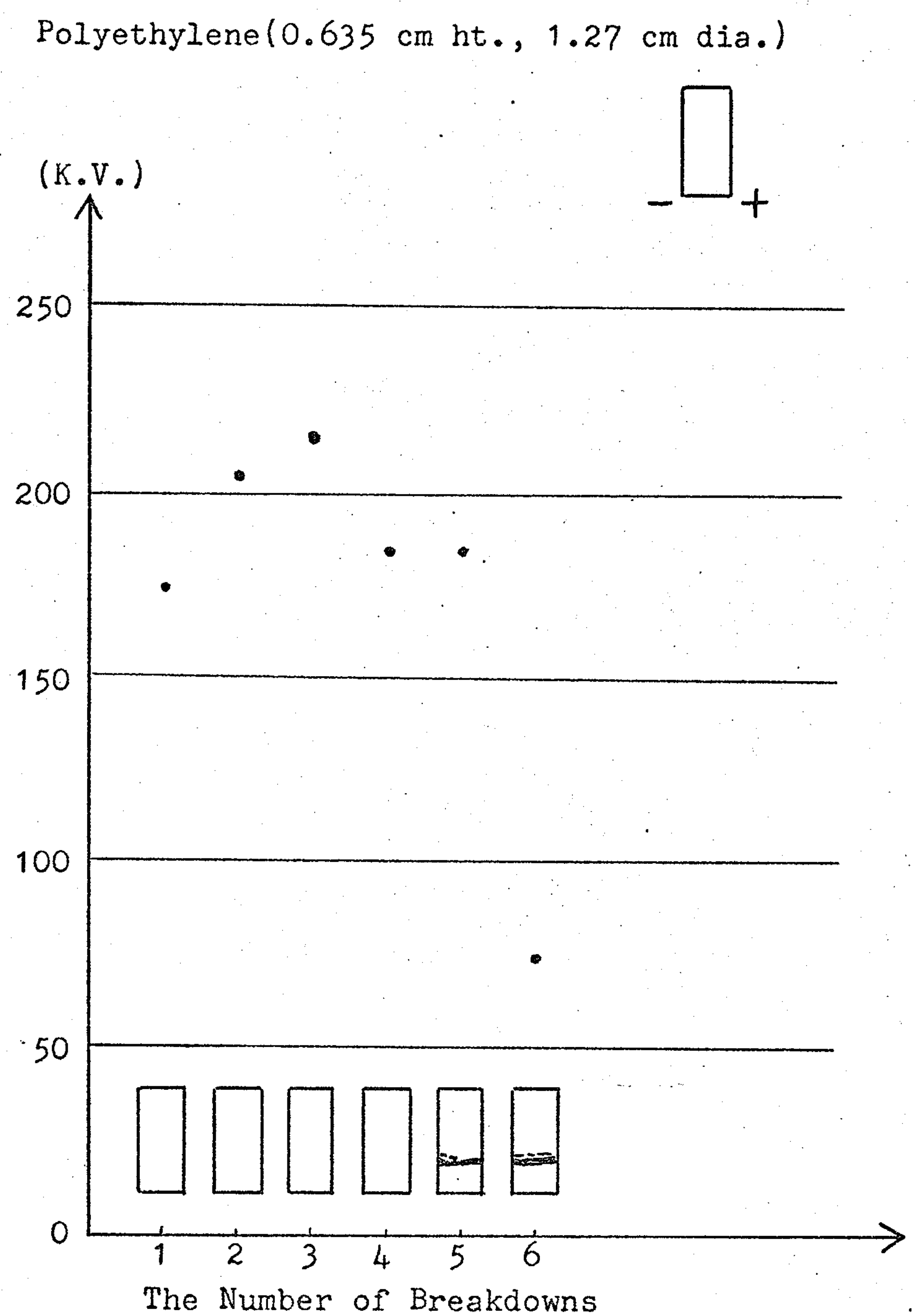


Fig.3-15 Breakdown Voltage across Polyethylene Surface

Polyethylene(0.635 cm ht., 1.27 cm dia.)

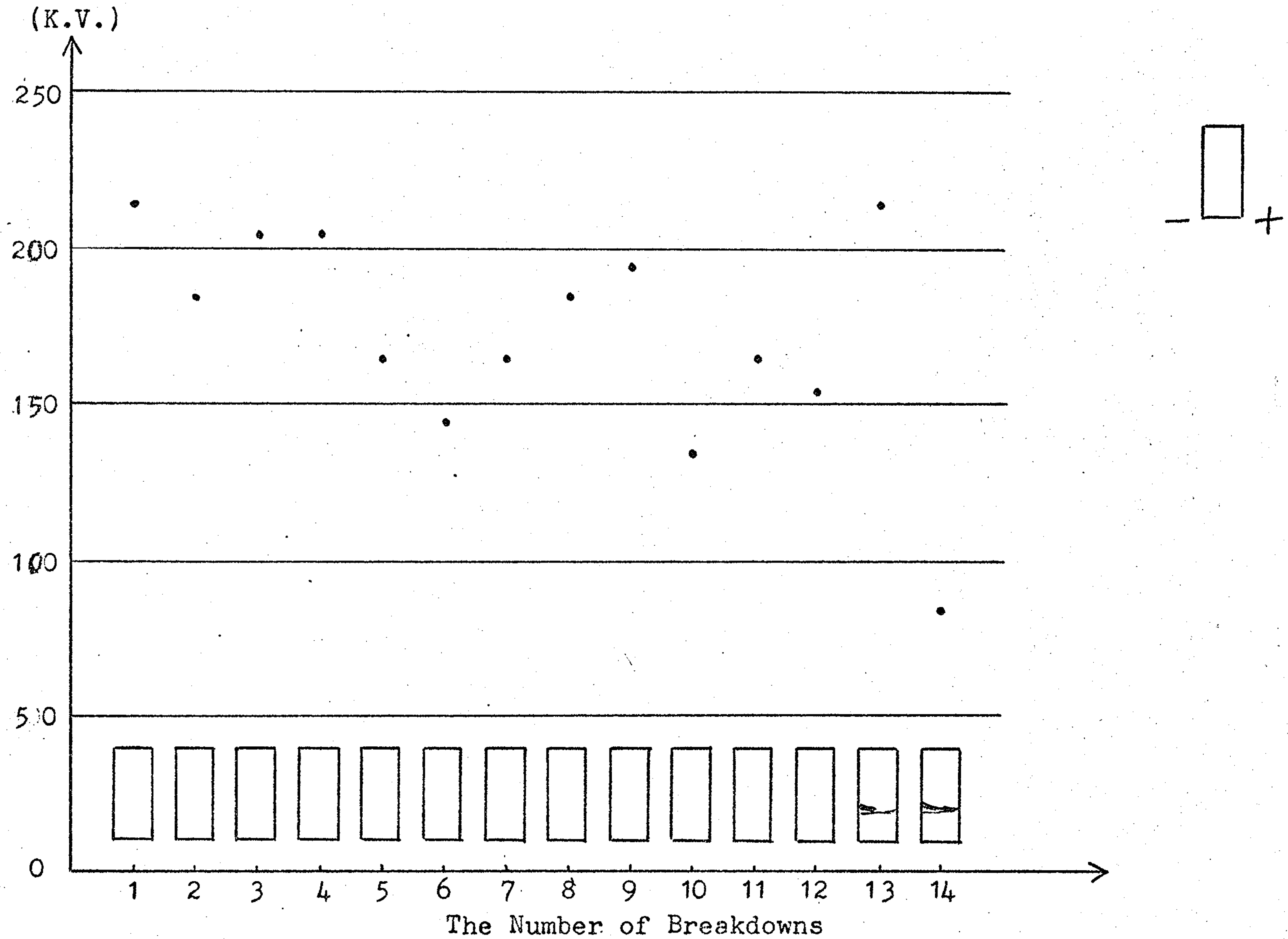


Fig. 3-16 Breakdown Voltage across Polyethylene Surface

3-4 FLASHOVER VOLTAGES ACROSS TEFLON SPECIMENS' SURFACE

Figures 3-17 and 3-18 show results obtained with the use of standard wave impulses and unpainted Teflon samples of 1.27 cm diameter and 0.635 cm high. Figures 3-19 to 3-24 show results obtained using the same type impulses and painted Teflon samples of the same size as the above.

From these figures, it can be seen that as far as Teflon samples with ends left unpainted are concerned, flashover voltages range from 170 to 260 kilovolts approximately until track formed on the sample surface; subsequent breakdown values are around 80 kilovolts. The rate of the decrease in breakdown values for unpainted Teflon samples is the greatest among those for three kinds of specimens tested in this investigation perspex, polyethylene and Teflon.

Breakdown values for painted Teflon samples range from 90 to 160 kilovolts as long as the sample surface is clean, and the subsequent breakdown values decrease to 80 kilovolts approximately as soon as the sample surface deteriorates. The values (about 80 kv) after the sample surface deteriorated are lower in the case of Teflon samples with ends painted and also without painting ends than those obtained for perspex and polyethylene samples.

The pattern of track marks is similar to that of polyethylene samples; i.e. there are some traces of deterioration, and these lead to a deep erosion on the sample surface. This occured for polyethylene samples but did not occur for perspex samples.

For the cases illustrated in Figures 3-17 and 3-18, the first several breakdowns did not produce deterioration on the sample surface. Similar observations are valid for perspex and polyethylene samples. The absence of deterioration is due to breakdowns occuring through the body of the oil and not along the surface of the sample. Throughout this work Bruce type electrodes were used, thereby achieving practically uniform field conditions when the gap between the electrodes is filled with a homogenous media. When a sample was inserted into the gap between the electrodes, a breakdown should have started from one of the irregularities around the edge of the cylindrical sample. But there might be some irregularities on the electrode surface even though the electrodes were polished and were cleaned carefully. If a breakdown started from one of the irregularities on the electrode surface, it might take place in the body of the oil and not along the oil-specimen interface, and does not produce a track mark on the sample surface.

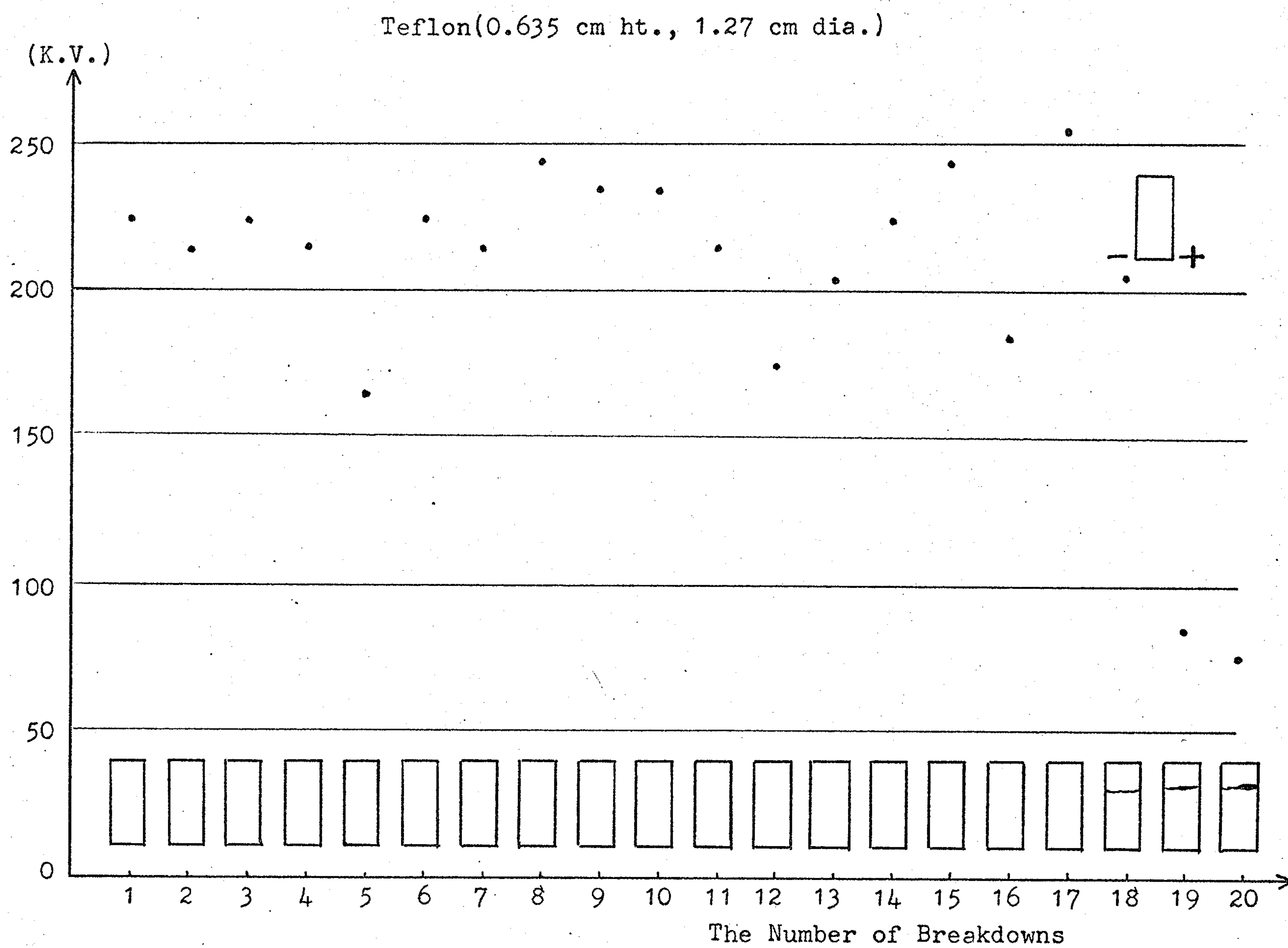


Fig. 3-17 Breakdown Voltage across Teflon Surface

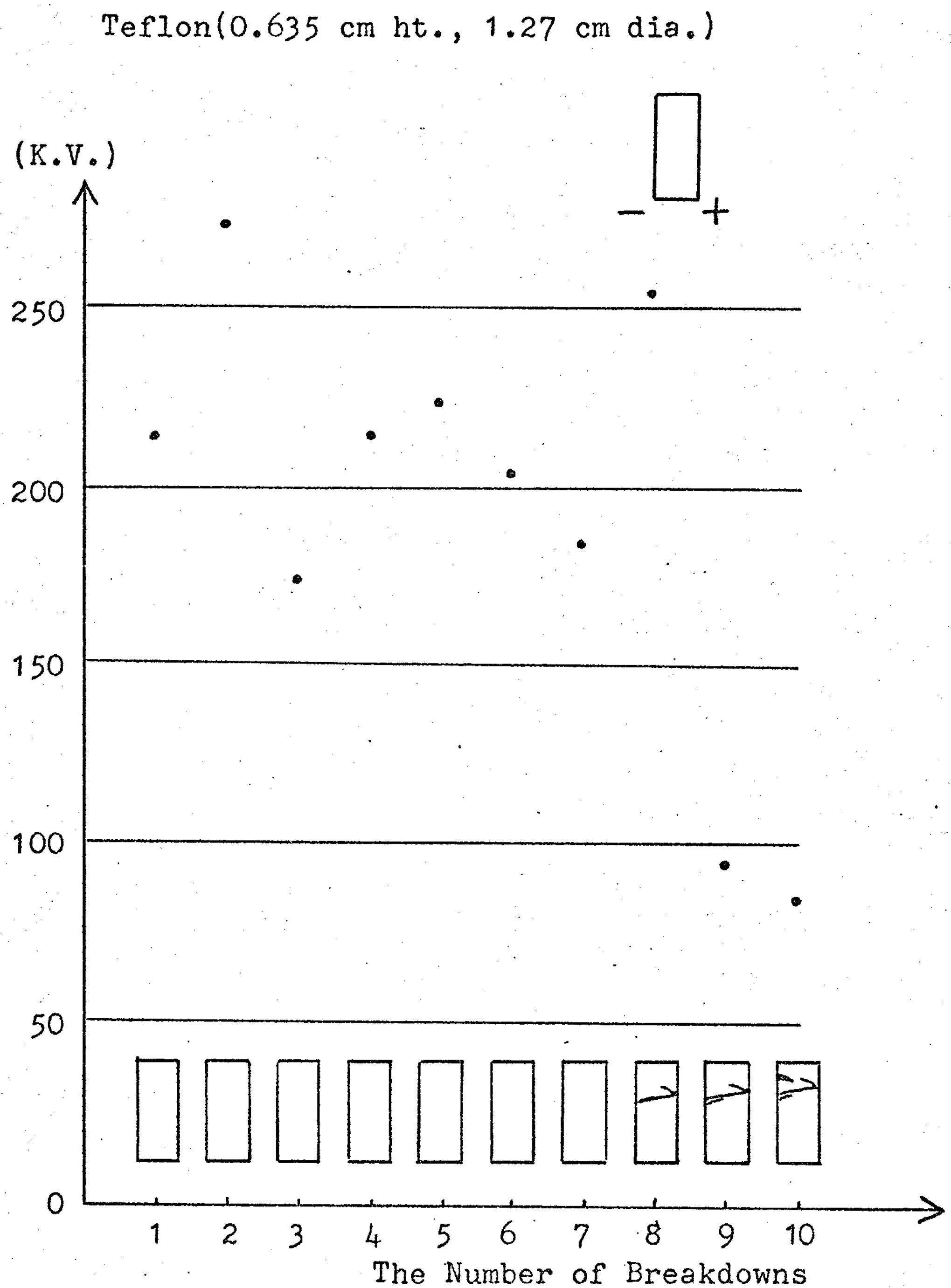


Fig. 3-18 Breakdown Voltage across Teflon Surface

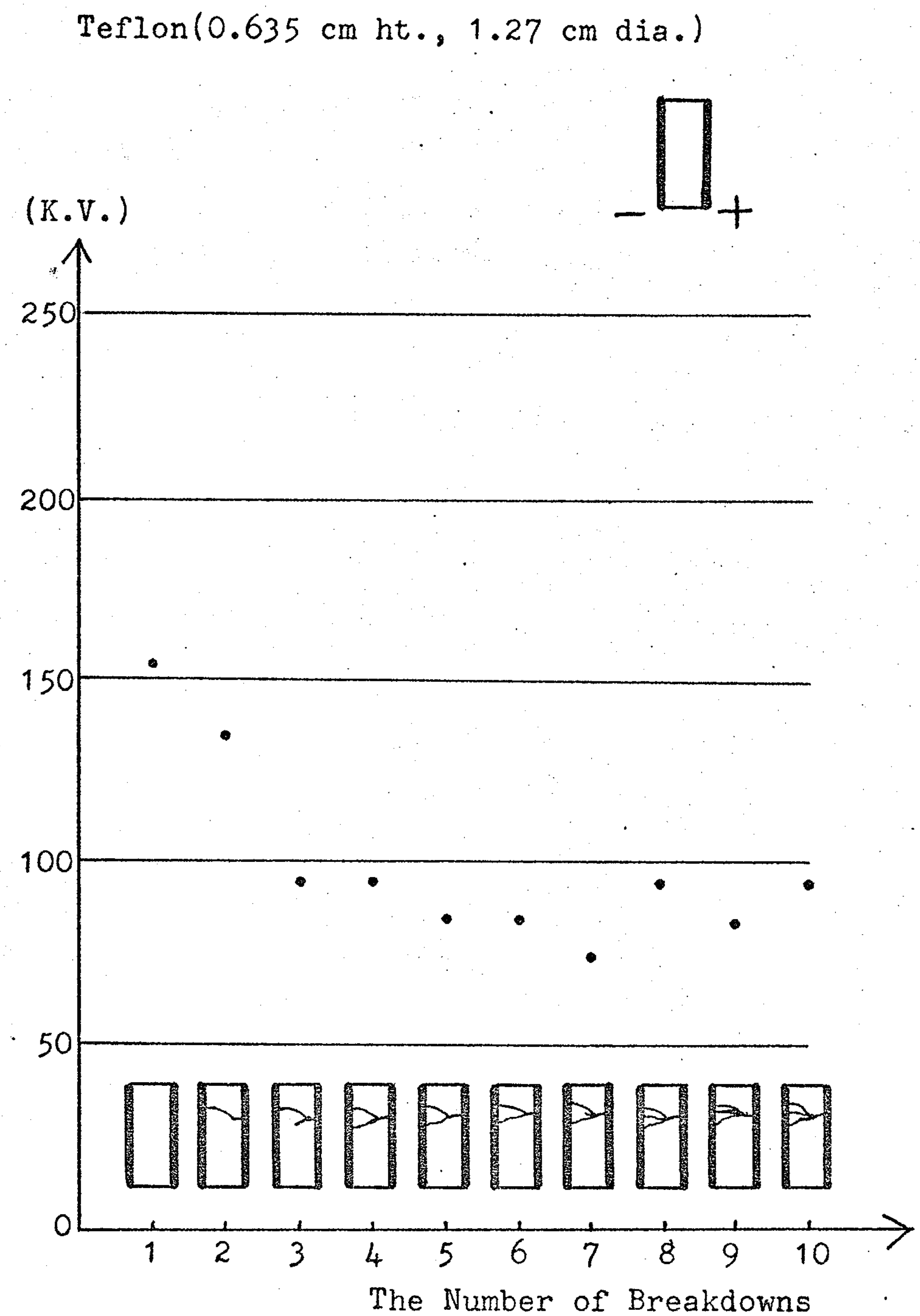


Fig. 3-19 Breakdown Voltage across Teflon Surface

Teflon(0.635 cm ht., 1.27 cm dia.)

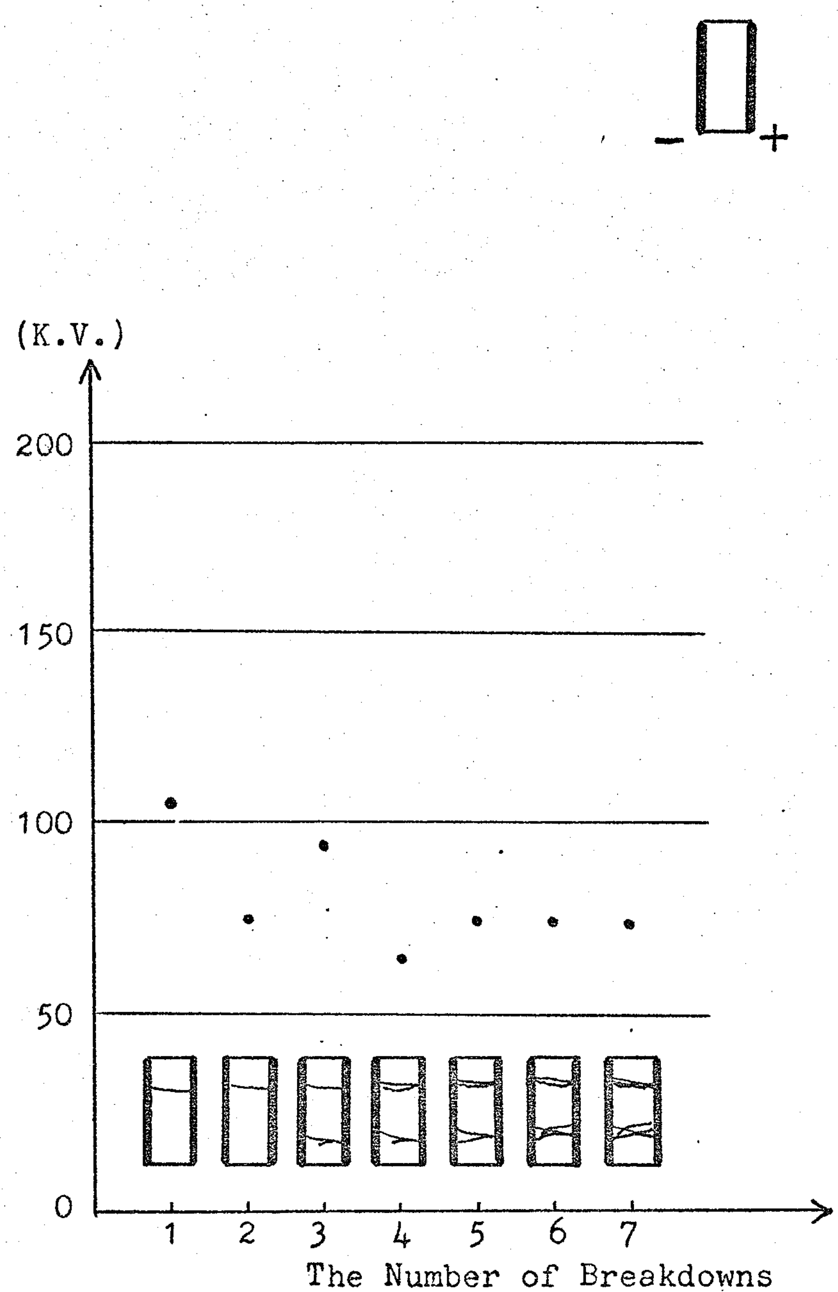


Fig. 3-20 Breadown Voltage across Teflon Surface

Teflon(0.635 cm ht., 1.27 cm dia.)

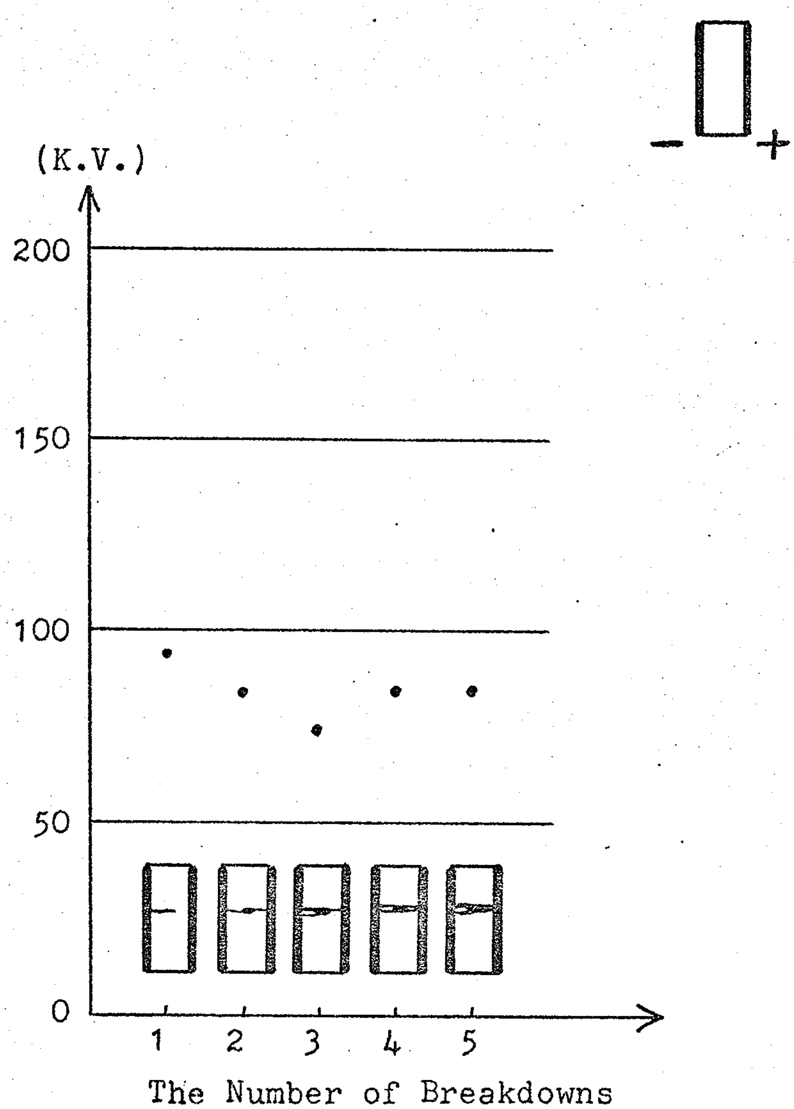


Fig. 3-21 Breakdown Voltage across Teflon Surface

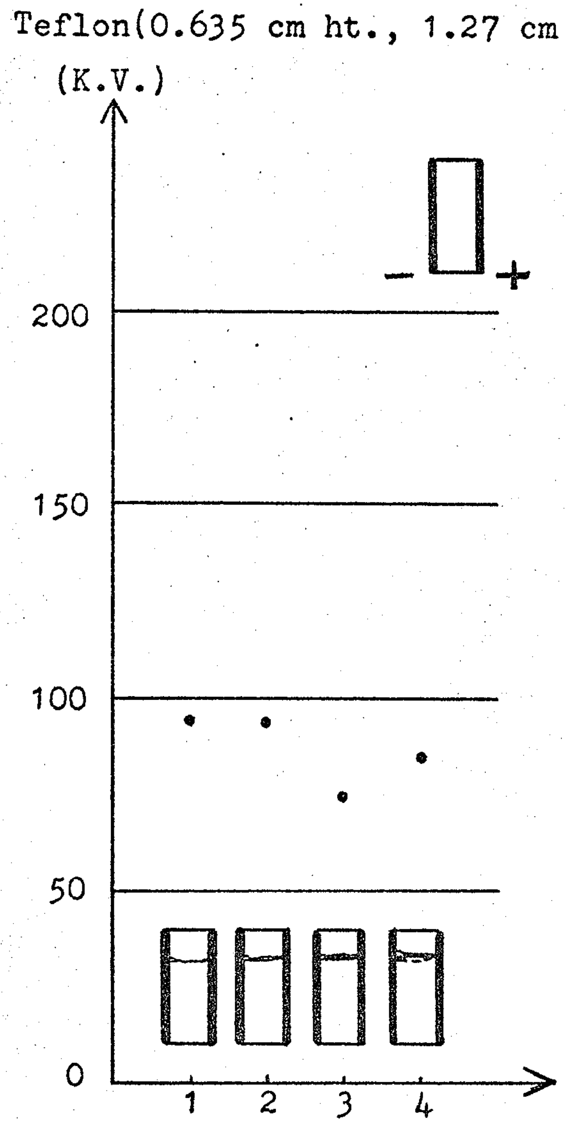


Fig. 3-22

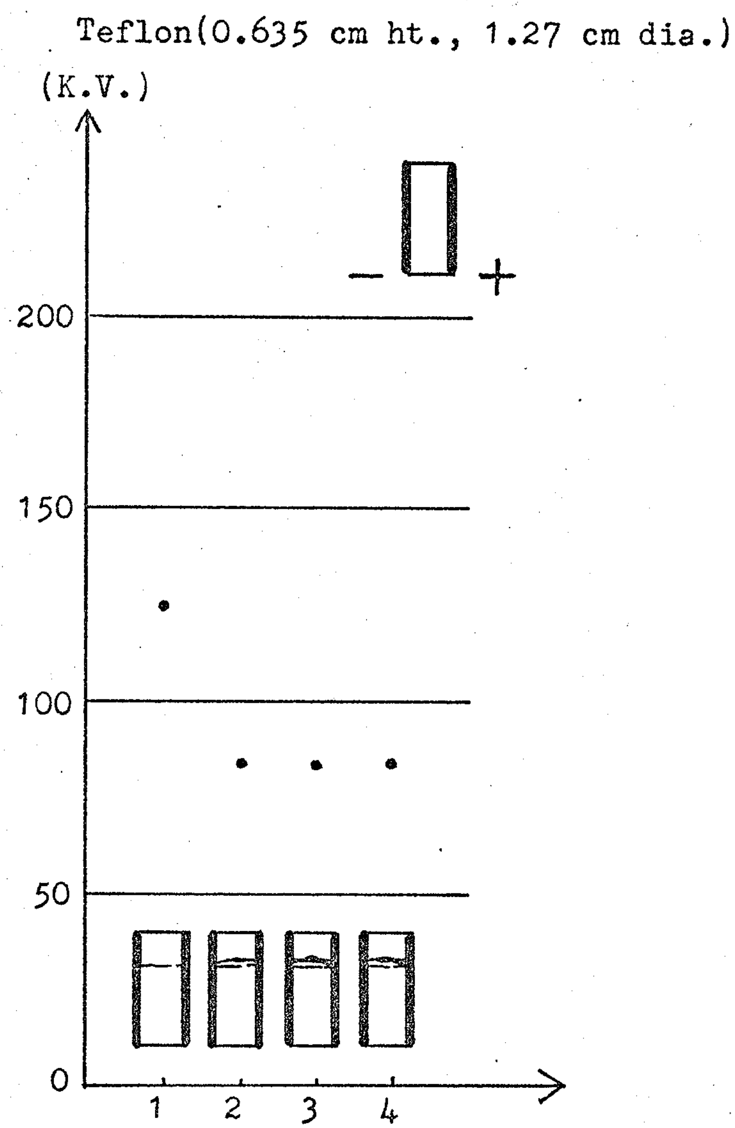


Fig. 3-23

Breakdown Voltage across Teflon Surface

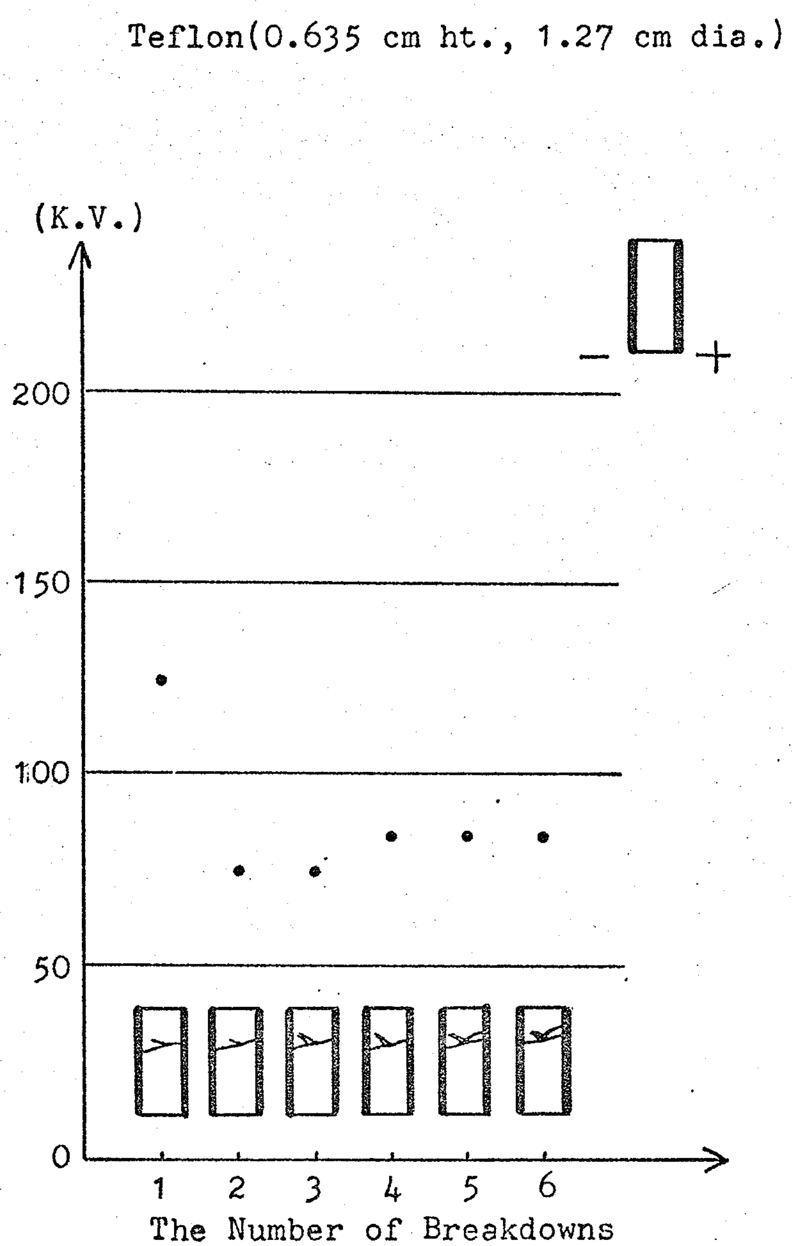


Fig. 3-24 Breakdown Voltage across Teflon Surface

3-5 EFFECTS OF ELECTRO-CONDUCTIVE SILVER PAINT

According to the results shown earlier in this thesis, silver paint on the electrode-sample interface played very important role in breakdown development and on the manner of deterioration of the sample surface.

It is generally observed that the interface painted at the cathode end is more effective in the breakdown development than that at the anode end, especially in vacuum. This is usually considered as field emission initiated from one of irregularities of the paint at the edge around the sample.

In order to check the polarity effect on the breakdown initiation, several experiments were performed with 8 perpex samples which had either the negative or the positive end painted. Figures 3-25 to 3-32 compare the results obtained for the two cases using the standard impulse voltages. From these figures, the polarity effect of the paint could be observed neither in breakdown voltages nor in the manner of deterioration. The difference of the polarity effect between liquid and vacuum has not been cleared yet.

Perspex(0.635 cm ht., 1.27 cm dia.)
with Negative End Painted

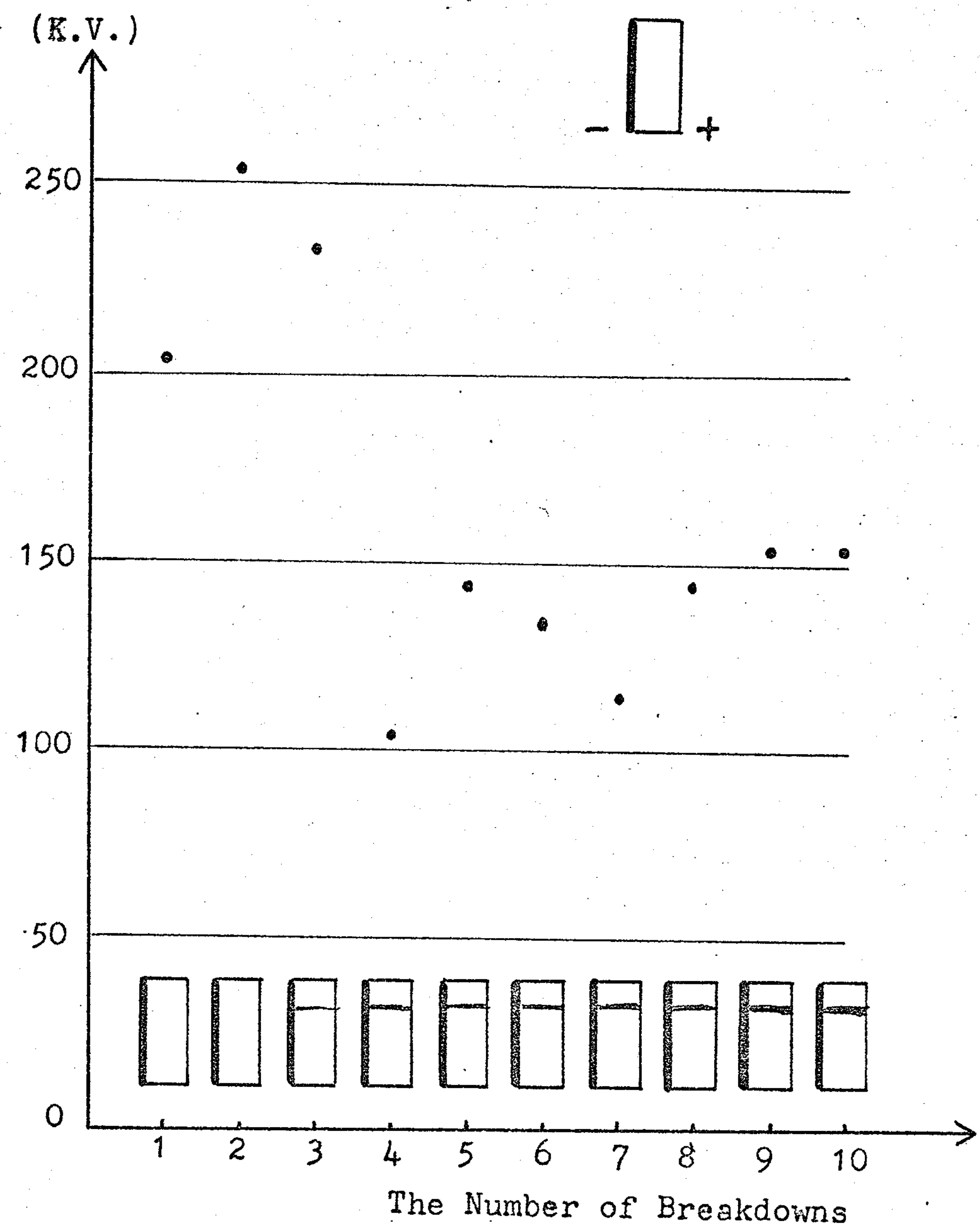


Fig. 3-25 Breakdown Voltage across Perspex Surface

Perspex(0.635 cm ht., 1.27 cm dia.)

with Negative End Painted

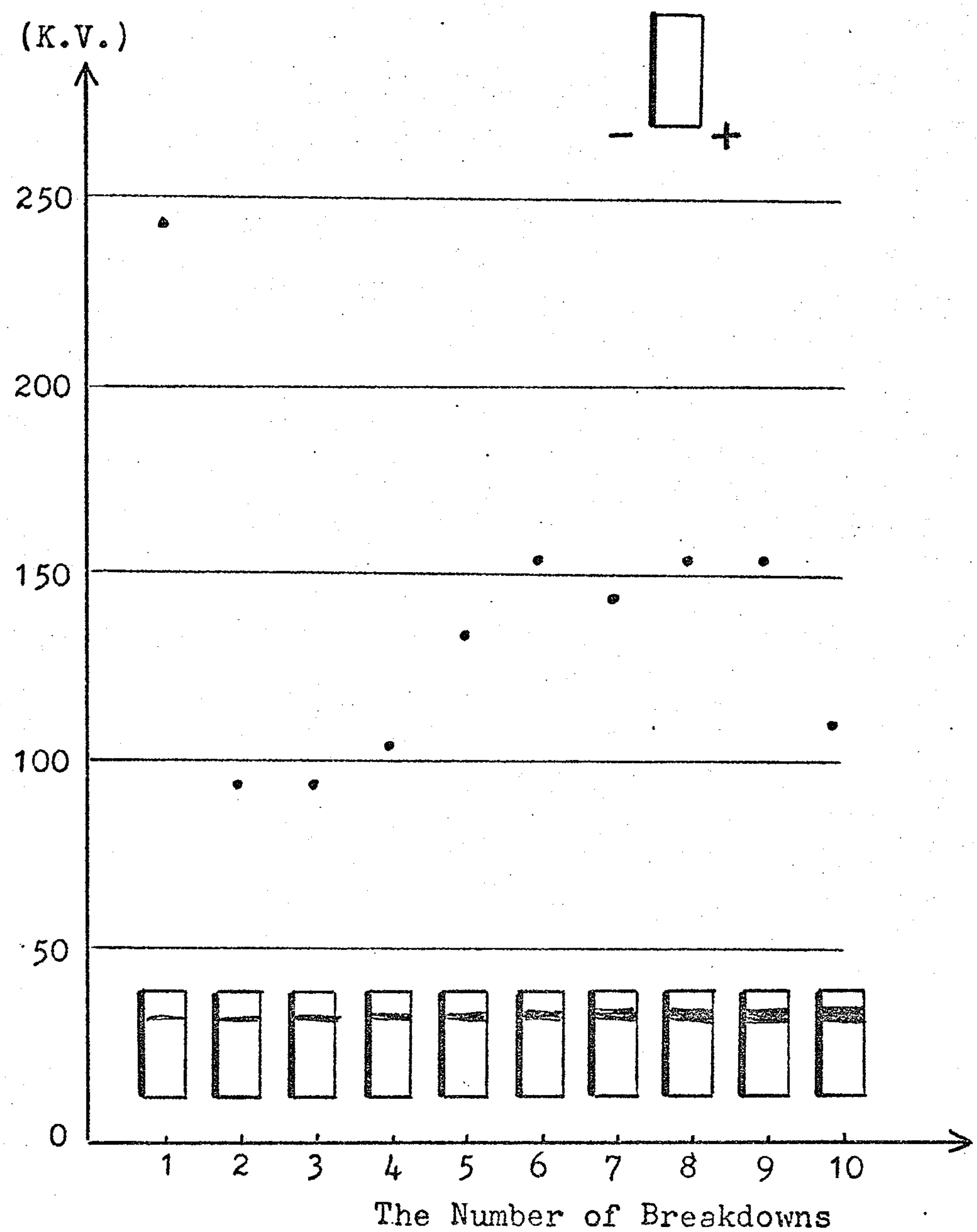


Fig. 3-26 Breakdown Voltage across Perspex Surface

Perspex(0.635 cm ht., 1.27 cm dia.)
with Positive End Painted

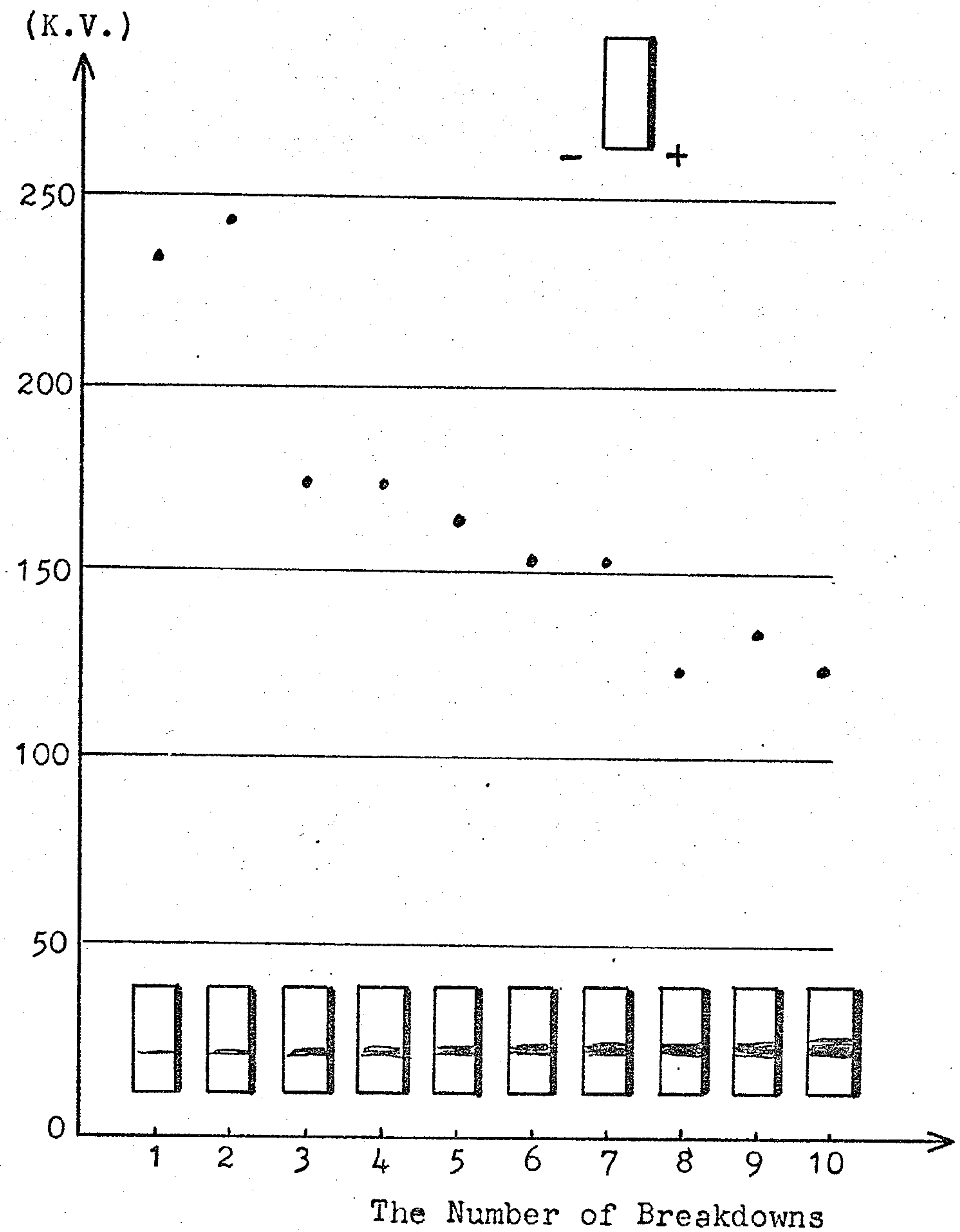


Fig. 3-27 Breakdown Voltage across Perspex Surface

Perspex(0.635 cm ht., 1.27 cm dia.)
with Positive End Painted

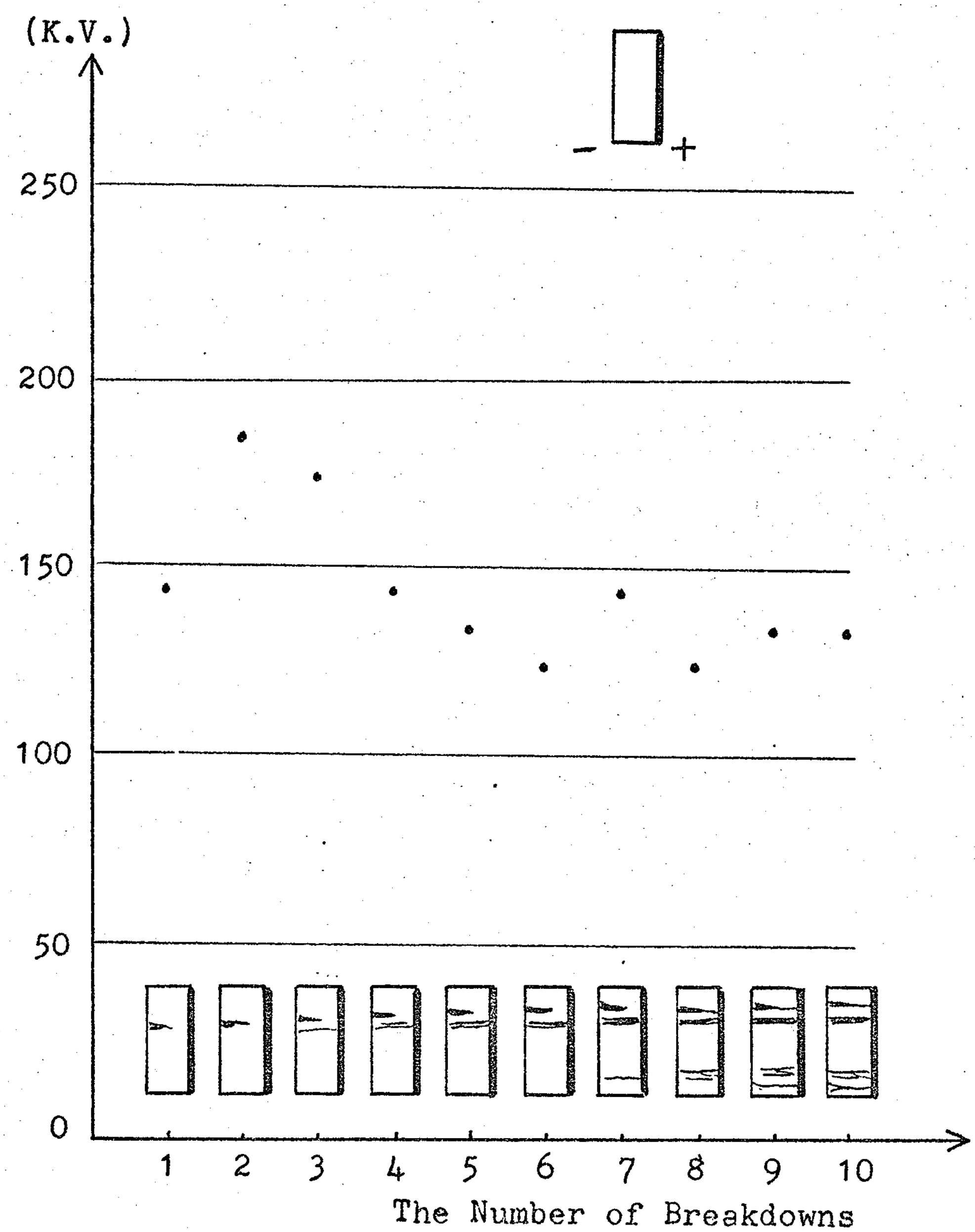


Fig. 3-28 Breakdown Voltage across Perspex Surface

Perspex(0.635 cm ht., 1.27 cm.dia.)
with Negative End Painted

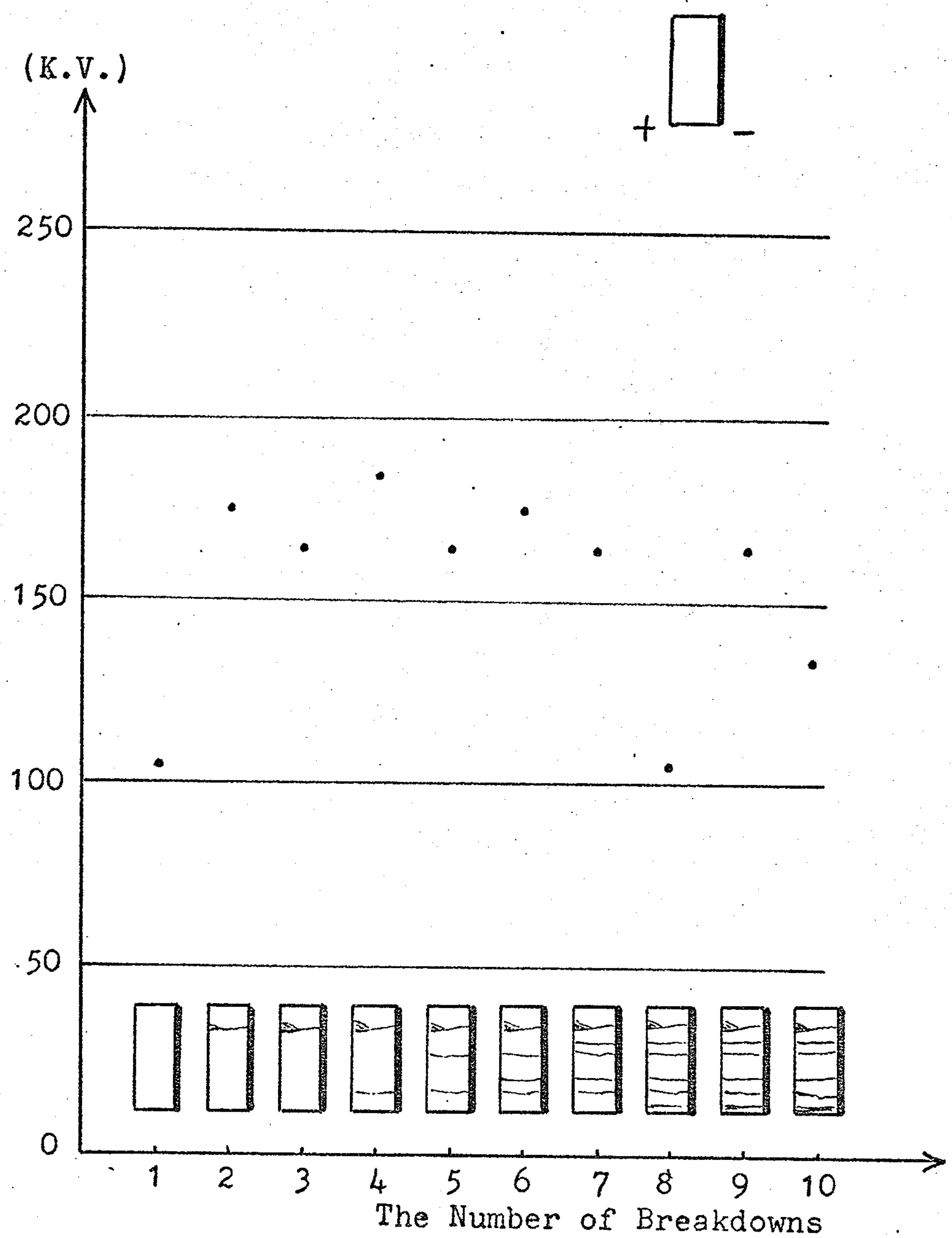


Fig. 3-29 Breakdown Voltage across Perspex Surface

Perspex(0.635 cm ht., 1.27 cm dia.)
with Negative End Painted

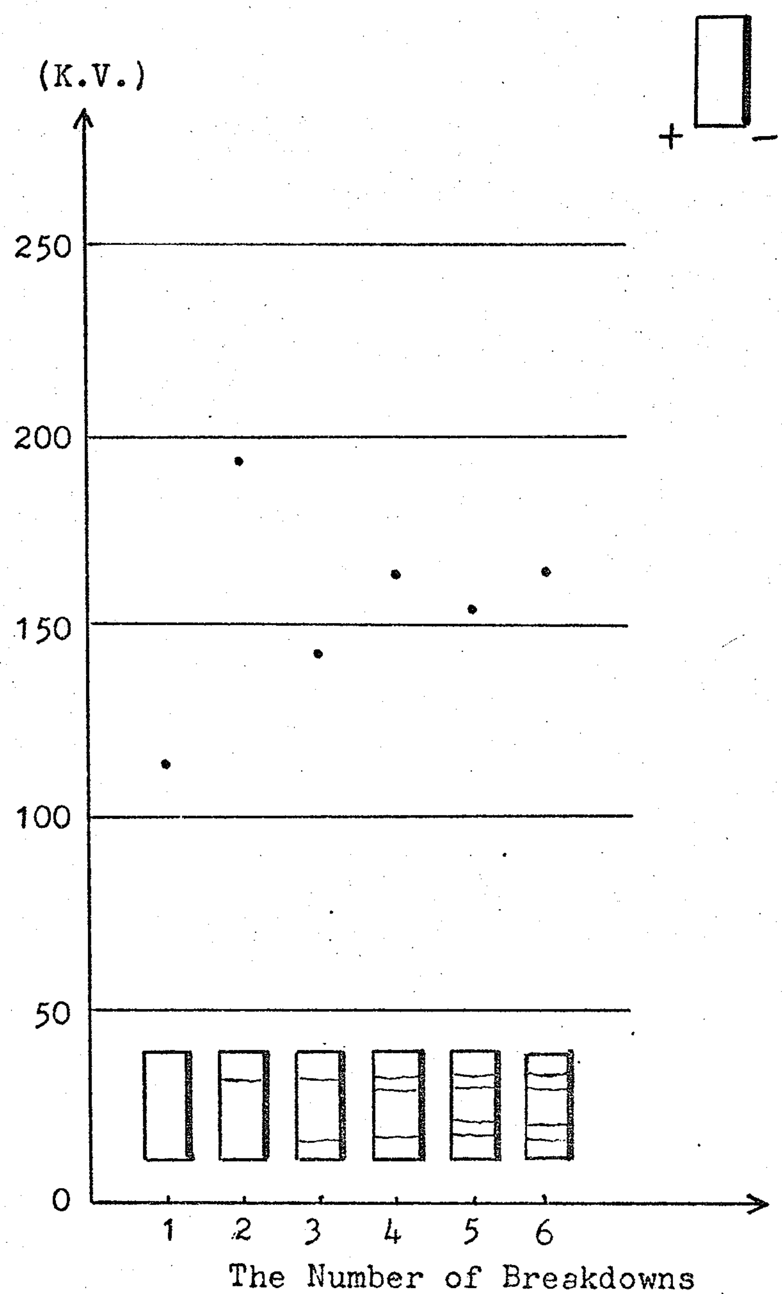


Fig. 3-30 Breakdown Voltage across Perspex Surface

Perspex(0.635 cm ht., 1.27 cm dia.)
with Positive End Painted

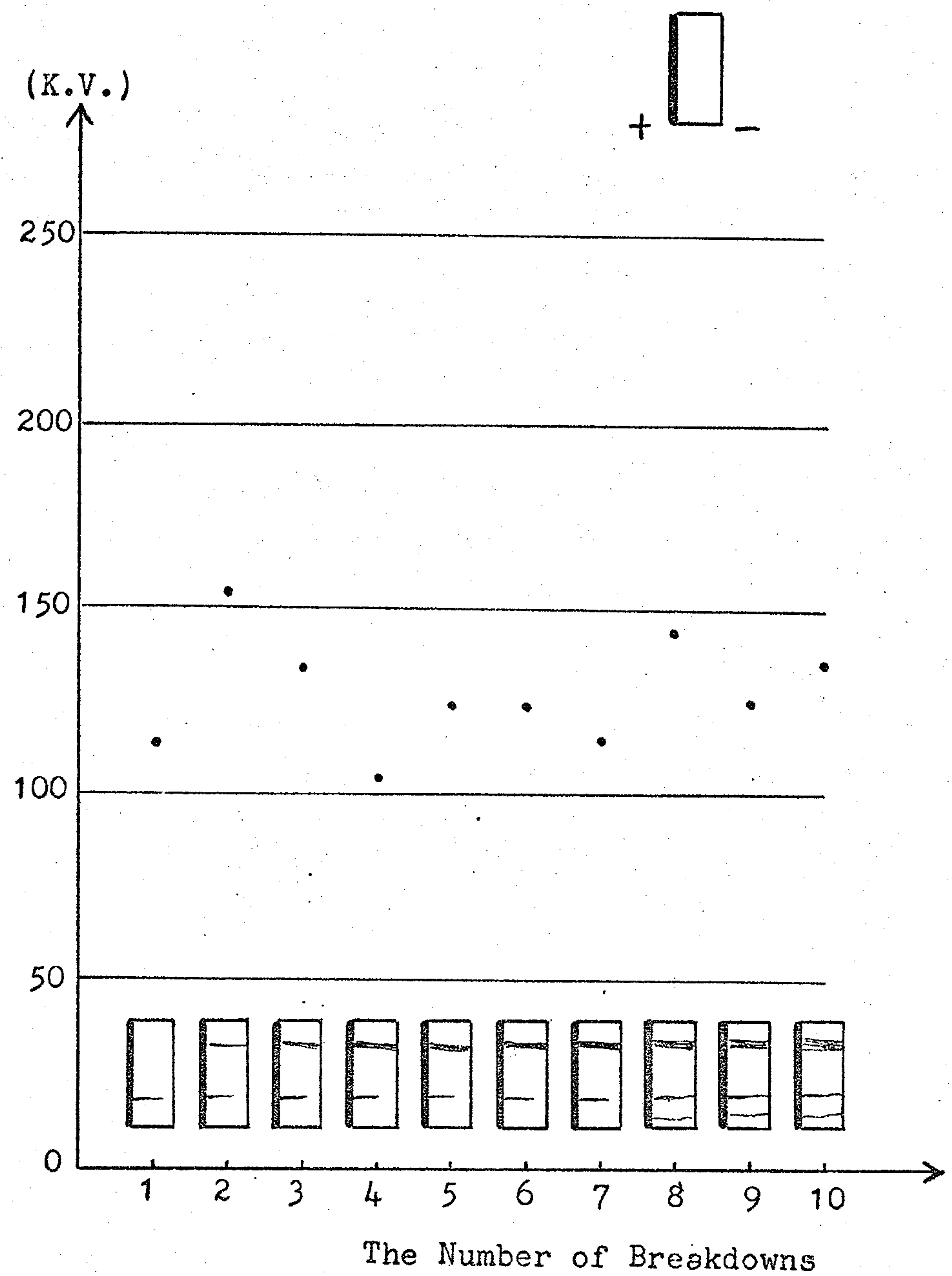


Fig. 3-31 Breakdown Voltage across Perspex Surface

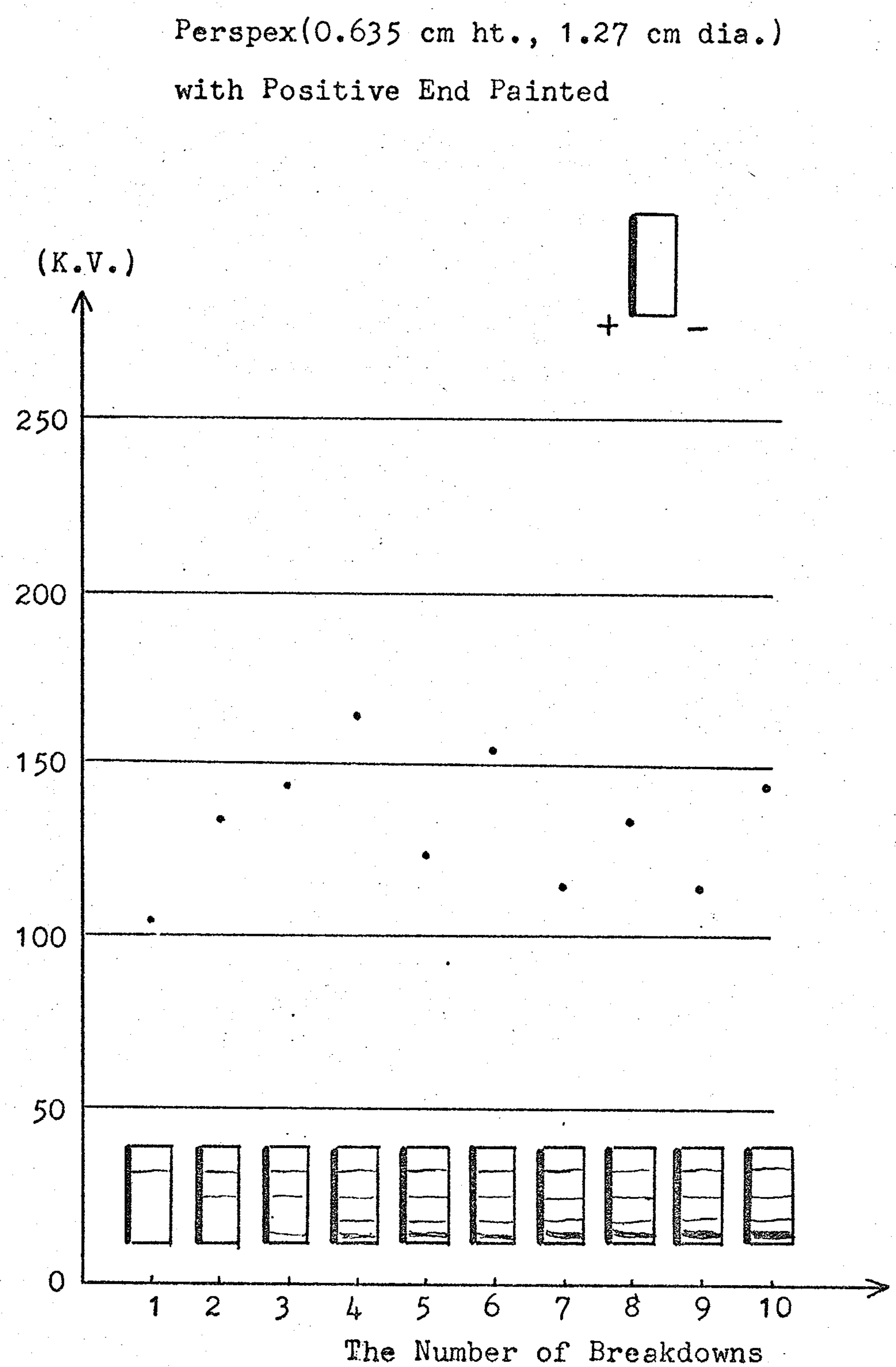


Fig. 3-32 Breakdown Voltage across Perspex Surface

3-6 COMPARISON OF BREAKDOWN STRENGTH ACROSS THE SURFACE OF TEFLON SPECIMEN IN VACUUM AND IN TRANSFORMER OIL

There are many papers related to breakdown strength across the insulator surface in vacuum, using cylindrical specimens inserted between uniform field electrodes. One of the results obtained in vacuum is referred to in this section 3-6, in order to compare those with the results obtained in transformer oil in this investigation.

The graph shown in Fig. 3-33 was obtained by R. I. Ugarte Berazain[8]. This graph shows successive breakdown voltages in vacuum (10^{-6} Torr) across the surface of a cylindrical Teflon specimen of 5 mm high and 25 mm diameter, using D.C. voltages. The first series of the results in this figure showed an increase in the breakdown voltage with the first three breakdowns; thereafter the breakdown value decreased to a steady value slightly lower than the first three breakdown values. After this series, the specimen was left in a vacuum of 10^{-6} Torr for twenty hours before the second series of tests was started.

In the second series, the first breakdown was the highest value in this series and was higher than the last value of the previous series. The third series of the tests was carried out after the sample was left for another twenty hours in a vacuum of 10^{-6} Torr. Again the first breakdown was the highest in this series and higher than the last value of the second series. The steady value was rapidly reached in

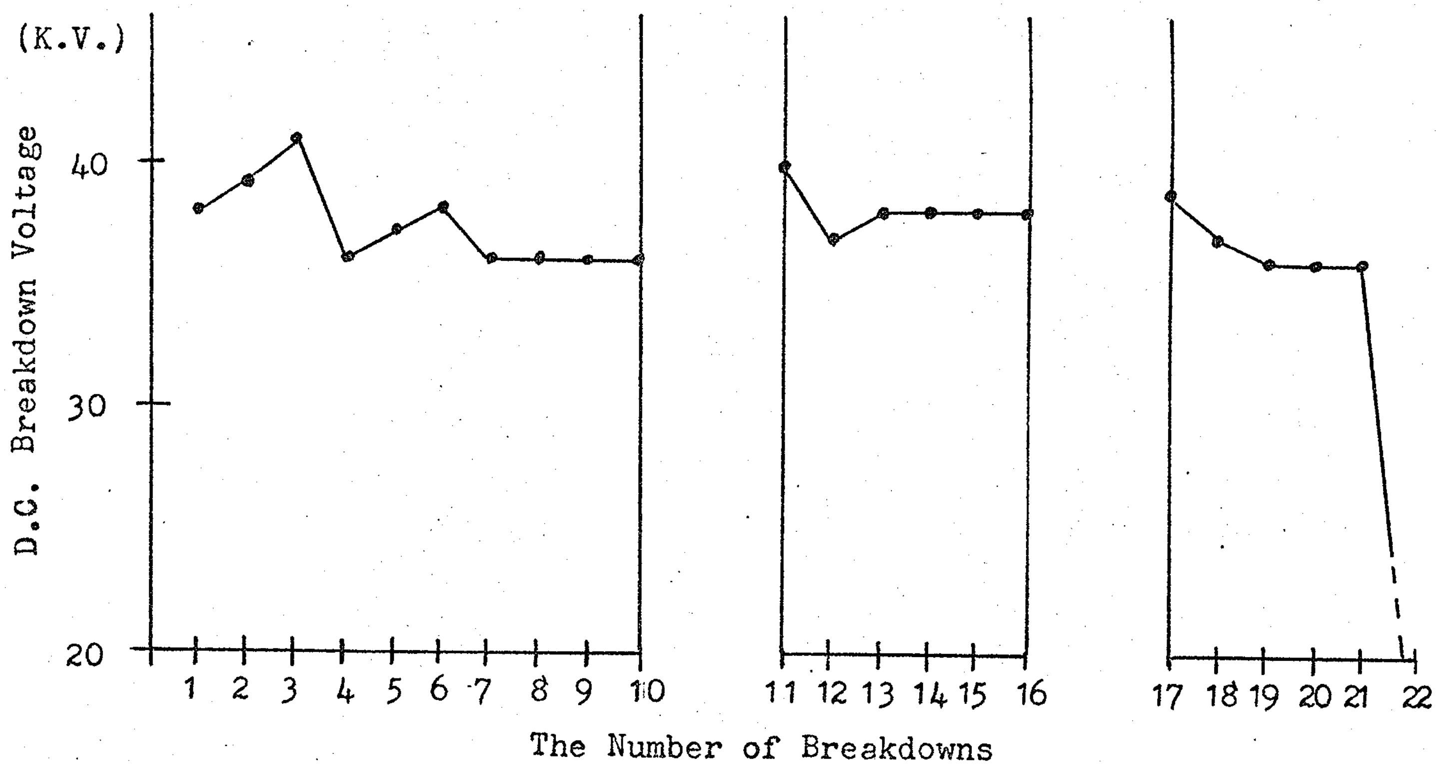


Fig. 3-33 Breakdown Voltage across Teflon Surface in Vacuum (10^{-6} Torr), after D.C. Conditioning

Teflon Sample: 5 mm ht., 25 mm dia.

the third series and was of the same magnitude as that obtained in the first series. Finally, a sudden deterioration occured and the breakdown voltages dropped to approximately 10 kilovolts.

Looking back at the results obtained on Teflon specimens in the section 3-4, it can be seen that there are some differences between those obtained in transformer oil and the results obtained in vacuum.

First, in vacuum, breakdown voltages range from 36 to 40 kilovolts before deterioration occuring, and these values are equivalent to 72 to 80 kilovolts per centimeter. On the other hand in transformer oil, breakdown strength for Teflon specimen range from 70 to 90 kilovolts which are same as 110 to 156 kilovolts per centimeter, even after track marks formed but before deep erosion was produced.

Secondly, in vacuum, breakdown strength across Teflon surface dropped drastically to a lower value (about 20 kilovolts per centimeter) as soon as the sample surface deteriorated. In turn, breakdown strength for Teflon samples in oil stayed at around 130 kilovolts per centimeter even after the sample surface deteriorated.

In order to establish the reason of these great differences between vacuum and oil, breakdown mechanism in the both cases have to be cleared. The breakdown mechanism, however, along the solid insulator surface is so complicated that no definite theory has been established yet, in the case of vacuum and also transformer oil.

The following statement may be made, which is not a theory of breakdown mechanism itself.

In vacuum, once breakdown occurs across the sample surface, a carbon track is produced along the path of the breakdown. A certain amount of the carbon may diffuse into the body of vacuum and be evacuated by the vacuum pump operating, but the rest of the carbon forms the electro-conductive path on the sample surface. Hence the subsequent breakdown value will be drastically lower than that of the previous breakdown.

On the other hand in transformer oil, carbon produced by a breakdown may be dissolved into the body of oil. In this experiment the oil was stirred by the stirrers after each breakdown occured in order to sweep the bubbles away, as mentioned in the section 2-3. This might help the dissolution of the carbon into the body of oil. Thus the conductivity along the path of the track is not as high in the case of oil as that in the case of vacuum, even though the carbon might not be completely dissolved into the oil.

Therefore the subsequent breakdown strength after the track formed is higher in the case of oil than that in the case of vacuum.

The above statement appears justified to some extent by the following observations.

In oil, more than one track mark were observed on the surface of Teflon specimen after several breakdowns occured. If the conductivity along the path of a breakdown which produced the first track mark was higher than that at any other place along the sample surface, the subsequent breakdown should have occured along the same path as the previous and only one track mark should have been observed as a result. But actually several track marks were observed in the case of oil.

In vacuum, visual observation indicated that all the breakdowns followed the same path on the surface of Teflon specimen [8]. This might be due to high-conductivity path along the track mark.

3-7 OTHER RESULTS

For record purposes other results obtained in this work are included in the Appendices. Appendix I shows the results obtained with 20/120 μsec. surges and 1 cm high and 1.27 cm diameter perspex, polyethylene and Teflon samples. Appendix II shows the results for polyethylene and Teflon samples whose dimensions are 1 cm in height and 1.27 cm in diameter, using standard wave impulses. These results shown in Appendices were obtained in the initial stages of this work as previously mentioned.

There appears no significant difference between results obtained using standard wave impulses and those with the use of 20/120 μsec. surges.

CONCLUSIONS

The following conclusions may be drawn.

1. Breakdown voltages across the interface of transformer oil and polymer specimens were so scattered that significant difference of flashover voltages could not be observed among perspex, polyethylene and Teflon specimens used in this investigation, as long as the sample surface was clean.
2. After deterioration produced on the specimen surface, the subsequent breakdown strength for perspex was the highest among the three kinds of the specimens, and the second highest was polyethylene specimens.
3. Electro-conductive silver paint played important roles in both of breakdown values and the manner of deterioration. As long as the specimen surface was clean, breakdown voltages across the sample surface with ends painted were lower than those for samples without painting ends.
4. As far as a perspex sample with ends left unpainted is concerned, breakdowns occured at one place across the surface. When the ends of the perspex specimen were painted multiple breakdown tracks occured across the surface.
5. For polyethylene and Teflon, some multiple track marks were observed in both cases of the sample with ends painted and without painting ends.
6. Polarity effect of the paint could be observed on neither breakdown values nor on the manner of deterioration.

7. There was no difference observed either in breakdown values or in the manner of deterioration between those obtained using a standard wave impulse and a 20/120 µsec. surge.

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(8) R. I. Ugarte Berazain, Thesis for Master of Science, Department of Electrical Engineering, University of Manitoba, May, 1971.

APPENDIX I

Figures A-1 to A-6 show results obtained using 20/120 μsec. surge and perspex, polyethylene and Teflon samples of 1 cm high and 1.27 cm diameter with silver painted ends.

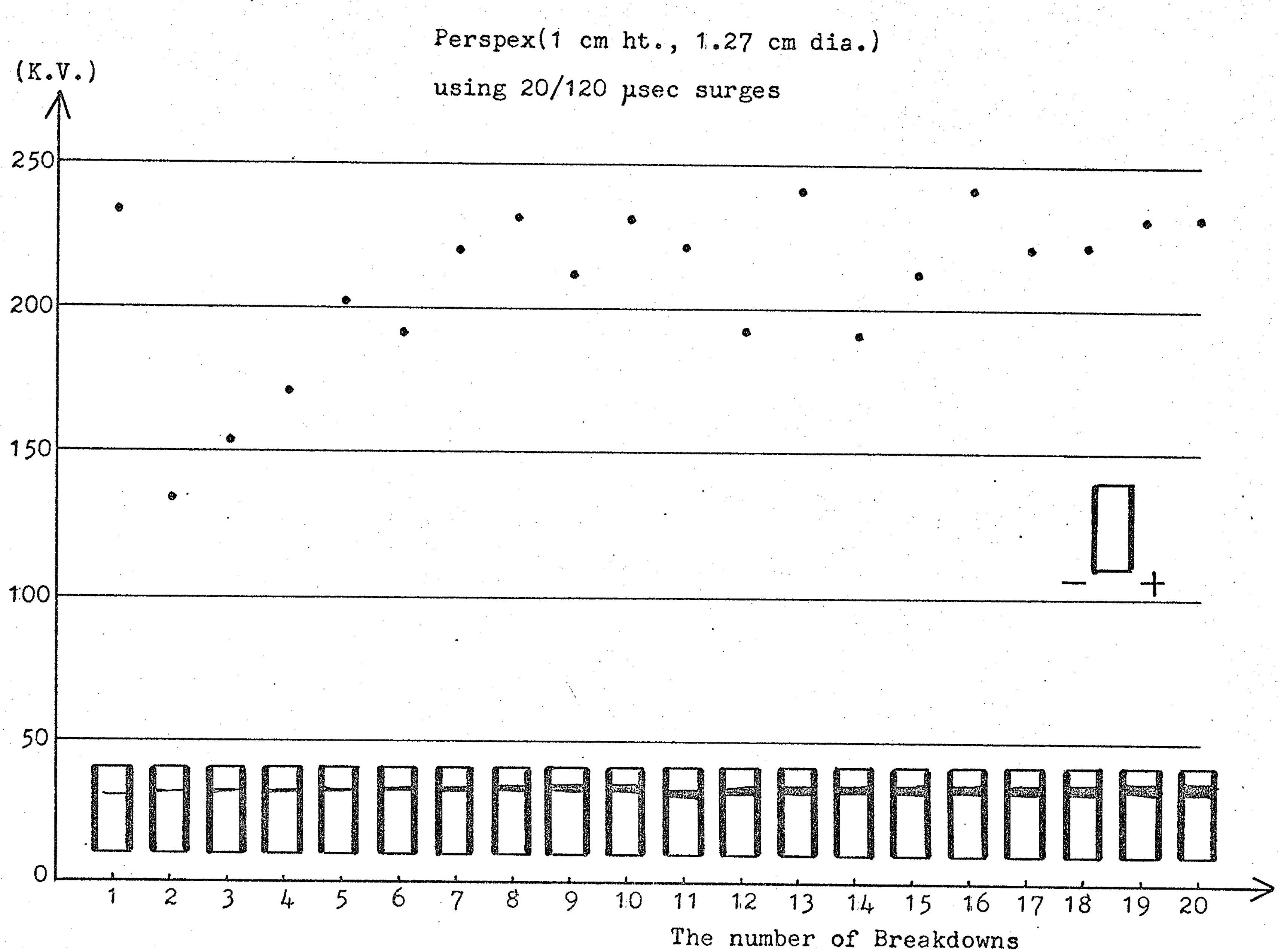


Fig. A-1 Breakdown Voltage across Perspex Surface

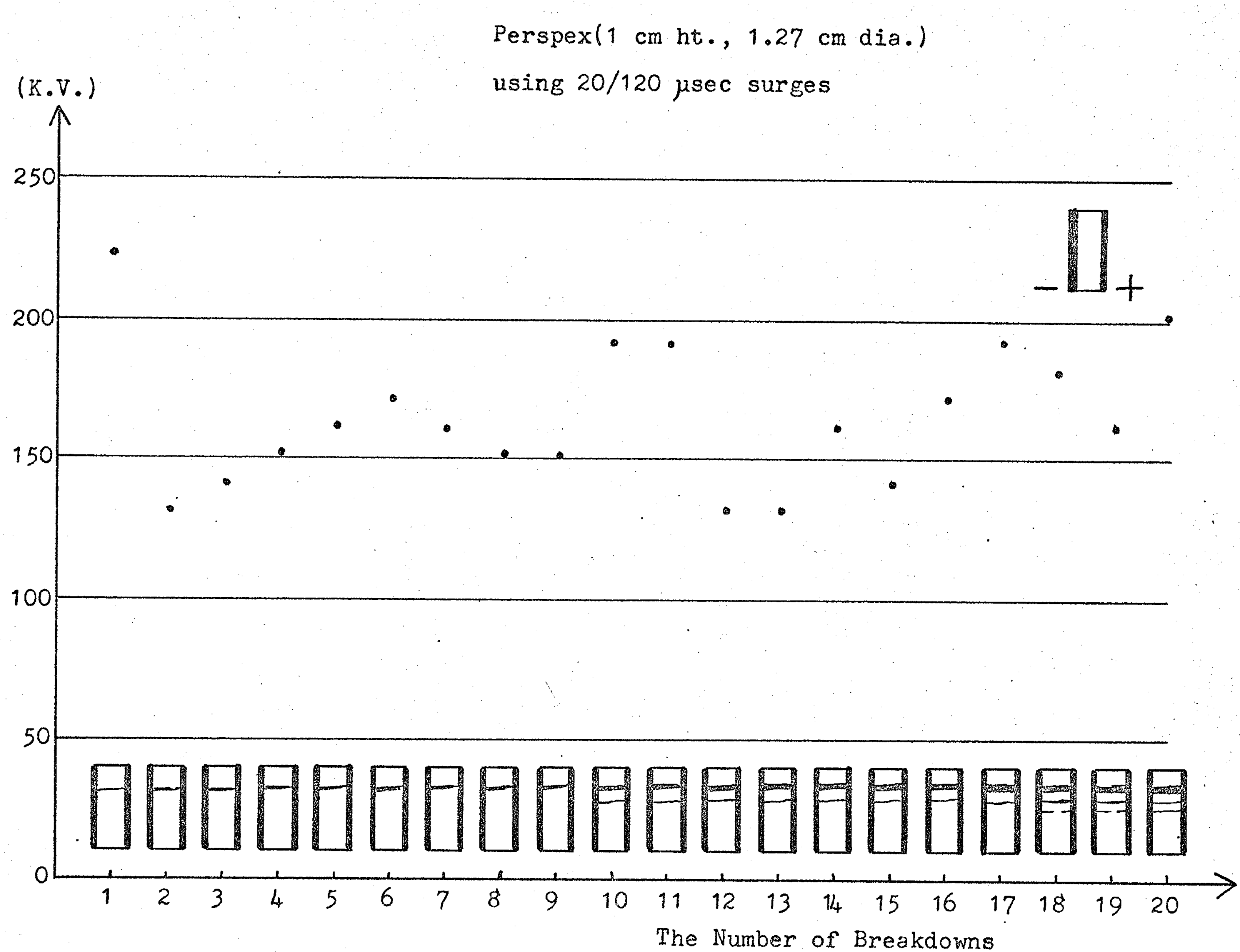


Fig. A-2 Breakdown Voltage across Perspex Surface

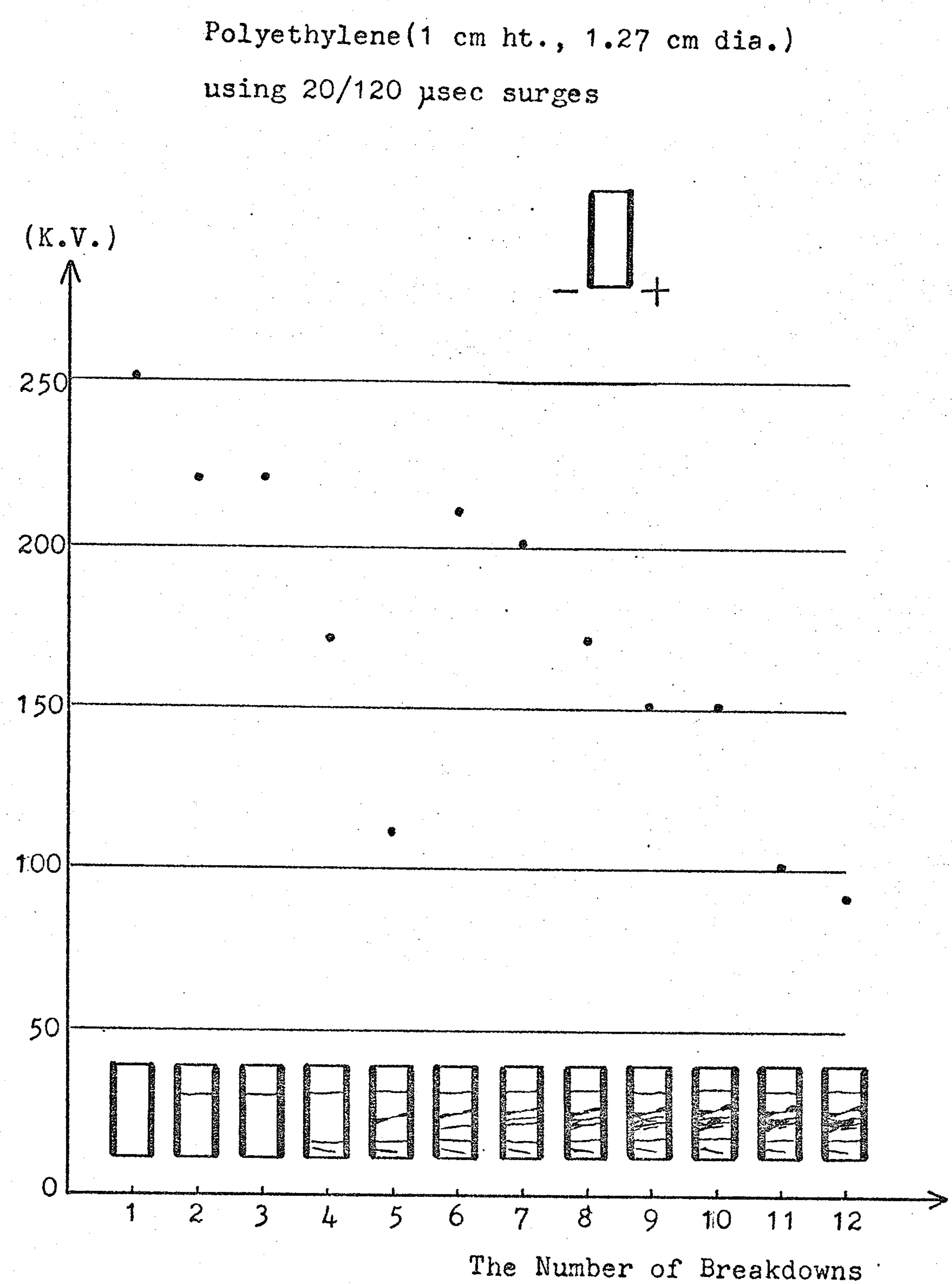


Fig. A-3 Breakdown Voltage across Polyethylene Surface

Polyethylene(1 cm ht., 1.27 cm dia.)
using 20/120 µsec surges

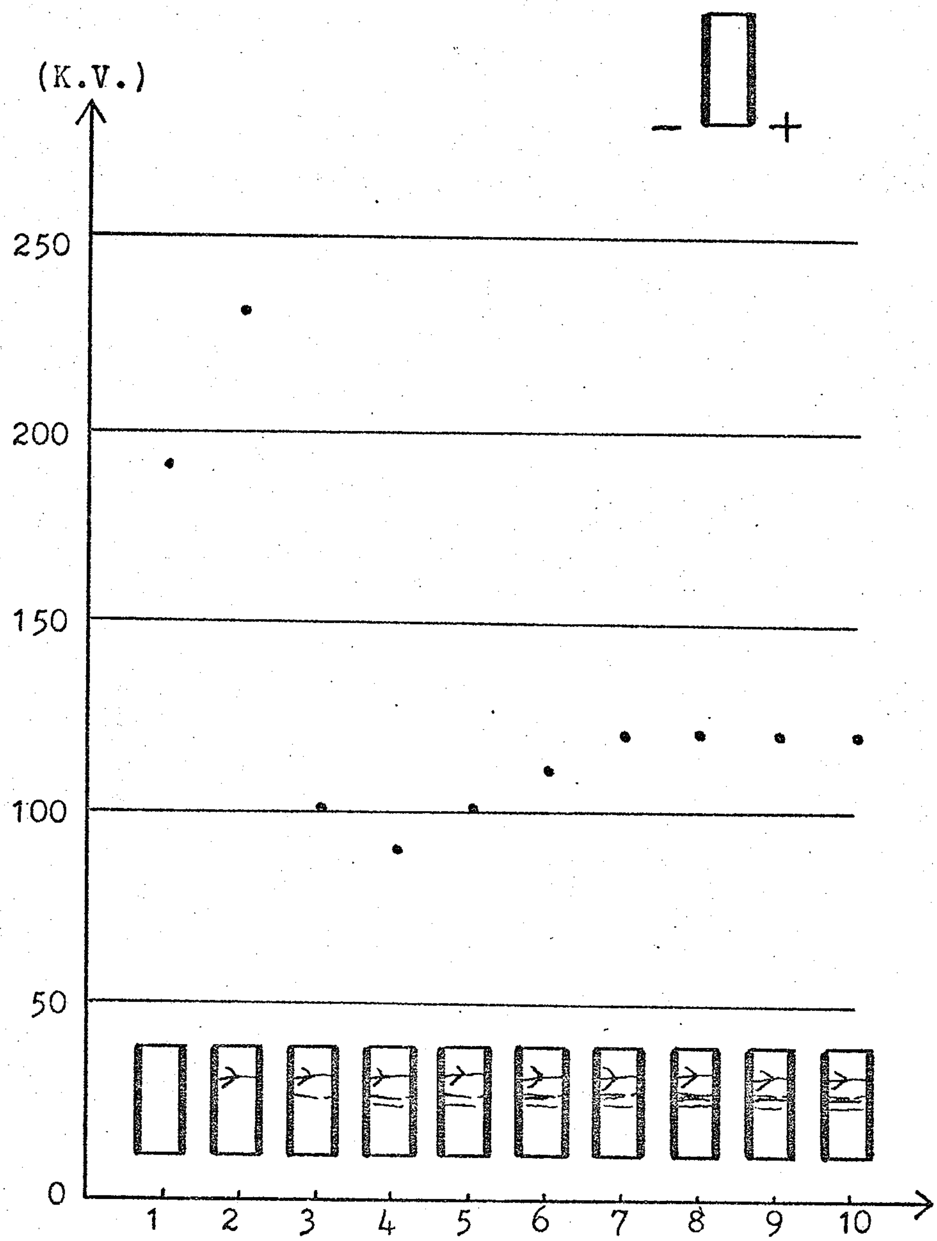


Fig. A-4 Breakdown Voltage across Polyethylene Surface

Teflon(1 cm ht., 1.27 cm dia.)

using 20/120 μsec surges

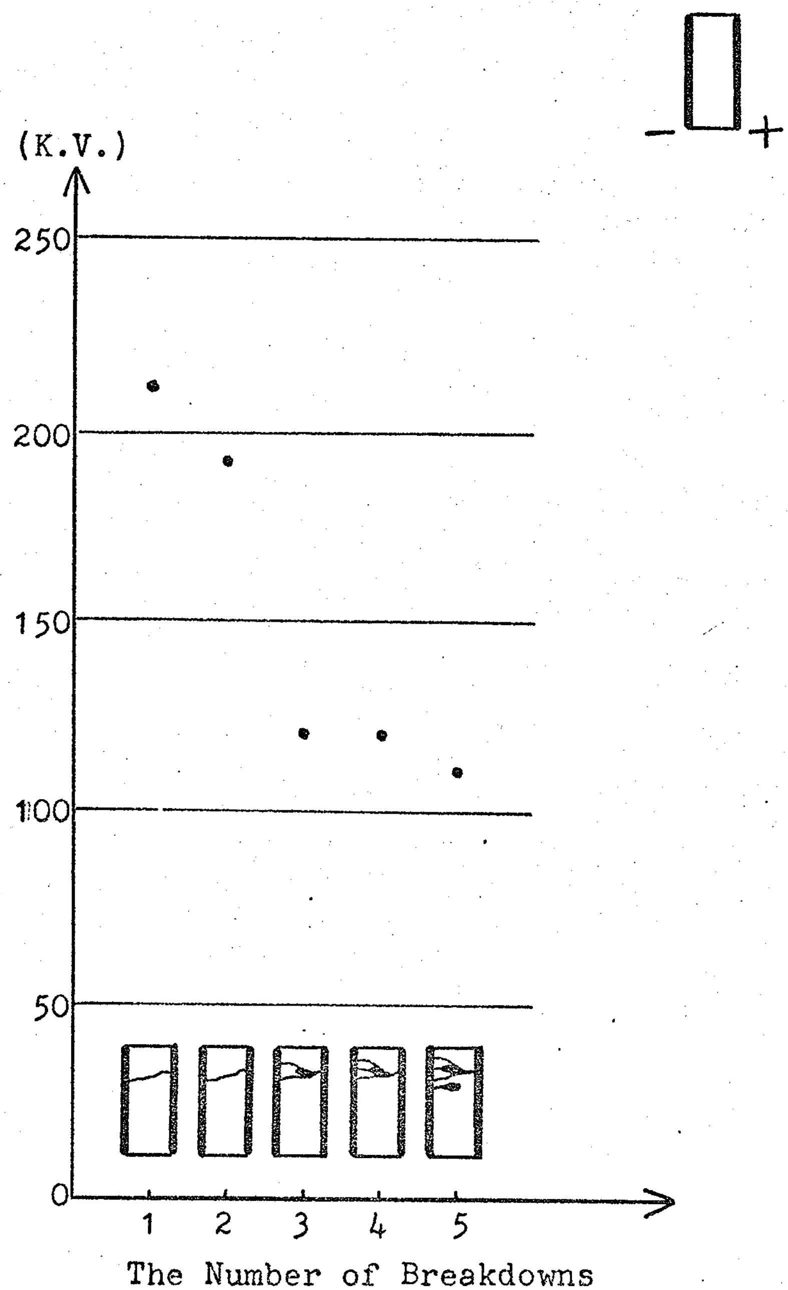


Fig. A-5 Breakdown Voltage across Teflon Surface

Teflon(1 cm ht., 1.27 cm dia.)
using 20/120 μsec surges

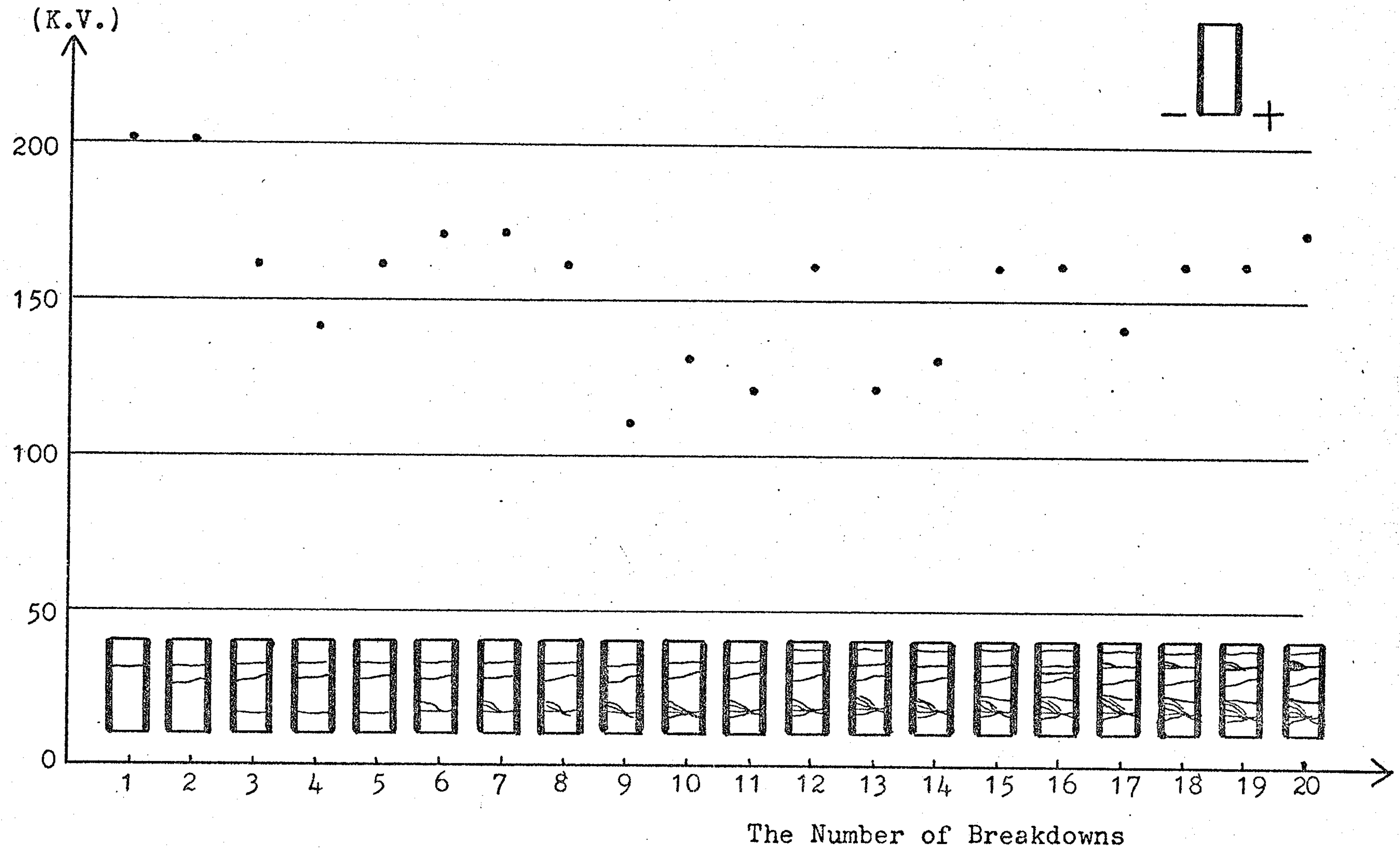


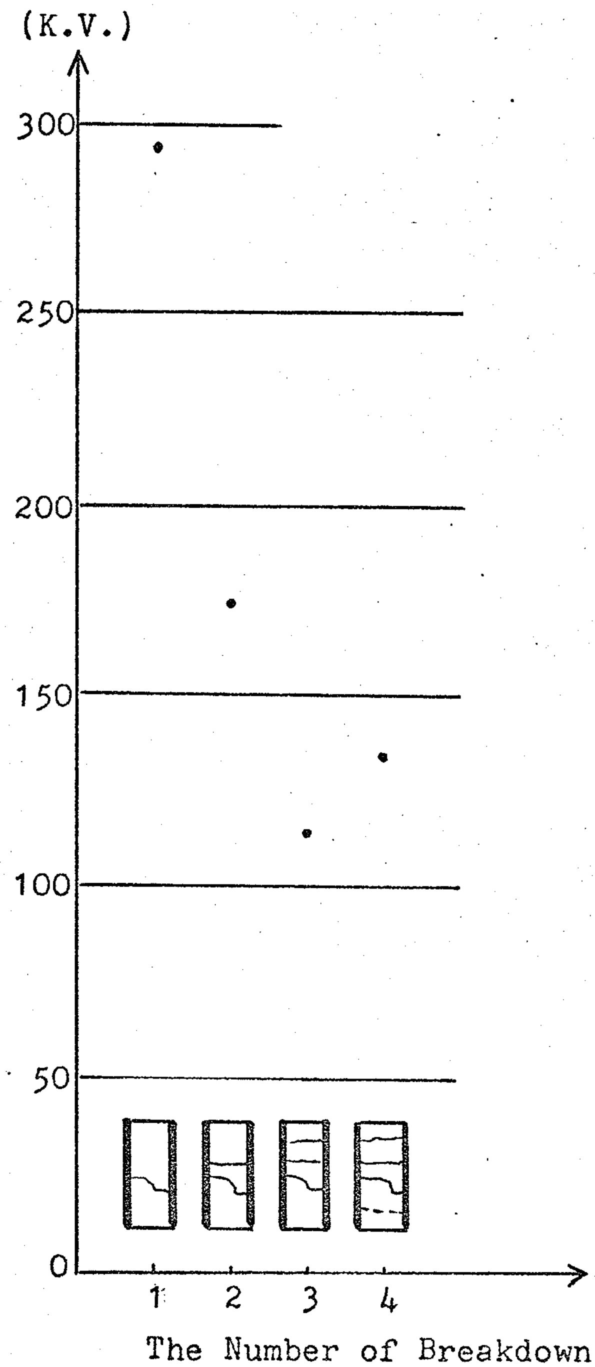
Fig. A-6 Breakdown Voltage across Teflon Surface

APPENDIX II

Figures A-7 to A-11 show results obtained with the use of standard wave impulses and painted polyethylene samples of 1 cm high and 1.27 cm diameter. Figures A-12 and A-13 show results obtained using the same impulses and painted Teflon samples of the same size as the above.

Polyethylene(1 cm ht., 1.27 cm dia.)

Standard Wave



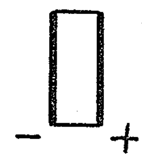


Fig. A-7 Breakdown Voltage across Polyethylene Surface

Polyethylene(1 cm ht., 1.27 cm dia.)

Standard Wave

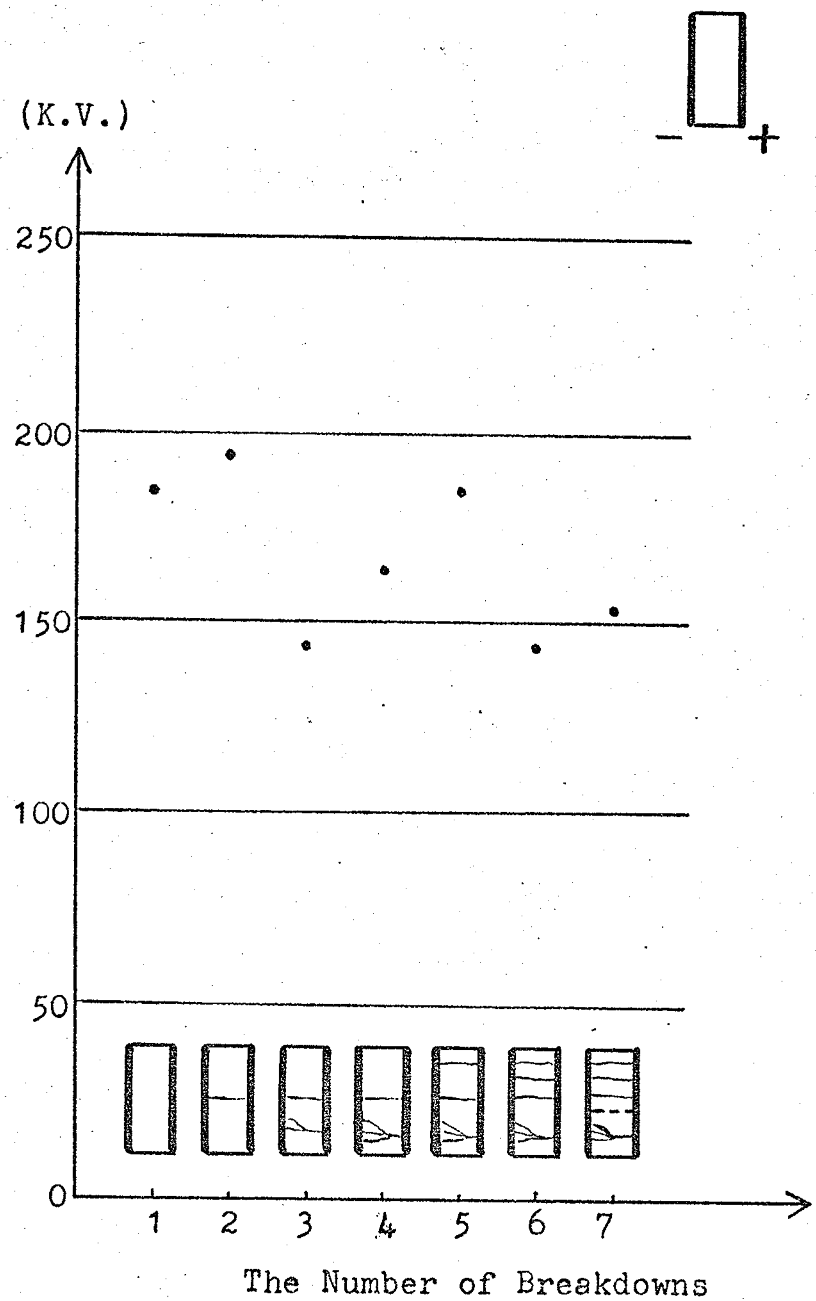
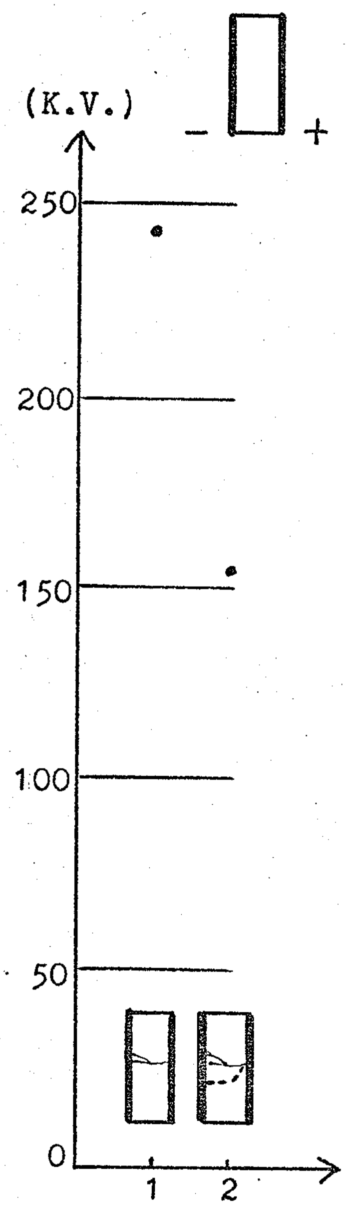


Fig. A-8 Breakdown Voltage across Polyethylene Surface

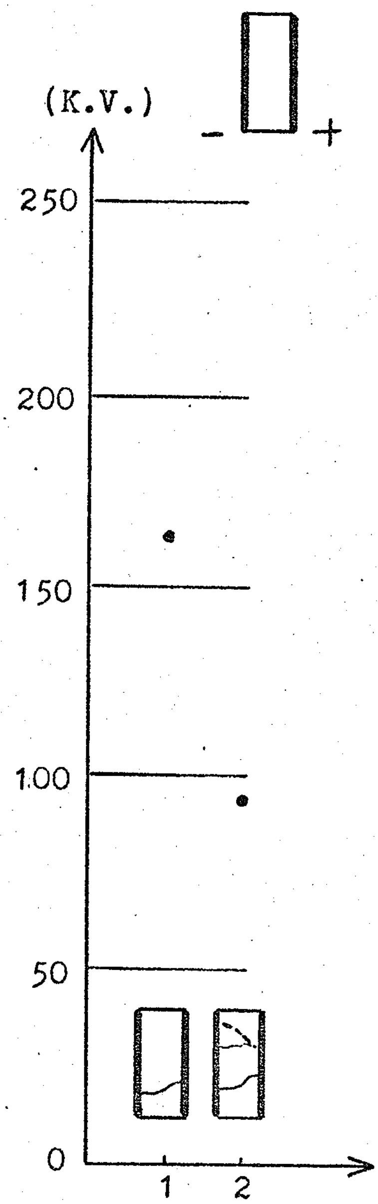
Polyethylene(1 cm ht., 1.27 cm dia.)

Standard Wave



The Number of B.D.'s

Fig. A-9



The Number of B.D.'s

Fig. A-10

Breakdown Voltage across Polyethylene Surface

Polyethylene(1 cm ht., 1.27 cm dia.)

Standard Wave

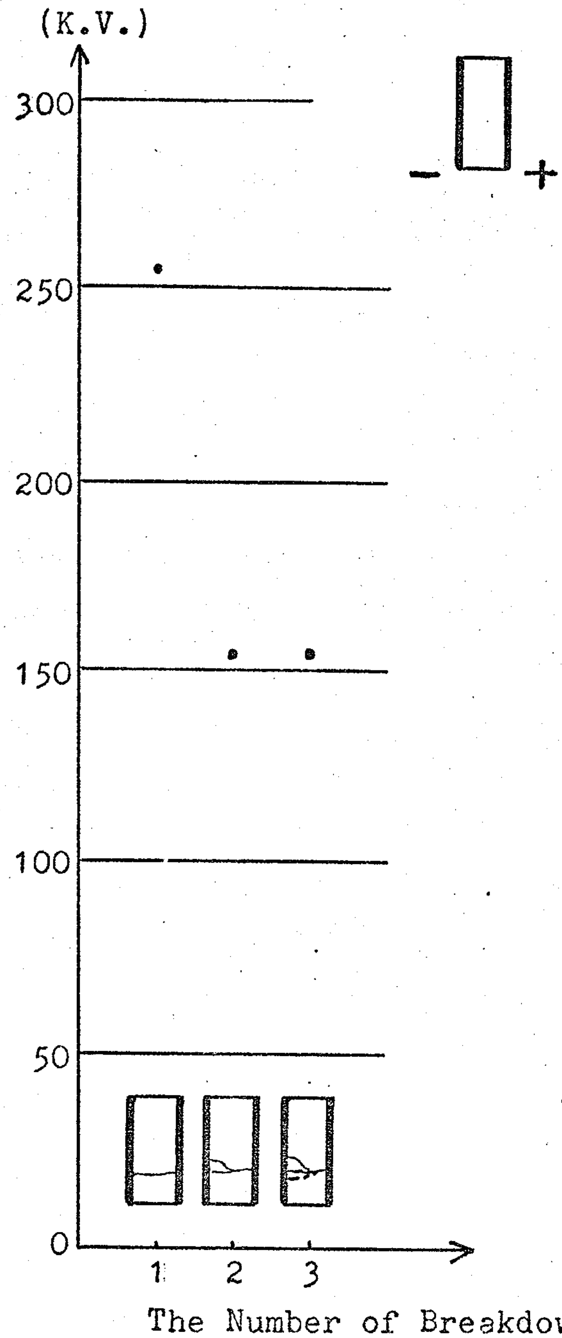


Fig. A-11 Breakdown Voltage across Polyethylene Surface

Teflon(1 cm ht., 1.27 cm dia.)

Standard Wave

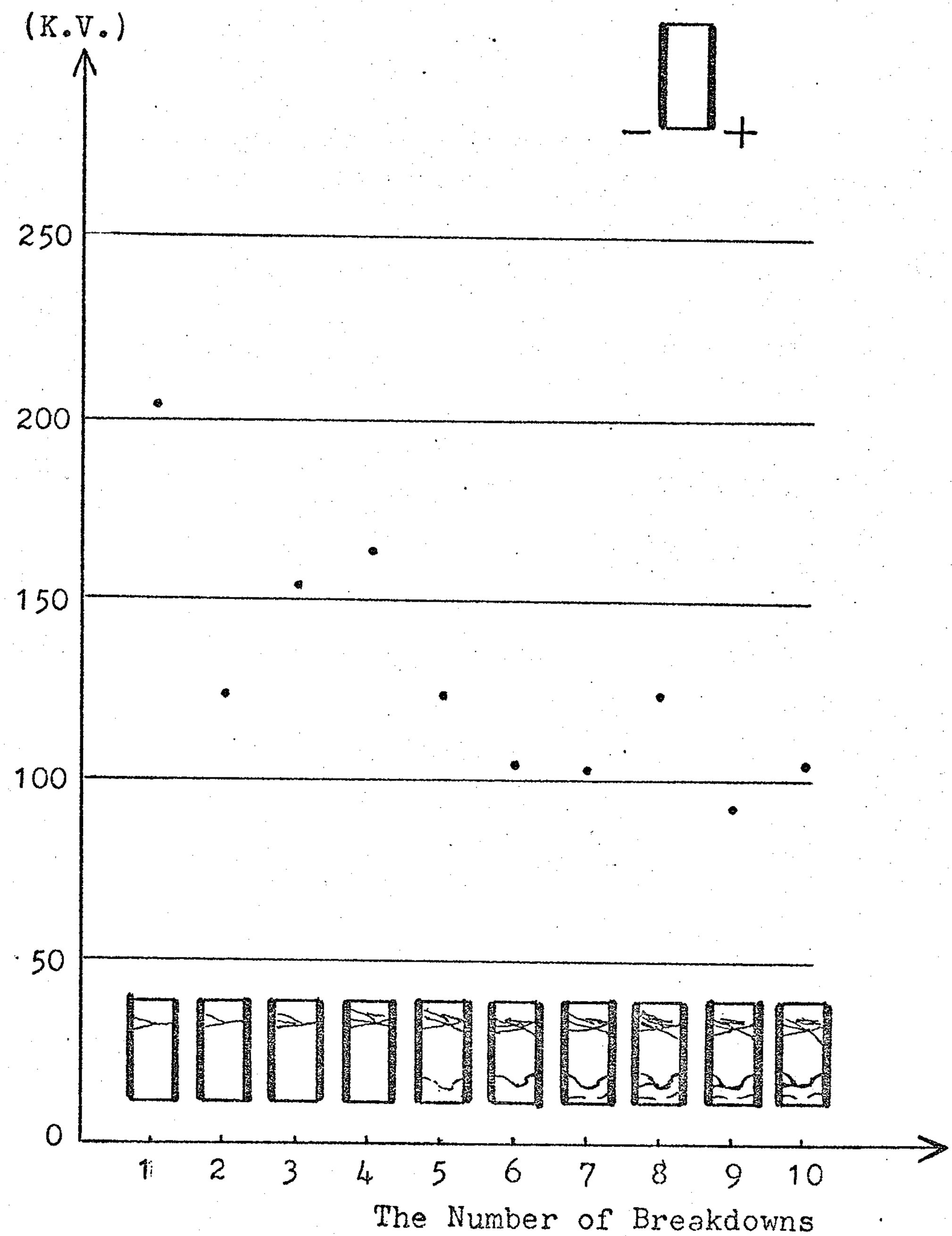


Fig. A-12 Breakdown Voltage across Teflon Surface

Teflon(1 cm ht., 1.27 cm dia.)

Standard Wave

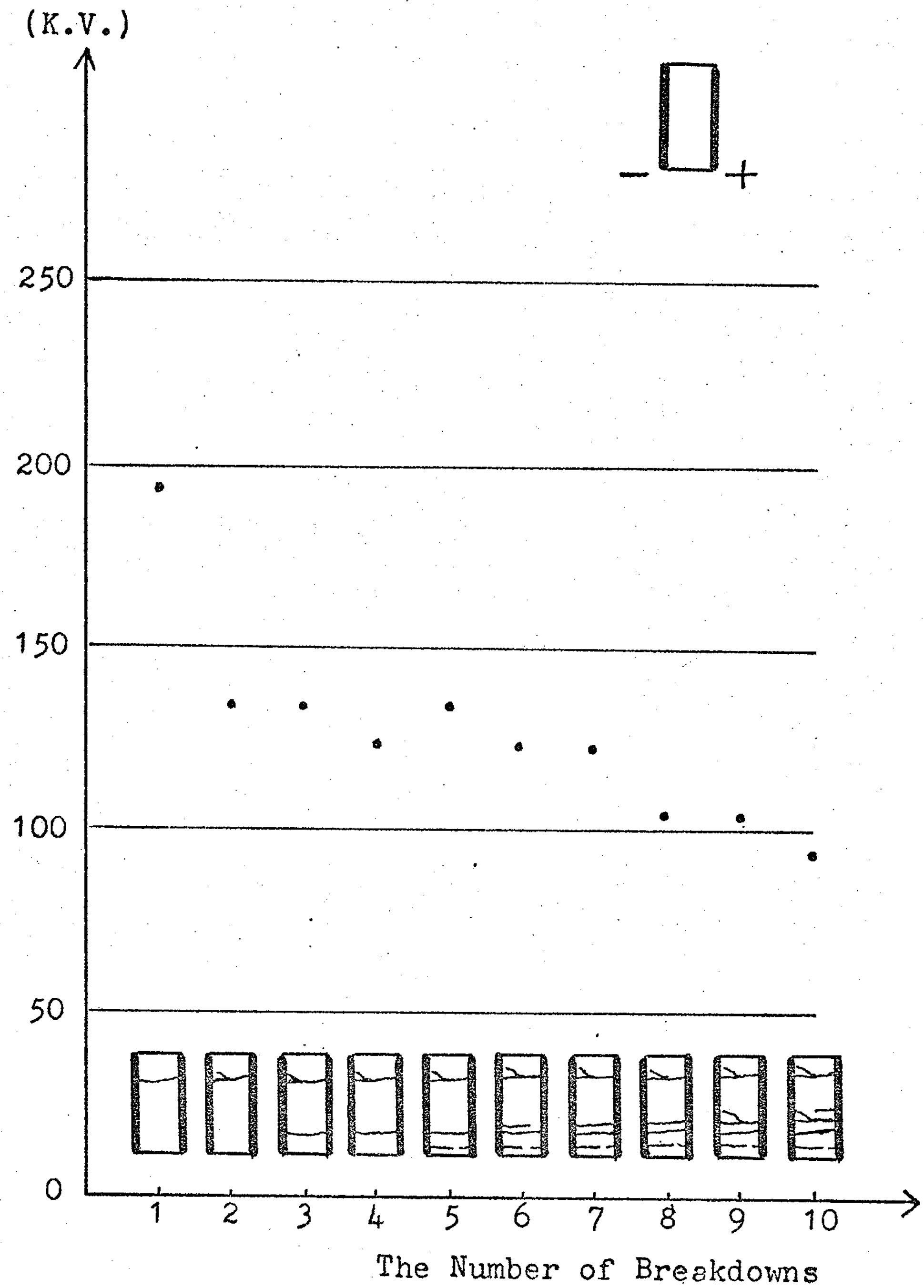


Fig. A-13 Breakdown Voltage across Teflon Surface

APPENDIX III

The following tables show all results shown in the main body of this thises. "FIGURE NUMBER" in the tables corresponds to that in the main body.

TABLE 1

BREAKDOWN VOLTAGES ACROSS THE SURFACE OF PERSPEX SPECIMENS (1 cm ht., 1.27 cm dia.) WITH ENDS PAINTED

STANDARD WAVE, UNIT: KILOVOLTS(PEAK)

BREAKDOWN NUMBER	SAMPLE No.1	SAMPLE No.2	SAMPLE No.3	SAMPLE No.4	SAMPLE No.5	AVERAGE
1	214	154	294	234	224	224
2	204	144	184	164	94	159
3	194	134	164	154	114	152
4	194	184	184	174	124	172
5	164	134	204	134	134	154
6	184	184	174	114	114	164
7	164	224	214	154	154	182
8	144	134	194	164	194	167
9	194	134	214	174	184	180
10	134	154	214	114	174	158
11	124	144	174	144	194	159
12	144	174	194	144	134	158
13	134	184	194	164	154	167
14	204	154	204	154	134	170
15	174	114	184	154	144	154
16	204	164	204	164	164	180
17	194	174	194	174	174	182
18	184	184	174	174	134	170
19	204	194	194	174	164	187
20	194	144	194	184	194	182

These results are shown in Fig. 3-3 in this thesis.

TABLE 2

BREAKDOWN VOLTAGE ACROSS THE SURFACE OF PERSPEX SPECIMENS(0.635 cm ht., 1.27 cm dia.) WITH ENDS PAINTED

STANDARD WAVE, UNIT: KILOVOLTS (PEAK)

BREAKDOWN NUMBER	SAMPLE No.1	SAMPLE No.2
1	174	164
2	144	164
3	134	144
4	144	104
5	124	134
6	114	134
7	134	134
8	104	134
9	124	154
10	124	134
11	134	134
12	144	134
13	124	144
14	94	134
15	84	114
16	94	134
17	84	124
18	104	124
19	114	124
20	124	124
FIGURE NUMBER	3-4	3-5

TABLE 3

BREAKDOWN VOLTAGES ACROSS THE SURFACE OF PERSPEX SPECIMENS(0.635 cm ht., 1.27 cm dia.) WITH ENDS LEFT UNPAINTED

STANDARD WAVE, UNIT: KILOVOLTS

BREAKDOWN NUMBER	SAMPLE No.1	SAMPLE No.2	SAMPLE No.3	SAMPLE No.4
1	204	184	174	254
2	214	214	184	114
3	104	224	164	124
4	104	104	174	124
5	124	114	134	154
6	134	124	124	144
7	144	154	144	154
8	144	144	154	144
9	144	134	134	144
10	144	154	114	154
11	154	124		
12	124	144		
13	144	134		
14	134	144		
15	114	134		
16	144	144		
17	154	164		
18	134	154		
19	154	154		
20	114	164		
FIGURE NUMBER	3-6	3-7	3-8	3-9

TABLE 4

BREAKDOWN VOLTAGES ACROSS THE SURFACE OF POLYETHYLENE SPECIMENS (0.635 cm ht., 1.27 cm dia.) WITH ENDS PAINTED

STANDARD WAVE, UNIT: KILOVOLTS (PEAK)

BREAKDOWN NUMBER	SAMPLE No.1	SAMPLE No.2
1	184	154
2	144	154
3	184	124
4	164	64
5	94	64
6	104	
7	104	
8	124	
9	134	
10	84	
11	74	
FIGURE NUMBER	3-10	3-11

TABLE 5

BREAKDOWN VOLTAGES ACROSS THE SURFACE OF POLYETHYLENE SPECIMENS(0.635 cm ht., 1.27 cm dia.) WITH ENDS UNPAINTED

STANDARD WAVE, UNIT: KILOVOLTS(PEAK)

BREAKDOWN NUMBER	SAMPLE No.1	SAMPLE No.2	SAMPLE No.3	SAMPLE No.4	SAMPLE No.5
1	104	224	204	174	234
2	144	264	174	204	184
3	154	224	224	214	204
4	164	234	204	184	204
5	194	234	234	184	164
6	164	114	254	74	144
7	104	134	204		164
8		154	224		184
9		114	174		194
10		94	214		134
11			214		164
12			224		154
13			254		214
14			234		84
15			154		
16			174		
17			94		
18			114		
19			124		
FIGURE NUMBER	3-12	3-13	3-14	3-15	3-16

TABLE 6

BREAKDOWN VOLTAGE ACROSS THE SURFACE OF TEFLON SPECIMENS(0.635 cm ht., 1.27 cm dia.) WITH ENDS UNPAINTED

STANDARD WAVE, UNIT: KILOVOLTS(PEAK)

BREAKDOWN NUMBER	SAMPLE No.1	SAMPLE No.2
1	224	214
2	214	274
3	224	174
4	214	214
5	164	224
6	224	204
7	214	184
8	224	254
9	234	94
10	234	84
11	214	
12	174	
13	204	
14	224	
15	244	
16	184	
17	254	
18	204	
19	84	
20	74	
FIGURE NUMBER	3-17	3-18

TABLE 7

BREAKDOWN VOLTAGE ACROSS THE SURFACE OF TEFLON SPECIMENS(0.635 cm ht., 1.27 cm dia.) WITH ENDS PAINTED

STANDARD WAVE, UNIT: KILOVOLTS(PEAK)

BREAKDOWN NUMBER	SAMPLE No.1	SAMPLE No.2	SAMPLE No.3	SAMPLE No.4	SAMPLE No.5	SAMPLE No.6
1	154	104	94	94	124	124
2	134	74	84	94	84	74
3	94	94	74	74	84	74
4	94	64	84	84	84	84
5	84	74	84			84
6	84	74				84
7	74	74				
8	94					
9	84					
10	94					
FIGURE NUMBER	3-19	3-20	3-21	3-22	3-23	3-24

TABLE 8

BREAKDOWN VOLTAGES ACROSS THE SURFACE OF PERSPEX SPECIMENS(0.635 cm ht., 1.27 cm dia.) WITH THE NEGATIVE END PAINTED

STANDARD WAVE, UNIT: KILOVOLTS(PEAK)

BREAKDOWN NUMBER	SAMPLE No.1	SAMPLE No.2	SAMPLE No.3	SAMPLE No.4
1	204	244	104	114
2	254	94	174	194
3	234	94	164	144
4	104	104	184	164
5	144	134	164	154
6	134	154	174	164
7	114	144	164	
8	144	154	104	
9	154	154	164	
10	154	114	134	
FIGURE NUMBER	3-25	3-26	3-29	3-30

TABLE 9

BREAKDOWN VOLTAGES ACROSS THE SURFACE OF PERSPEX SPECIMENS(0.635 cm ht., 1.27 cm dia.) WITH THE POSITIVE END PAINTED

STANDARD WAVE, UNIT: KILOVOLTS(PEAK)

BREAKDOWN NUMBER	SAMPLE No.1	SAMPLE No.2	SAMPLE No.3	SAMPLE No.4
1	234	144	114	104
2	244	184	154	134
3	174	174	134	144
4	174	144	104	164
5	164	134	124	123
6	154	124	124	154
7	154	144	114	114
8	124	124	144	134
9	134	134	124	114
10	124	134	134	144
FIGURE NUMBER	3-27	3-28	3-31	3-32