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SURFACE BREAKDOWN OF POLYMERIC MATERIALS IN A VACUUM UNDER DIRECT, ALTERNATING AND SURGE VOLTAGES

BY

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ABSTRACT

The present investigations provide data on surface breakdown of a solid insulator in vacuum. The main features investigated included: the effects of wave front durations of the applied voltage, and the effects of conditioning technique on the surface breakdown voltage.

Breakdown voltages across insulation surface in a vacuum of 10^{-6}torr were measured under direct, alternating, and surge voltages of front durations extending from 1.2 μsec. to 500 μsec. using cylindrical samples of Teflon and polyethylene placed between uniform field electrodes.

A dependence of the surface breakdown value on the rate of rise of the applied voltage was observed. The magnitude of the breakdown voltage for polyethylene samples decreased progressively with increasing wave front duration, and reached a minimum value somewhere between 150 μsec. and 500 μsec. Further increase in the wave front duration increased the breakdown voltage. When Teflon samples were tested, a similar decrease of breakdown voltage with the increase of wave front duration was observed, but a minimum was not reached.

During the present work, three different conditioning techniques (d.c., a.c., and pulse) were investigated. The results showed that the magnitude of the surface breakdown voltage, and the surface deterioration of the materials were strongly influenced by the conditioning technique. When the samples were tested using a.c. conditioning, the breakdown values were the least scattered, and the slowest surface deterioration of the material occurred. For these reasons, the majority of measurements during the present work were made following a.c. conditioning.

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CHAPTER I

INTRODUCTION

The main interest in the electric surface breakdown of solids in vacuum arises because of the limitation it presents in high-vacuum high-voltage devices. Breakdown voltages over insulators are usually low compared with breakdown voltages in vacuum gaps having the same separation of electrodes.[7,8,15] Quite often breakdown along the surface of a piece of insulation can be the limiting factor in the operation of vacuum insulated equipment.

The understanding of the mechanism of electrical breakdown across an insulating surface in vacuum is therefore of great practical importance, because at the moment, the operation of any high-vacuum high-voltage device necessitates either constructing the vacuum chamber itself of an insulating material, or insulating the high-voltage conductor as it passes through the wall of a metallic vacuum chamber. In addition there is often the problem of supporting the high-voltage conductor within the vacuum chamber.

A large amount of data is available on the surface breakdown of solids in vacuum subjected to d.c. voltage, but no such data are available for a.c. power frequency voltages and surge voltages with different front durations. The interest in insulator surface breakdown under d.c. voltages arose from the use of a vacuum as an insulator in devices subjected to d.c. voltages in which a large mean free path for charged particles is necessary, such as accelerators and electron microscopes.

Vacuum is a potentially good insulator for special applications in the power industry, such as cables, and vacuum breakers. Direct application of this knowledge of d.c. breakdown is not possible because of the different requirements of the various applications mentioned above. Here the effects of steep front and short duration over-voltages due to switching or lightning on the voltage withstand capability of the insulators are important.

Thus, the present experiments were designed to investigate the effects of the wave shape of the applied voltage on the breakdown value of polymeric materials under a constant pressure of 10^{-6}torr. Measurements were made on samples of Teflon and samples of polyethylene 25 mm. in diameter and 5, 10, 15, and 20 mm in length, placed between Rogowski's profile electrodes. The voltages used included unidirectional surge voltages with front durations extending from the standard 1.2 μsec. to 500 μsec. with corresponding wave tail durations extending from 50 μsec. to 2500 μsec. For comparison purposes measurements were also made under direct and 60 Hz. alternanting voltages.

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CHAPTER II

GENERAL CHARACTERISTICS OF DIELECTRIC SURFACE BREAKDOWN IN VACUUM

The present investigation was carried out with a view of obtaining data on surface breakdown of polymeric materials in vacuum under direct, alternating and surge voltages of various wave shapes. Previous investigators observed various phenomena, discussed later, that appear when a solid insulator held between two electrodes in a vacuum gap is subjected to high voltage. Further, they have shown that several factors affect the surface breakdown voltage of a solid insulator in vacuum. The more recent works are reviewed in the present chapter.

2.1 PREBREAKDOWN PHENOMENA

As the voltage across an insulator in vacuum is gradually increased from zero, several events occur. A prebreakdown leakage current (either relatively steady or pulsed in form) starts to flow as electrons are released into the vacuum from the cathode-insulator junction. These electrons then cause charging of the insulator surface and the release of X-rays from the anode surface. Luminous areas appear on the insulator due to release of gas from the insulator surface. Further increase in voltage produces increased leakage currents, outgassing, and luminosity until ultimately streamers start to propagate across the insulator surface and breakdown then takes place.[10]

Gleichauf,[7,8] investigating prebreakdown current under d.c. voltage, found that the prebreakdown current decreased in magnitude with successive voltage applications to the same insulator but that the results were widely scattered. No critical prebreakdown current was found since sometimes breakdown occurred after a current of about 5 x 10^{-11}amp. and in other cases after a current of 5 x 10^{-7}amp.

Hamisch et al.,[1,9,] who also studied prebreakdown discharges with d.c. voltages, found that weak current discharges occurred, causing only small voltage drops between the electrodes. Such discharges were associated with glow phenomena and at a fixed voltage their frequency decreased with time. In addition to these micro-discharges there was a steady current component that fluctuated only very slowly. During this steady current stage the insulator surface exhibited a uniform weak glow. This fact they took to indicate that the surface was being uniformly bombarded by electrons. This presupposes an electric field directed toward the insulator due to positive charges on the insulator surface.

Hamisch *et al*. showed theoretically that the surface charge on the insulator was proportional to the field strength and dependent on the angle of inclination of the insulator to the cathode surface. With the sides of the insulator perpendicular to the cathode the charge is positive and as the angle of inclination increases the charge decreases. At some angle the surface charge is zero and as the angle increases further, the charge becomes negative.

2.2 BREAKDOWN PHENOMENA

The main limitation of high vacuum insulation is a spontaneous discharge, often called breakdown. The characteristics of electrical breakdown over insulators in vacuum are: high currents, preceded by very low pre-breakdown currents; the voltage between the electrodes drops to a low value; a spark may be observed along the surface of the insulator, and on rare occasions a puncture of the insulator occurs. The breakdown voltages over insulators in vacuum are usually low compared with the breakdown voltages in vacuum gaps.[7,8,14] The vacuum at which the breakdown phenomena are initiated is below that required for the Paschen minimum and hence cannot be fully explained in terms of the Paschen relation.[8,14]

2.3 FACTORS AFFECTING THE BREAKDOWN VOLTAGE ACROSS A SOLID INSULATOR IN VACUUM

The surface breakdown value of a solid insulator in vacuum is affected by many different factors, such as conditioning, surface finish, insulator materials, length and shape of the insulator, wave shape and polarity of the applied voltage, and shape of the electrodes.

2.3.1 CONDITIONING

Experiments with solid insulation in vacuum have shown that the phenomenon usually known as conditioning takes place when a sample is subjected to successive breakdowns. There is an increase of the electrical strength of the insulator with successive breakdowns; when the number of breakdowns increases, the electrical strength reaches a maximum value and further breakdowns cause the electrical strength to remain constant or to decrease. In most cases such a high value does not represent one isolated reading but can be repeated several times before degradation of the material appears as sputtered metallic deposits on the insulator surface, forming conduction paths.

This conditioning phenomenon has been observed by many investigators and under different test voltages, for example Finke[5] and Shannon et al.[19] using d.c. voltage, Kuffel et al.[16] using 60 Hz alternating voltage, and Watson and Shannon[26] using pulse voltages.

A comprehensive study of conditioning under d.c. voltage was carried out by Gleichauf.[7] He investigated the general behaviour of the conditioning process, and the influence of the electrodes and of the insulators on this process. He also looked at the effect on conditioning of the circumstances under which the breakdown arc extinguished. He found out that with successive breakdowns, the breakdown voltage followed a general trend toward higher voltages, the rate of increase diminishing with time. When the voltage was removed temporarily, part of the conditioning was lost but the insulator subsequently recovered at a faster rate. The extent of conditioning loss was dependent on the previous treatment of the test sample. As the time interval between successive series of tests was increased, the initial breakdown voltage on resumption of testing was considerably lower than at the end of the previous tests, but was usually of higher value than the very first breakdown of the sample. Similar loss of conditioning was found if the insulator was taken from the continuously pumped vacuum chamber and exposed to the atmosphere, the length of the exposure to the atmosphere being immaterial. Multiple breakdowns caused irreversible damage to the insulator surface or to the junction between the insulator and the electrodes, thus lowering rather than increasing the breakdown strength. When permanent degradation of the sample occurred, it was generally in the form of sputtered metallic deposits on the insulator surface which formed conduction paths.

Gleichauf was also able to condition insulators by continuously applying a high voltage to the insulator.

In this case breakdown occurred less and less frequently at the constant voltage. When the voltage was raised, breakdowns were again frequent but the probability of a breakdown's occurring decreased with the length of time of voltage application. After reaching sufficiently high voltages, the breakdowns became very frequent and no further conditioning could be observed.

Shannon et al.[19] and Kuffel et al.[16] have also achieved conditioning by maintaining across their insulators a direct voltage below the breakdown value. Under these circumstances, the prebreakdown current, the luminosity, and the quantity of gas measured by an ionisation gauge released from the insulators decreased with time and allowed the application of higher voltages. Such a procedure has the obvious advantage of minimizing the possibility of permanent damage to the insulator.

2.3.2 ELECTRODE MATERIAL

The influence of the electrode material on the surface breakdown voltage of solid insulators in vacuum has not been studied by many investigators, but results given by Gleichauf[8] and Kalyatskii et al.[13] suggest that the material and finish of the electrodes does not have any significant effect on the breakdown voltage. Gleichauf, using electrodes of 18-8 stainless steel, copper, magnesium, or aluminum, tested insulators of pyrex glass and fused quartz, but found no appreciable difference in the breakdown voltage with changes of electrodes. Kalyatskii examined the effect of the surface finish and the material of the electrodes on the breakdown voltage. He used an organic glass insulator placed between polished and ground aluminum electrodes, and also between graphite electrodes. He reached the same conclusions as Gleichauf: there was no significant effect of the material and the finish of the electrodes on the breakdown voltage of the insulator.

2.3.3 MATERIAL OF THE INSULATOR

The data available on surface breakdown in vacuum demonstrate that the breakdown voltage of an insulator of fixed shape and length in a vacuum is strongly dependent on the material of the insulator. Imperfect contact between the insulator and the electrodes creates small voids at the cathode end of the insulator. The electric field in these voids increases with the increase of the dielectric constant of the insulator. Kofoid,[14,15] working with short insulators in a vacuum of 10^{-4} to 10^{-5}torr, indicated that the voltage required to release electrons from the cathode-insulator junction and bring about breakdown is systematically lower for materials of higher dielectric constant.

Borovik and Batrakov, [2] working at pressures of 10^{-6} to 10^{-8}torr, found no correlation between electric field in the dielectric at breakdown and the dielectric constant of the insulator. This suggests that perhaps junction-discharge phenomena and subsequent ion actions cannot exist to a degree sufficient to lower the breakdown voltage at such low pressures. From the practical point of view, considerations must include the bulk properties of the insulator material. For example it is pointless to use a material of low dielectric strength because breakdown will then occur through the body of the insulator.

Shrivastava[21,22] has pointed out that unglazed electrical-quality porcelain is unsuitable because it is porous and often has cavities and inclusions close to the surface, from which absorbed gases are released under the action of the electrical stress. Pyrex glass is a good material, providing that it is free from bubbles, but it is prone to mechanical damage. Hydrostatically pressed aluminium ceramic insulators can be made free from bubbles and inclusions, but if extruded can still exhibit surface defects.

2.3.4 SURFACE CONDITION

The breakdown voltage of an insulator of fixed shape and length in vacuum is strongly dependent on the surface condition of the insulator. This has been demonstrated by many investigators. In particular, Kalyatskii and Kassirov[13] improved the impulse breakdown strength of a polished insulator of organic glass by 40 to 70 per cent by roughening the surface with fine emery cloth.

Gleichauf[8] found that roughening the surface of glass or quartz insulators improved the breakdown strength about 40 per cent. He also investigated the influence of roughening the region close to the anode or close to the cathode. This was done by roughening a ring about 3.5 mm wide at one end of a polished glass rod 22.3 mm long and 12.5 mm in diameter. When the roughened edge of the cylindrical surface of the glass rod was adjacent to the anode, the breakdown voltage was 49.5 Kv. This value is not significantly different from the breakdown voltage of a glass rod where the cylindrical surface has not been roughened. In reversed polarity, that is, when the roughened part of the insulator was close to the cathode, the breakdown voltage was 68 Kv. Further tests were made with another glass rod which had a roughened ring about 2.5 mm wide. With the roughened end at the cathode, the breakdown voltage was 68 Kv. This fact shows that only the region of the insulator immediately adjacent to the cathode is critical.

Gleichauf also found indications that the breakdown voltage increased with the surface resistivity of the material. To check this effect he increased the surface resistivity of an 857-AJ glass sample by applying a coat of silicone oil on the surface of the insulator. The breakdown voltage increased by more than 50 per cent. Improvements in the breakdown voltage due to surface coating have been reported by other investigators. Vierstra,[24] for example, observed an increase in the breakdown strength of an insulator from about 40 Kv. to 70 Kv. by baking a layer of chromic oxide in silicate binder onto the surface. Fryszman *et al.*[6] improved the strength of an insulator by coating the surface with a semi-conducting film of ferric oxide.

2.3.5 LENGTH AND SHAPE OF INSULATORS

As in straight vacuum gaps, the breakdown voltage across an insulator in vacuum does not increase in a linear manner as the length of the insulator increases. The rate of rise of the breakdown voltage decreases with increase of length. This fact has been reported by many investigators, and in general all agree about the non linearity of the breakdown-length characteristic of solid insulators in vacuum, but the breakdown voltages observed for insulators of a given material and length diverge widely, showing the importance of the cathode insulator junction, the conditioning, and the type of applied voltage.

The breakdown voltage of an insulator in vacuum is dependent on the angle that the dielectric makes with the electric field.[17,20,26] Milton,[17] using specimens in the shape of a frustum in a vacuum of 10^{-5} torr, obtained data as a function of cone angle for positive and negative pulses of 5 μsec. rise time and several kilovolts amplitude. The results indicate that most materials exhibit a greater resistance to breakdown if the base of the cone is at the cathode and that the breakdown strength is dependent on the cone angle that the dielectric makes with the applied field.

Milton also found that the optimum angle for maximum breakdown voltages differed for the three insulating materials used, but that breakdown voltages were lowest with cylindrical specimens irrespective of the insulation material used.

2.3.6 PRESSURE

There is not a great deal of information available about the effect of pressure on breakdown voltages of solid insulators in vacuum. Gleichauf,[7] testing samples of quartz and 7740 pyrex glass 23 mm long and 13 mm in diameter under d.c. voltage, found no effect of pressure on the breakdown voltage in the range 5×10^{-3} to 10^{-7} torr. A similar absence of a significant effect was observed by Smith[20] in the range 10^{-2} to 10^{-4} torr under pulses which rose in 5-10 nanoseconds and lasted about 30 nanoseconds. Smith tested samples 2.5, 10, and 25 cm long and found that at pressures of about 0.03 torr and higher, the breakdown voltage began to decrease independently of the length of the insulator, thus demonstrating the existence of a pressure effect and not a pressure distance effect.

Kuffel et al.[16] have shown that there is a definite dependence of the breakdown voltage on pressure. They investigated the variation of d.c. breakdown voltage with pressure across samples of plexiglass 5 to 20 mm long. For all sample lengths the average breakdown values tended to decrease slowly when the pressure was increased from 10^{-6} to 10^{-4} torr. Thereafter the curves increased sharply and reached maximum values at pressures of about 5×10^{-4} torr subsequently falling to low values at pressures of around 10^{-3} torr. A similar effect was noted earlier by Ramm[18] for long insulators in vacuum.

2.3.7 PARTICLE BOMBARDMENT

Gleichauf,[8] using fused quartz and uranium glass insulators, found that the breakdown voltage remained unchanged when the test sample was exposed to ultraviolet radiations. He also found that 60 to 90 Kv X-rays, of intensities between 0.2 and 0.3 roentgens/sec., did not affect the breakdown voltage over pyrex glass, fused quartz or uranium glass.

Hawley[10] reported that under the action of r.f. fields, electron bombardment can result in multipactoring, whereby, if the secondary emission coefficient of the insulator surface is greater than one, the release of more than one secondary electron by the impingement of one primary electron can result in cumulative processes leading to a breakdown.

2.4 BREAKDOWN OVER INSULATOR SURFACE IN A POOR VACUUM

The behavior of the breakdown phenomenon over insulators in a poor vacuum has been investigated by Smith.[20] He studied the breakdown strength of insulators under pulse conditions in a poor vacuum (10^{-4} to 10^{-1} torr). The voltage generator he used produced an output pulse which rose to maximum in 5-10 nanoseconds and lasted about 30 nanoseconds, followed by a voltage reversal of similar duration but smaller amplitude and still further decaying oscillations. Under these conditions the breakdown process was extremely fast, forming a discharge 50 cm. long in 2×10^{-8} sec., the resistance of the breakdown path falling to a few ohms in a few nanoseconds. Breakdown strength proved to be independent of:

(a) Gap in the range 0.5 cm. to 20 cm.
(b) Diameter of the test cell if this was greater than the gap.
(c) Gas pressure, provided this was lower than 0.03 torr.
(d) Electrode material.
(e) Type of residual gas.
(f) Existence of X-ray dose rates up to 10^{10} roentgens/sec.

Smith also investigated the effect of varying the half angle of a frustum-shaped insulator for several different materials. He found that:

(a) A given material exhibited a wide range of breakdown strengths, from 20 to 300 Kv/cm.

(b) This dependence of breakdown strengths on the angles between the insulator and the electric field was strongest when the angles were less than about 25°

(c) There was a marked effect of polarity.

(d) Insulators withstood the highest gradients when the semiangle was about 50°, higher angles eventually leading to erratic behavior as well as a reduction in strength.

(e) Breakdowns occurred most readily when half angles were small and negative.

2.5 HIGH FREQUENCY BREAKDOWN

Several studies have been made of the failure of ceramic insulators due to surface sparking at microwave frequencies. Walker and Lewis[25] found that breakdown was liable to occur across a titanium dioxide ceramic disc, with electric fields of the order of 10 Kv/cm. normal to the surface of the disc. A glazing only a few thousandths of an inch thick on the disc, consisting mainly of lead borate, increased the strength to above 300 Kv/cm, which was the limit attainable with the power source. The reasons for this improvement were investigated by Hayes and Walker,[11] who concluded that the breakdown strength was improved because the glaze provided a protective coating. They found that plain titanic ceramic gave resistance to sparking so that a single spark or any weak initial discharge caused permanent damage to the materials, destroying the surface insulation. Coating the ceramic with a lead-borate glaze prevented this damage and any initial discharge caused a clean-up process to take place, raising the breakdown voltage considerably.

2.6 PULSE BREAKDOWN

Several studies have been made of the impulse breakdown voltage of insulators in vacuum. Kofoid[14] reported no significant trend in the crest voltage required to release electrons from the cathode-insulator junction when the impulse wave shape changed. Nevertheless, other investigators did show that the breakdown voltage for a given material and length was strongly dependent on the rise time of the applied pulse.

Thumwood,[23] investigating breakdowns across glass cylinders 18 inches long under pulse voltages of front durations extending from 10^{-7}sec. to 10 sec., found that the breakdown voltage increased with the increase of the wave front duration. For a long enough wave front, the breakdown voltage approached the d.c. breakdown value, which in this case was the highest breakdown value observed. This was the inverse of the effect observed by Kalyatskii and Kassirov,[13] who tested several materials with lengths up to 20 mm under pulse voltages with front durations extending from 0.1 μsec. to 3 μsec. They found that the breakdown voltage increased with reduction of the wave front duration and that the d.c. breakdown voltage was the lowest observed.

Kuffel et al.[16] investigated the effect of the wave front duration extending from 1 μsec. to 600 μsec. on the breakdown voltages of plexiglass samples of 25 mm diameter and 5 to 20 mm length placed between Rogowski's profile electrodes in a vacuum of 10^{-5} torr. They also recorded the d.c. and a.c. breakdown voltages for purposes of comparison. Their results showed the highest breakdown values with d.c. voltages, which remained about 10% above the standard impulse breakdown voltages. The 60 Hz values were, in turn, up to 40% below the standard impulse values. The results also showed that under surge voltages the standard impulse gave the highest breakdown values and that when the wave front duration was increased, the breakdown values decreased reaching a minimum lower than the corresponding 60 Hz breakdown value, for a surge of front duration somewhere in the range 50 μsec. to 150 μsec. Thereafter the breakdown values increased gradually with increases of the wave front duration.

2.7 FORMATIVE TIME LAG

The formative time lag of breakdowns across an insulator in vacuum was investigated by Bugaev and Mesyats[3]. For 3 mm long insulators subjected to an over voltage under a very fast pulse, the formative time lags varied between 7 and 20 nanoseconds depending on the insulating material used. Watson and Shannon[26] have postulated that the formative time lag is governed by thermionic emission of hot electrons from within the dielectric.

2.8 PHENOMENA IN THE REGION OF THE CATHODE-INSULATOR JUNCTION

A general agreement exists among most investigators in the field of high voltage vacuum phenomena that most breakdowns across a solid insulator originate at the triple junction of dielectric, vacuum and negative electrode.[4,12,15] Most of the hypotheses put forward to explain the flashover across insulators in vacuum assume an initial stage in which electrons are released from the region of the cathode-insulator junction. In addition, careful design of this junction can have a marked effect on the electrical strength of a given length of insulator. It is therefore of interest to list the various observations made of phenomena that occur in this region, and the methods employed to reduce electron emission from the triple interface between cathode, insulator and vacuum.

2.8.1 VISUAL PHENOMENA

If the voltage is gradually increased until it is close to the breakdown value, discharges are seen more or less uniformly spaced around the cathode-insulator junction. These discharges appear as zones of diffused blue glow that are steady in location, intensity and shape. Increasing the voltage further extends the luminosity toward the anode. Additional increases in voltage propagate streamers across the insulator surface and breakdown then takes place.[10]

2.8.2 METHODS OF REDUCING STRESS AT CATHODE INSULATOR JUNCTION

Where a cylindrical insulator simply rests with a butt joint on the surface of the cathode, the surfaces of the metal and dielectric cannot be made perfectly flat, and thus voids will exist at the junction. In such voids the field is sufficiently strong to produce electron emission leading to the initiation of breakdown across the insulator surface. Kofoid[15] made a comprenhensive study of the effect of the metal-dielectric junction phenomena. He showed that success in reducing discharge phenomena at the edge of a cathode-dielectric junction was achieved only by reducing, below a critical value the electric gradient, in the normally unavoidable small highly stressed gas volumes between electrode and dielectric at the edge of the junction. He also showed that attempts to prevent the junction phenomena by applying a metal coating to the ends of the dielectric specimens to eliminate voids at the end of the junction were unsuccessful because the discharge phenomena were simply transferred to the edge of the metal coating.

Kofoid also demonstrated that the magnitude of the voltage at which junction discharge phenomena contribute significantly to the breakdown processes can be increased by using electrodes of simple designs which act to reduce the field at the edge of the junction. Transfer of the location of the edge of the dielectric metal junction to a region of low electric field by glass coating of the electrode was shown to be particularly effective in preventing junction phenomena. Finally, he showed that the method of making the positive metal dielectric junction has no important effect on the breakdown voltage.

Shannon *et al.*[19] also investigated methods of reducing the field intensity in the region of the cathode-insulator junction. They showed that insulators with poor dielectric-to-cathode contact consistently gave inferior performances while similar poor dielectric-to-anode contacts showed little adverse effect. They also looked into the effects on breakdown of various insulator shapes. The results showed that those designs that provided a barrier to surface discharges and were shaped to reduce the field at the insulator cathode junction increased the breakdown voltage appreciably.

2.9 HYPOTHETICAL BREAKDOWN MECHANISM

The experimental evidence reviewed so far indicates the important role played by electrons released at the insulator cathode junction in initiating a breakdown across a solid insulator in a vacuum gap. For example, Kofoid[14,15] showed that electrons and negative ions were produced at the insulator cathode junction, and he postulated that when these negative particles impacted on the solid insulator or the anode surface they released X-rays which in turn released further electrons from the cathode and the solid dielectric, thus leading to a cumulative breakdown process. That the release of electrons initiated the breakdown was confirmed by Kofoid when he designed the usual butting insulator-cathode junction to inhibit the release of electrons until much higher fields were reached, and found that the breakdown strength was also much increased.

Fryzman *et al.*[6] postulated the following hypothesis for the breakdown mechanism: free electrons emitted at the cathode-insulator junction bombard the anode or insulator near the anode, and release secondary electrons. Thus the surface of the insulator near the anode becomes positively charged to a potential approaching that of the anode. The charged area gradually moves closer to the cathode so that the stress at the cathode eventually increases to a value sufficient to cause the release of electrons and hence breakdown. Once the arc is formed the insulator surface discharges, the field strength decreases, the arc is extinguished, and the cycle is repeated. After many breakdowns the insulator becomes covered with a layer of evaporated metal, and leakage currents prevent the accumulation of charges on the insulator surface.

Fryzman et al.[6] also found that by screening the part of the insulator surface near the cathode or covering this part with a semi-conducting layer, the breakdown voltage was raised by a factor of approximately 2.5. These workers suggested that insulators having a small secondary emission rate and a low surface resistivity should also improve the breakdown voltage.

Hamisch et al.,[9] who measured the surface charge on insulators, also postulated a breakdown mechanism relying on surface charging of the insulator due to the release of secondary electrons. Watson,[27] on the other hand, proposed that electrons are emitted from the dielectric surface, by thermionic emission at a rate depending on the square of the electric field strength. Thus the surface becomes positively charged to a degree sufficient to draw any other electrons into it, where they will multiply by secondary emission up to a breakdown condition. Hence, while the breakdown is produced by secondary emission, the initial charging of the surface is governed by thermionic emission of hot electrons from within the dielectric.

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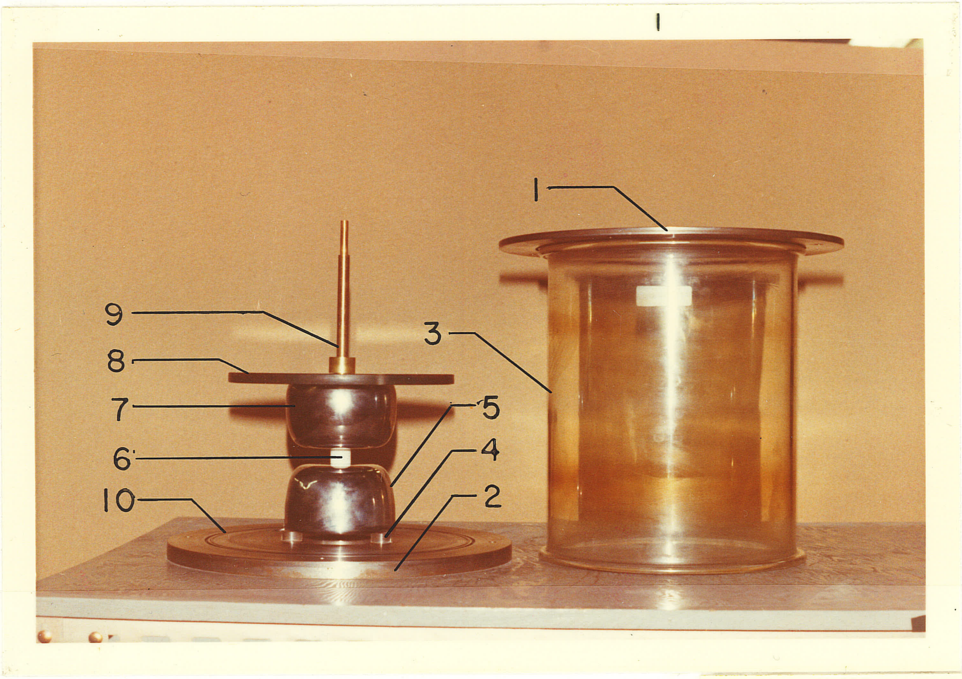
CHAPTER III

APPARATUS

3.1 THE VACUUM TEST CHAMBER

The vacuum chamber consisted of a pyrex glass cylinder 40 cm high and 30 cm in diameter, fitted with two metal end-plates. The top plate was 0.8 cm. thick and 42 cm. in diameter, but the bottom plate was 2 cm. thick and 42 cm. in diameter, with a central hole 9.5 cm. in diameter to permit the connection of the chamber to a pumping system, and with a hole 2.5 cm. in diameter to allow placement of a high voltage feed-through. These plates were sealed to the pyrex glass cylinder with neoprene O-rings covered with silicone high vacuum grease.

The nickel plated electrodes were of Rogowski's profile, designed to give a uniform field for spacing up to 3 cm. A glass disc 1.3 cm. thick and 28 cm. in diameter was fastened on top of the upper electrode to increase its weight and stability. The electrical contact between the upper electrode and the top metal plate was achieved by means of an upper contact assembly. This consisted of a brass rod 11 cm. long and 0.9 cm. in diameter fitted into a bored brass cylinder which was 13 cm. long, 0.95 cm. internal diameter, and of 0.7 cm. wall thick-



1 - Top Metal Plate
2 - Bottom Metal Plate
3 - Pyrex Glass Cylinder
4 - Plexiglass insulator
5 - Lower Electrode
6 - Test Sample
7 - Upper Electrode
8 - Glass Disc
9 - Upper Contact Assembly
10 - Neoprene O-Rings

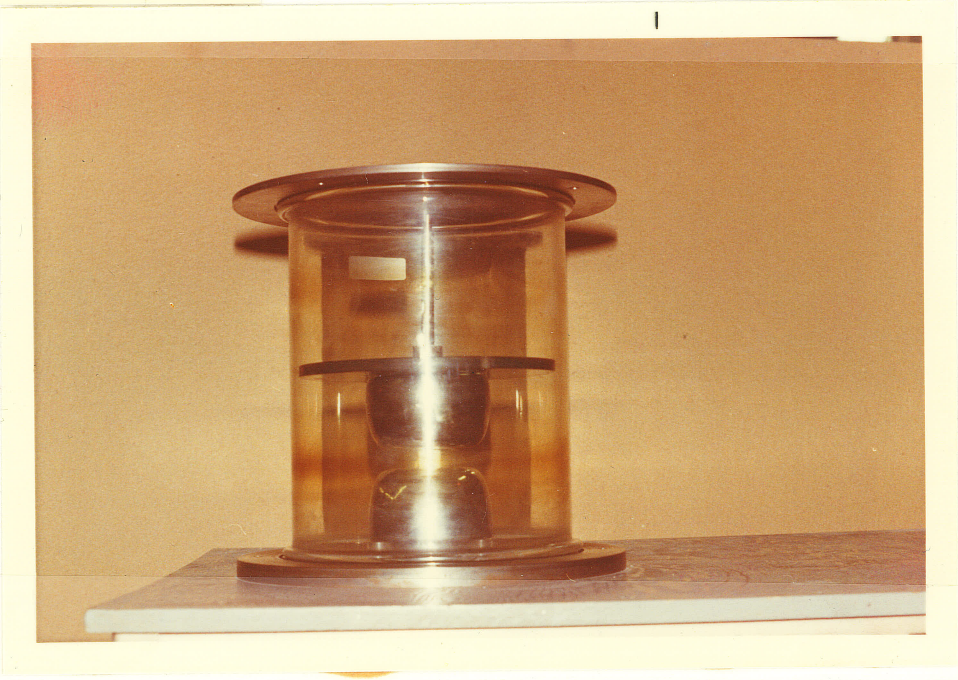


FIGURE 3.1 Vacumm Test Chamber

ness. This, in turn, was spring-loaded to maintain a good contact with the top metal plate where the high voltages were applied.

The lower electrode was placed on top of three pieces of plexiglass 1.3 cm thick and 2.5 cm in diameter to provide good working conditions for the vacuum system and to avoid electrical contact between the electrode and the bottom metal plate which was at ground potential. Electrical connection of the lower electrode with the external circuit was achieved by means of a high voltage feed-through, located in the bottom metal plate, connected by a copper wire to the bottom of the lower electrode. Figure 3.1 illustrates the chamber and its different components.

3.2 THE EVACUATING SYSTEM

The present research was carried out in a vacuum chamber continuously evacuated by a rotary-diffusion pump system equipped with a liquid nitrogen trap, giving an ultimate vacuum of about 5×10^{-7}torr. The pressure was monitored by an ionization gauge (Edwards Penning Gauge Model 7) with a pressure range of 10^{-2} to 10^{-6}torr. The oil rotary pump (Edwards Speedivac Model ES100) was of 1.2 litres capacity, with a pumping rate of 100 litres per minute and was filled with Edwards No. 16 oil. A diffusion pump (Edwards Speedivac Model E02 Air Cooled) of 75 ml fluid charge was used with silicone 704 fluid. The vapour trap (Edwards Vapour Trap Model NTMZA) of 0.9 litres coolant capacity was used with liquid nitrogen as a coolant to give a maximum vacuum of about 5 x 10^{-7}torr. Figure 3.2 illustrates the different components of this evacuating system.

3.3 OPERATION OF THE EVACUATING SYSTEM

In the operation of the evacuating system, the following procedures were adopted:

3.3.1 STARTING UP

If both, the pump and the apparatus were at atmospheric pressure then:

(1) The baffle valve, the air admittance valve, and all other openings to the atmosphere were closed.

(2) The roughing and backing valves were opened.

(3) The fan motor and the rotary pump were switched on.

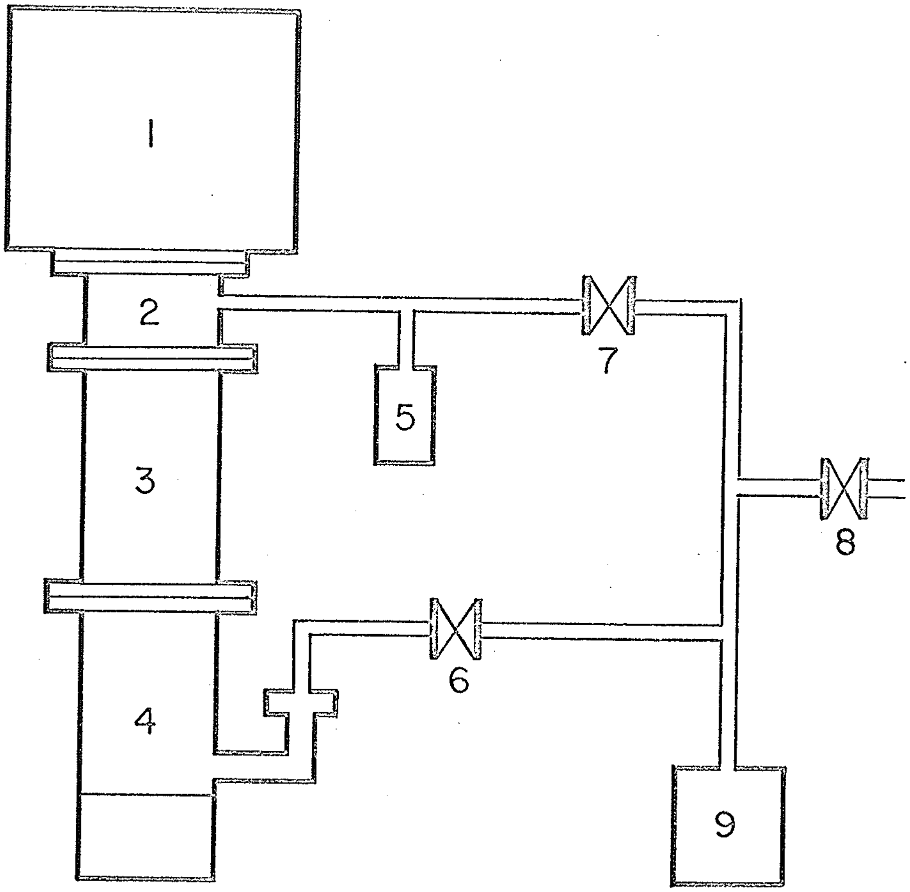
(4) When the backing pressure reached 0.5 torr or lower, the supply to the diffusion pump heater was switched on.

(5) After a warming up period of 10 to 15 minutes, the roughing valve was closed and the baffle valve was opened.

3.3.2 RE-ADMISSION OF AIR TO THE VACUUM CHAMBER

(1) The baffle valve was closed.

(2) The backing valve was closed.



1— Vacuum Chamber
2— High Vacuum Isolation Valve (Baffle Valve)
3— Vapour Trap
4— Diffusion Pump
5— Penning Vacuum Gauge
6— Backing Valve
7— Roughing Valve
8— Air Admittance Valve
9— Backing Pump (Rotary Vacuum Pump)

FIGURE 3.2 Vacuum System Diagram

(3) The roughing valve was opened.

(4) The air admittance valve was opened.

3.3.3 RE-EVACUATING THE TEST CHAMBER

(1) The air admittance valve was closed.

(2) When the system pressure reached 0.5 torr or lower, the roughing valve was closed.

(3) The backing valve was opened.

(4) The baffle valve was opened.

3.3.4 CLOSING DOWN

(1) The baffle valve was closed and the diffusion pump heater was switched off.

(2) The backing valve was closed.

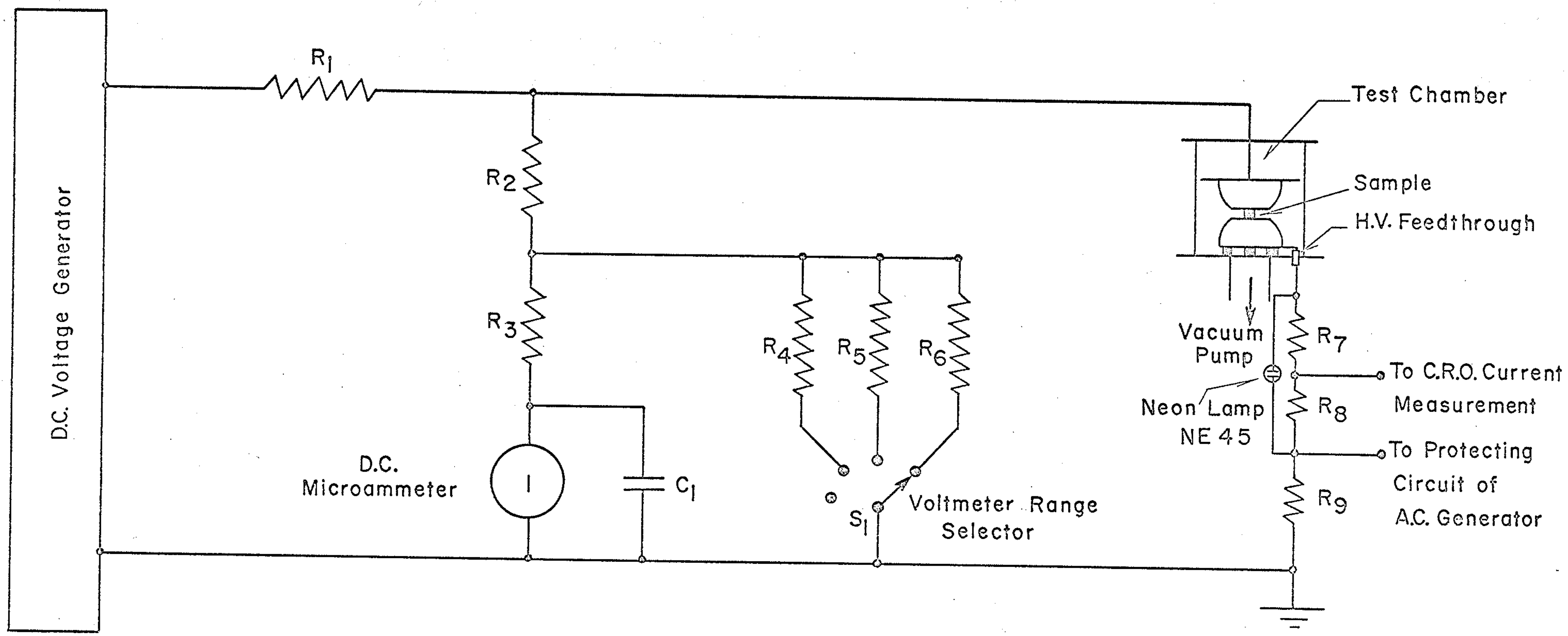
(3) The air admittance valve was opened and the rotary pump was switched off.

(4) After a cooling down period of 15 to 20 minutes, the fan motor was switched off.

This method of closing down the system ensured that the diffusion pump was left evacuated, thus preventing the pump fluid from absorbing air. When the system was subsequently started up, the chamber was evacuated via the roughing line to a pressure of about 0.5 torr before the backing valve was opened.

3.4 THE HIGH VOLTAGE D.C. SOURCE

The d.c. voltage test circuit used is shown in Figure 3.3. The voltage was derived from a Ferranti X-Ray D.C. Generator. The generator was rated for a



I.— D.C. Microammeter
Weston Model 1971-66
CH-A
F.S.= 50 μa D.C.
Rint. = 5 KΩ

$R_1 = 6\ M\Omega$
$R_2 = 600\ M\Omega$
$R_3 = 15\ K\Omega$
$R_4 = 20\ K\Omega$
$R_5 = 6.8\ K\Omega$

$R_6 = 2\ 7\ K\Omega$
$R_7 = 100\ \Omega$
$R_8 = 11\ \Omega$
$R_9 = 0.2\ \Omega$
$C_1 = 0.22$ M.F.D.

FIGURE 3.3 D.C. Test Circuit Diagram

maximum output of 1.1 Kw at a maximum voltage of 220 Kv, although during the present work the maximum voltage applied to the test chamber never exceeded 135 Kv. The voltage in the test chamber was controlled by adjusting the primary voltage of the insulating transformer of the generator by means of a variac located in the control console (not shown in Figure 3.3).

The voltage was measured with a resistance divider-microammeter arrangement. The microammeter (1) was in series with a 15 KΩ resistance (R_3) and was connected to a variable ratio 600 MΩ resistance divider. The divider ratios were varied by connecting any of the resistors (R_4, R_5, or R_6) in series with resistor R_2 through a multipole switch (S_1). Thus the meter could have ranges of 0-30 Kv, 0-60 Kv, 0-120 Kv, and 0-240 Kv. depending on the switch position. A 0.22 μf. capacitor (C_1) was connected in parallel with the microammeter to protect it against current surges during voltage transients.

A 6 MΩ limiting resistor (R_1) was connected in series with the generator output and the test chamber to limit the breakdown current. In this way fast deterioration of the test sample was avoided.

An attempt to measure the d.c. breakdown current was made by means of the circuit shown in Figure 3.3 and expanded in Figure 3.4. The circuit consisted of a cathode ray oscilloscope (Tektronix Type 585A) fed from

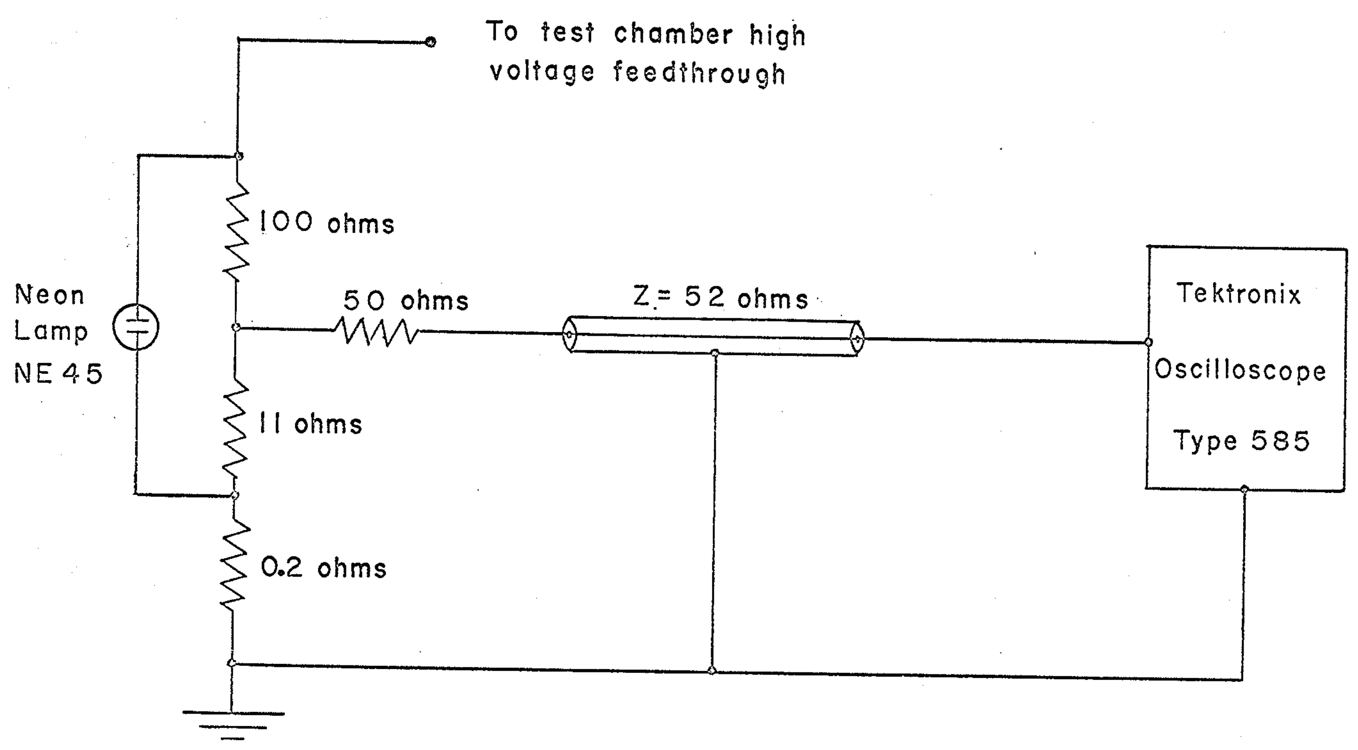


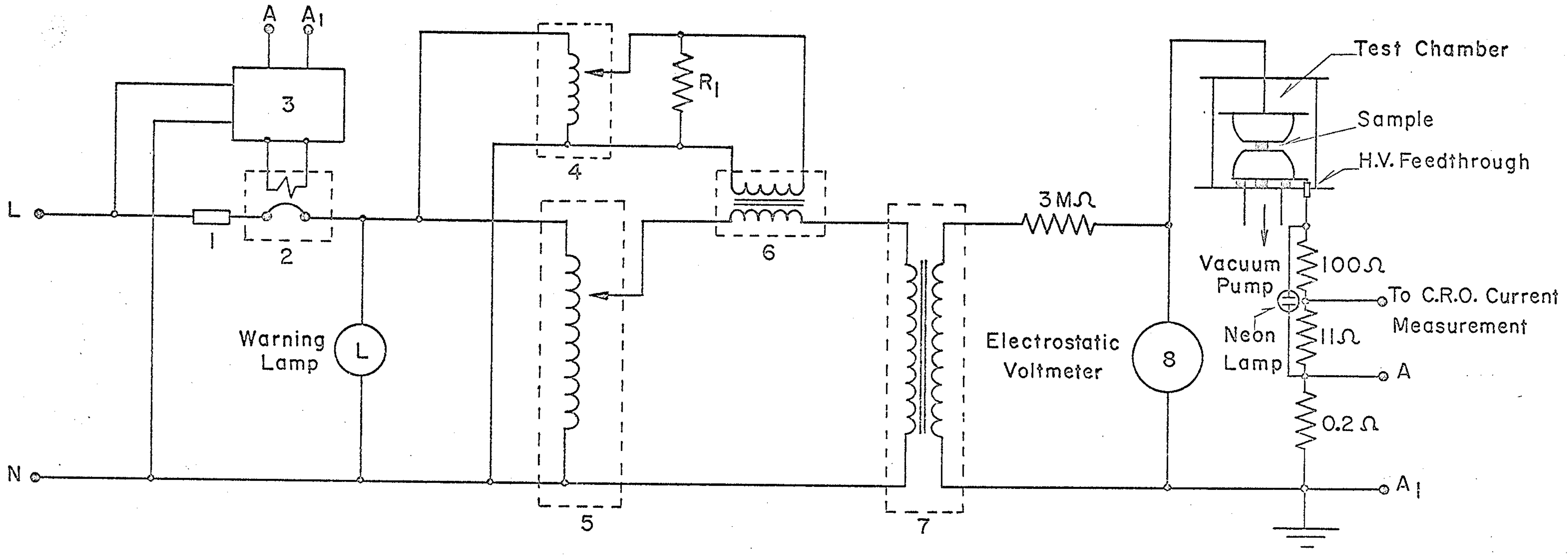
FIGURE 3.4 Current Measurement Circuit Diagram

a resistance divider connected in series with the test sample. A neon lamp NE45 was connected to protect the oscilloscope and a 50Ω resistor was used for matching the impedance of the cable connecting the divider to the oscilloscope. Unfortunately, the fastest sweep speed of the oscilloscope (0.05 μs/cm) was not fast enough to record the actual breakdown current. The speed of breakdown across insulators in a vacuum reported by Shannon _et al._[19,26] and Bugaev _et al._[3] was between 7 and 20 nanoseconds, depending on the insulator material.

3.5 THE HIGH VOLTAGE A.C. TEST CIRCUIT

The a.c. voltage test circuit used in this work is shown in Figure 3.5. The high voltage was obtained from a Victor High Voltage Transformer (7), rated for a maximum output voltage of 50 Kv. The voltage applied to the vacuum chamber was controlled by adjusting the primary input of the high voltage transformer. This was achieved by the combined action of a variable auto-transformer (5) to give rough control and a booster transformer (6) controlled by a variac (4) to give fine control. A non-linear thyrite resistor (R_1) was connected in parallel to the primary of the booster transformer for its protection.

A 3 MΩ limiting resistor was connected between the high voltage transformer output and the test chamber to limit the breakdown current. This avoided fast deterioration of the test sample.



1– Fuse 30 Amps

2–Circuit Breaker

3–Electronic Relay

4–General Radio Co. Variac

20 Amps 0–220V 50–60 Hz

5–Powerstat Variable Autotransformer

Type 11560 Input 120V Output 0–140V

Amp 45 50–60 Hz KVA max 6.3

6– RCA Transformer

Primary 0–115 V Secondary 65V 100 Amps

7– Victor Transformer Ratio 1/520

Maximum Secondary Output 50 KV

8– Singer Electrostatic Voltmeter

Model ESH Range 0–40 KV

R_1–Thyrite Resistor

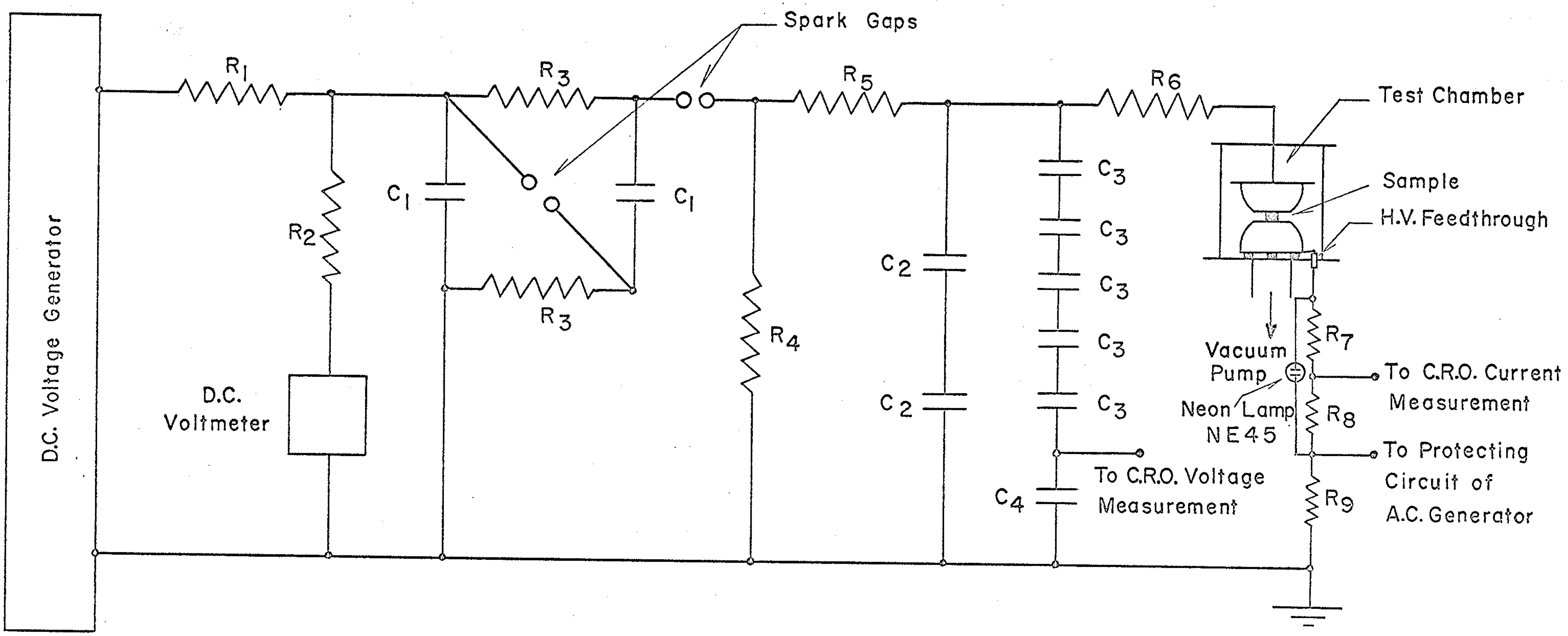
FIGURE 3.5 A.C. Test Circuit Diagram

The protection system of the a.c. equipment consisted of a 0.2Ω non-inductive resistor, which was connected in series with the test sample to provide a signal for an electronic relay (3). This in turn energized the trip coil of the circuit breaker which therefore removed the low voltage supply when a breakdown occurred. A 30 amp. fuse was placed in the low voltage supply to protect against overload, and a warning lamp was lit when the circuit breaker was switched on.

The a.c. voltage measurements were carried out by means of an electrostatic voltmeter (8). For measurements of a.c. breakdown current the circuit shown in Figure 3.5 and expanded in Figure 3.4 was used, but for the same reasons as described in the case of d.c. breakdown currents, no results were obtained.

3.6 THE SURGE VOLTAGE TEST CIRCUIT

The surge voltage test circuit used during the course of this project is shown in Figure 3.6. The surge voltage was obtained from a two-stage impulse generator with a maximum stage voltage of 100 Kv and a stage output capacitance of 0.25 μf. The capacitors were charged from a Ferranti X-Ray D.C. Generator (previously described) through a 6 MΩ resistor (R_1). Stress equalization across the capacitors was controlled by using two 3.58 KΩ non-inductive wire resistors (R_3). The stage charging voltage was recorded by means of a high voltage resistance divider (R_2) and series voltmeter



$R_1 = 6\,M\Omega$

$R_2 = 600\,M\Omega$

$R_3 = 3.58\,K\Omega$

$R_7 = 100\,\Omega$

$R_8 = 11\,\Omega$

$R_9 = 0.2\,\Omega$

$C_1 = 0.25$ M.F.D. 100 K.V.

$C_3 = 0.0005$ M.F.D. 50 K.V. D.C.

$C_4 = 0.1$ M.F.D. 4 K.V. D.C.

The Values of R_4, R_5, R_6, and C_2 Depend on the Wave Shape Wanted (See Table 3.1)

FIGURE 3.6 Surge Voltage Circuit Diagram connected across the first stage charging capacitor.

The magnitude of the surge voltage was controlled by manually adjusting the spark gaps of the impulse generator. The voltage wave shapes were varied by changing the circuit parameters as shown in Table 3.1.

Table 3.1

VALUES OF CIRCUIT PARAMETERS AND VOLTAGE WAVE SHAPE OBTAINED

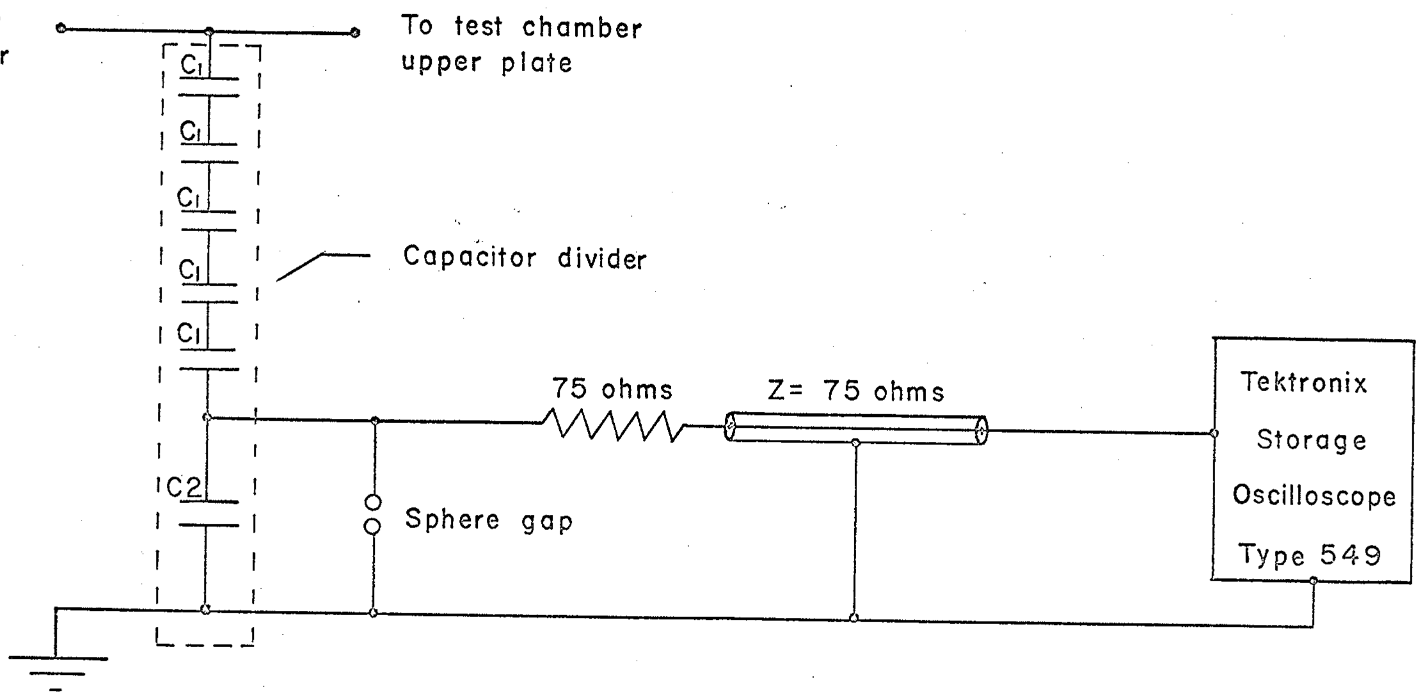
Voltage Wave Front μs	Voltage Wave Tail μs	R4 Tail Resistor KΩ	R5 Front Resistor KΩ	R6 Lim. Resistor KΩ	C2 Loading Cap. μf
1.2	50	0.52	1.9	0	0
40	120	0.52	5	10	0.01
70	350	4.06	5	10	0.01
100	700	85	5	10	0.01
150	1800	600	11	10	0.01
300	2000	600	50	10	0.01
500	2500	600	85	10	0.01

A 10 KΩ limiting resistor (R6) connected in series with the test sample limited the breakdown current and thus prevented fast deterioration of the sample. In testing standard wave impulses, this resistor was removed to avoid the wave shape distortion.

The surge voltages were measured by a capacitance divider and a cathode ray oscilloscope (Tektronix Storage Oscilloscope Type 549). The circuit is shown in Figures 3.6 and 3.7, and is described below.

The high voltage end of the divider had a capacitance of 0.0001 μf made up of a series connection of five capacitors (0.0005 μf and 50,000 v.d.c.). The lower arm consisted of one capacitor (0.1 μf and 4000 v.d.c.). The divider ratio was thus $\frac{1}{1001} \approx 0.001$

An additional sphere gap was connected across the lower arm of the capacitor divider, which protected the oscilloscope against over voltages. Also a 75Ω resistor was used to match the impedance of the cable connecting the divider to the oscilloscope. For measurements of pulse breakdown currents the circuit shown in Figure 3.4 was used, but, as in the cases of a.c. and d.c. breakdown currents the attempt failed for the reasons explained previously.



C_1 = 00005 M.F.D. 50000 V. D.C.

C_2 = 0.1 M.F.D. 4000 V. D.C.

FIGURE 3.7 Pulse Voltage Measuring Circuit Diagram

CHAPTER IV

MEASUREMENT AND PROCEDURES

4.1 PREPARATION OF THE SAMPLES

The specimens tested in this work were samples of Teflon and polyethylene of cylindrical shape with 25 mm diameter and 5, 10, 15, 20, and 25 mm lengths. The specimens were ground and polished with emery paper, the finest of which was 2/0. The ends of the cylinders were plated with a thin silver coating to secure a good electrical contact at the electrode-insulator junctions. Finally, the samples were washed in trichloro-ethylene and dried with a clean cloth before they were placed between the electrodes.

The Rogowski's profile electrodes used during the present investigations were polished with jeweler's rouge, wiped with a soft cloth saturated in trichloroethylene, and dried with a clean cloth before the insulation sample was placed between them. The contact pressure at the specimen-electrode junction was maintained constant in all tests by allowing the upper electrode to rest on top of the specimen which gave a contact surface pressure of about 2 Kg/cm^2. To reduce the effects of time and pressure of degassing on breakdown, the samples were kept inside the vacuum chamber for 24 hours at the testing pressure of 10^{-6}torr before surge voltages were applied.

4.2 CONDITIONING TECHNIQUES

Most investigators have stated that their measured breakdowns were strongly dependent upon preconditioning of the samples, but no standard conditioning technique has yet been suggested. During the present work, three different techniques were investigated (d.c., a.c., and pulse).

The consistency of the results (presented later) and the time saving following a.c. conditioning showed that its use in conditioning is most efficient, and for this reason the majority of measurements were made following a.c. conditioning.

4.2.1 CONDITIONING USING D.C. VOLTAGE

The d.c. voltage applied to a new unconditioned sample was increased at a rate of 2 Kv/min until seventy per cent of the anticipated breakdown value was reached. At this value the voltage was maintained constant for one hour before the sample was tested to breakdown. After the first and subsequent breakdowns the sample was conditioned at the same voltage as before but the time of conditioning was reduced to 30 minutes. Preliminary measurements showed that when the rate of rise of the applied voltage was increased or the conditioning time was reduced, the results were appreciably scattered.

4.2.2. CONDITIONING USING A.C. VOLTAGE

The a.c. voltage applied to a new unconditioned sample was again increased at a rate of 2 Kv/min up to about seventy per cent of the a.c. breakdown voltage. The voltage was maintained constant at this value for 30 minutes before the sample was tested to breakdown. After the first and subsequent breakdowns the sample was conditioned at the same voltage as before but the time of conditioning was reduced to 15 minutes. As above, any attempt to increase the rate of rise of the applied voltage or to reduce the conditioning time have led to scattered results.

4.2.3 CONDITIONING USING PULSED VOLTAGE

For comparison purposes a 5 mm thick sample of polyethylene was tested using standard wave pulse conditioning. In this case, the unconditioned sample was repeatedly pulsed at intervals of one minute with a standard impulse wave whose amplitude was fifty per cent of the standard wave breakdown value. One hour later the voltage was increased until breakdown took place. After the first and subsequent breakdowns, the sample was conditioned at the same voltage as before, but the time of conditioning was reduced to 30 minutes.

4.3 VOLTAGE APPLICATIONS AND MEASUREMENTS

4.3.1 D.C. VOLTAGE APPLICATIONS AND MEASUREMENTS

When direct voltages were used, the samples were conditioned before the first reading and after each breakdown. The d.c. voltage was raised at 2-3 Kv/sec. until breakdown took place. The voltages were measured by means of a high voltage resistance divider and series voltmeter. The measuring circuit is shown in Figure 3.3 and was described in § 3.4. The accuracy of the measurements depended upon the accuracy with which the deflections of the voltmeter could be read.

The voltage measurements were made at different ratios of the high voltage resistance divider and in each case the resistance ratio was adjusted to give approximately half scale deflection. Every care was taken to read the deflection precisely; however, it was not possible to read it to an accuracy better than 1 Kv, thus giving an error of about ± 2%. The resistance divider-voltmeter set was calibrated against a sphere gap, a method which itself has an eror of ± 3%. The overall accuracy of the d.c. voltage measurements can, therefore, be taken as ± 5%, but the relative readings were considerably more accurate.

4.3.2 A.C. VOLTAGE APPLICATIONS AND MEASUREMENTS

Under alternating test voltages, the samples were conditioned before the first reading and after each breakdown. After conditioning, a.c. voltage was raised at 2-3 Kv/sec until breakdown occurred. The voltages were measured with an electrostatic voltmeter connected as shown in Figure 3.5. Again the voltages were measured with different voltmeter ranges to give approximately half scale deflection. Every care was taken to read the deflection precisely, but it was not possible to read it with an accuracy better than 0.5 Kv, thus given an error of about ± 2%. As in the d.c. case, the voltmeter was calibrated against a sphere gap, which has an inherent error of ± 3%, thus reducing the overall absolute accuracy of the a.c. voltage measurements to ± 5%.

4.3.3 SURGE VOLTAGE APPLICATIONS AND MEASUREMENTS

Under surge test voltages the samples were conditioned before the first reading was taken and after each breakdown. The surge voltage was increased in steps of 5% of the breakdown voltage and 10 surges were applied for each voltage level at intervals of one minute until breakdown occurred.

The surge voltages were measured with a capacitance divider and a cathode ray oscilloscope. The measuring circuit is shown in Figure 3.7 and was described in § 3.6. The voltage oscillograms were taken at different V/cm ranges of the C.R.O. to give a deflection of the beam of about 30 mm. It was possible to read the deflection to within about one millimeter, thus giving an error of about 3%. The capacitance divider - C.R.O. Set was again calibrated against a sphere gap, reducing the overall absolute accuracy of the impulse measurements to within ± 7%.

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CHAPTER V

EXPERIMENTAL RESULTS AND ANALYSIS

Studies of surface breakdown in a vacuum of 10^{-6}torr under direct, alternating, and surge voltages were made using various sample lengths of Teflon and polyethylene. The results obtained are presented in this chapter.

5.1 SURFACE BREAKDOWNS OF TEFLON SAMPLES USING D.C. CONDITIONING

In the following sections, the results obtained on d.c.-conditioned Teflon samples are discussed. Factors considered are: fluctuation of the d.c. breakdown voltage with successive breakdowns; the effect of surge front duration on the breakdown voltage; and the d.c., a.c., and standard impulse breakdown characteristics.

5.1.1 FLUCTUATION OF THE D.C. BREAKDOWN VOLTAGE WITH SUCCESSIVE BREAKDOWNS

The effect of successive breakdowns on the d.c. breakdown voltage was studied by applying d.c. voltage and using d.c. conditioning (as described in § 4.3.1 and § 4.2.1) on a 5 mm long Teflon sample. The results obtained in three series of tests are presented in Table 5.1, and the same values are plotted against the number of breakdowns in Figure 5.1. The first series

TABLE 5.1

SEQUENTIAL VARIATION IN D.C. BREAKDOWN OF A 5 mm TEFLON SAMPLE (PRESSURE 10^{-6}torr, AND D.C. CONDITIONING)

BREAKDOWN No.	D.C. VOLTAGE Kv
1	38
2	39
3	41
4	36
5	37
6	38
7	36
8	36
9	36
10	36
20 hour rest in vacuum	
11	40
12	37
13	38
14	38
15	38
16	38
20 hour rest in vacuum	
17	39
18	37
19	36
20	36
21	36
22	10

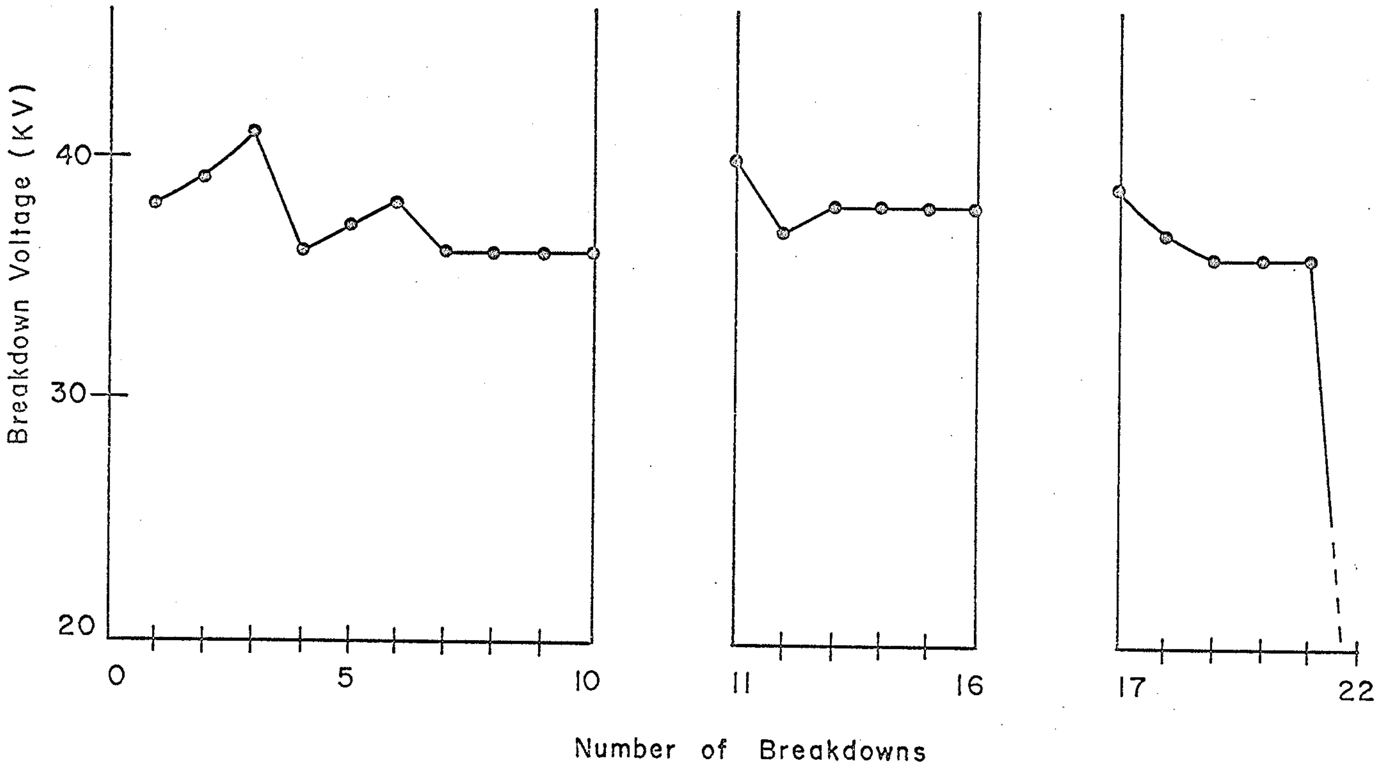

FIGURE 5.1 Effect of Successive Breakdowns on the D.C. Breakdown Voltage of a 5 mm Teflon Sample (Pressure 10^{-6} torr, and D.C. Conditioning)

of tests showed little increase in the breakdown value with the first three breakdowns; thereafter, the breakdown value decreased to a relatively steady value slightly lower than the first breakdown. After this series of tests the sample was maintained in a vacuum of 10^{-6}torr for twenty hours before the second series of tests was carried out.

In the second series of tests, the first breakdown was the highest value in this series and was higher than the last breakdown of the previous series. The steady value was reached more quickly than in the previous series; and was also a little higher than that for series I. A third series of tests was carried out after the sample was left for another twenty hours in vacuum. Again the first breakdown was the highest in this series and higher than the last breakdown of the previous series. As in series II a steady breakdown value was rapidly reached. This steady value was of the same magnitude as that obtained in series I. Finally, a sudden deterioration occurred.

The results presented above, and similar results obtained for samples of different lengths under d.c. voltage, indicate the following facts associated with the d.c. conditioning of Teflon: Firstly, there was a little or no increase in the d.c. breakdown voltage with the first few breakdowns of the sample, after which the breakdown value decreased to a relatively steady value until a sudden deterioration occurred. Secondly, visual observations indicated that all the breakdowns followed the same path on the insulator surface, and finally that when the voltage was removed temporarily, the initial breakdown voltage on resumption of testing was appreciably higher than at the end of the previous tests.

These facts suggest that space charges partially trapped in some way at the surface may have been responsible for the lower breakdowns previous to the rest period and following the first breakdown after the rest period. This may also have been responsible for establishing a low breakdown path on the insulator surface which in turn accelerated the deterioration of the sample.

5.1.2 EFFECT OF SURGE FRONT DURATION ON THE BREAKDOWN VOLTAGE

The effect of the wave shapes of the applied voltage on the surface breakdown strength of Teflon samples was studied using surges of various front durations (1.2, 40, 70, 100, 150, 300, and 500 μsec) and following d.c. conditioning (as described in § 4.3.3 and § 4.2.1) on Teflon samples of 5, 15 and 20 mm lengths. The d.c. and a.c. breakdown voltages were also recorded to the same samples. Tables 5.2, 5.3, and 5.4 list the results obtained for sample lengths of 5, 10, and 20 mm respectively. There was no appreciable effect of the wave shape of the applied voltage on the breakdown values for wave front

TABLE 5.2

SURFACE BREAKDOWN OF 5 mm TEFLON SAMPLES UNDER DIRECT, ALTERNATING, AND SURGE VOLTAGES (PRESSURE 10^{-6} torr, AND D.C. CONDITIONING)

Sample No	D.C. Kv	1.2/50 Kv(Peak)	40/120 Kv(Peak)	70/350 Kv(Peak)	100/700 Kv(Peak)	150/1800 Kv(Peak)	300/2000 Kv(Peak)	500/2500 Kv(Peak)	A.C. Kv(Peak)
1	40	39	37	--	--	--	--	--	--
	43	++	--	--	--	--	--	--	--
2	47	49	33	38	--	--	--	--	--
	45	++	++	--	--	--	--	--	--
3	46	40	29	33	35	--	--	--	--
	46	++	++	++	--	--	--	--	--
4	49	++	++	++	++	28	--	--	--
	47	++	++	++	++	--	--	--	--
5	46	39	--	--	--	--	--	--	--
	52	--	--	--	--	--	--	--	--
6	50	++	28	--	--	--	--	--	--
	++	++	--	--	--	--	--	--	--
7	51	++	++	37	++	40	42	27	--
	++	++	++	++	++	40	++	--	--
8	++	++	++	35	42	40	--	--	--
	++	++	++	++	36	38	--	--	--
9	++	++	++	++	38	36	34	28	23
	++	++	++	++	36	++	++	30	--
10	38	34	30	30	30	31	33	30	25
	38	34	31	31	29	31	32	29	25
Overall Average	47	40	32	35	35	35	36	29	24
Extreme Values	38-52	34-49	28-37	30-38	29-42	28-40	32-42	27-30	23-25

++ The sample was not tested under this particular wave shape to allow testing it under the other wave shapes (The tests were carried out from left to right in the Table).

-- The sample was not tested because it was already deteriorated (The sample did not withstand 70% of the D.C. Breakdown Voltage.

TABLE 5.3

SURFACE BREAKDOWN OF 15 mm TEFLON SAMPLES UNDER DIRECT, ALTERNATING, AND SURGE VOLTAGES (PRESSURE 10^{-6} torr, AND D.C. CONDITIONING)

Sample No	D.C. Kv	1.2/50 Kv(Peak)	40/120 Kv(Peak)	70/350 Kv(Peak)	100/700 Kv(Peak)	150/1800 Kv(Peak)	300/2000 Kv(Peak)	500/2500 Kv(Peak)	A.C. Kv(Peak)
1	76	++	++	++	++	48	48	48	30
	78	++	++	++	++	54	54	48	31
	76	++	++	++	++	57	57	45	33
	++	++	++	++	++	70	58	58	32
	++	++	++	++	++	68	56	58	33
2	75	70	++	63	74	++	73	++	34
	75	62	++	60	64	++	65	++	35
	75	68	++	70	70	++	74	++	34
	++	60	++	68	60	++	63	++	34
	++	65	++	65	60	++	68	++	34
3	85	75	60	++	62	++	++	++	34
	82	70	68	++	63	++	++	++	34
	82	67	70	++	68	++	++	++	35
	++	70	70	++	70	++	++	++	34
	++	65	65	++	65	++	++	++	35
4	80	++	++	++	++	50	48	52	30
	75	++	++	++	++	61	52	52	33
	78	++	++	++	++	68	54	52	33
	++	++	++	++	++	62	54	56	35
	++	++	++	++	++	60	63	60	35
						80	88	83	
						76	85	78	
						79	88	78	
Overall Average	78	67	63	65	66	60	60	53	33
Extreme Values	75-85	60-75	60-70	60-70	60-74	50-70	48-74	45-58	30-35

TABLE 5.4

SURFACE BREAKDOWN OF 20 mm TEFLON SAMPLES UNDER DIRECT, ALTERNATING, AND SURGE VOLTAGES (PRESSURE 10^{-6}torr, AND D.C. CONDITIONING)

Sample No	D.C. Kv	1.2/50 Kv(Peak)	40/120 Kv(Peak)	70/350 Kv(Peak)	100/700 Kv(Peak)	150/1800 Kv(Peak)	300/2000 Kv(Peak)	500/2500 Kv(Peak)	A.C. Kv(Peak)
1	95 92	70 ++	60 67	58 58	57 63	67 67	57 61	64 66	35 35
2	95 93	++ ++	++ ++	++ ++	++ ++	62 ++	64 64	68 69	-- --
3	98 ++	70 65	66 75	64 68	62 64	70 78	73 75	70 71	34 35
4	92 ++	75 ++	72 68	72 ++	77 ++	79 62	74 74	81 81	34 35
5	++ ++	++ ++	72 ++	80 70	70 84	++ ++	83 ++	71 ++	35 --
Overall Average	94	71	69	68	69	69	71	71	35
Extreme Values	92-98	65-75	60-75	58-80	57-84	62-79	57-83	64-81	34-35

durations from 1.2 μsec to 300 μsec, but a fast surface deterioration took place independently of the wave shape used. Further, interesting effect of the a.c. breakdowns on the subsequent behavior of the sample was found. This effect is recorded in Table 5.3 (sample 4). This sample was tested with 150/1800 μsec, 300/2000 μsec, and 500/2500 μsec switching surges following the procedure described above. The first five entries in each of these columns record the breakdown values measured. Subsequently tests were carried out under a.c. voltages, after which the sample was tested again with 150/1800 μsec, 300/2000 μsec, and 500/2500 μsec switching surges. The last three entries in each of these columns list the values measured. Comparison of breakdown voltages measured before and after subjecting the sample to a.c. breakdowns shows that the surge breakdown values increased to about 30% above the former breakdown values obtained under surge voltages.

5.1.3 COMPARISON OF THE D.C., THE A.C. AND THE STANDARD IMPULSE BREAKDOWN CHARACTERISTICS

To compare the d.c., a.c., and standard impulse breakdown characteristics of Teflon samples following d.c. conditioning, the average breakdown values obtained from Tables 5.2, 5.3, and 5.4 were plotted against the sample lengths in Figure 5.2. It can be seen that the d.c. breakdown voltages are the highest values obtained for each sample length, followed by the standard wave breakdown voltages, with the a.c. voltage giving the lowest breakdown

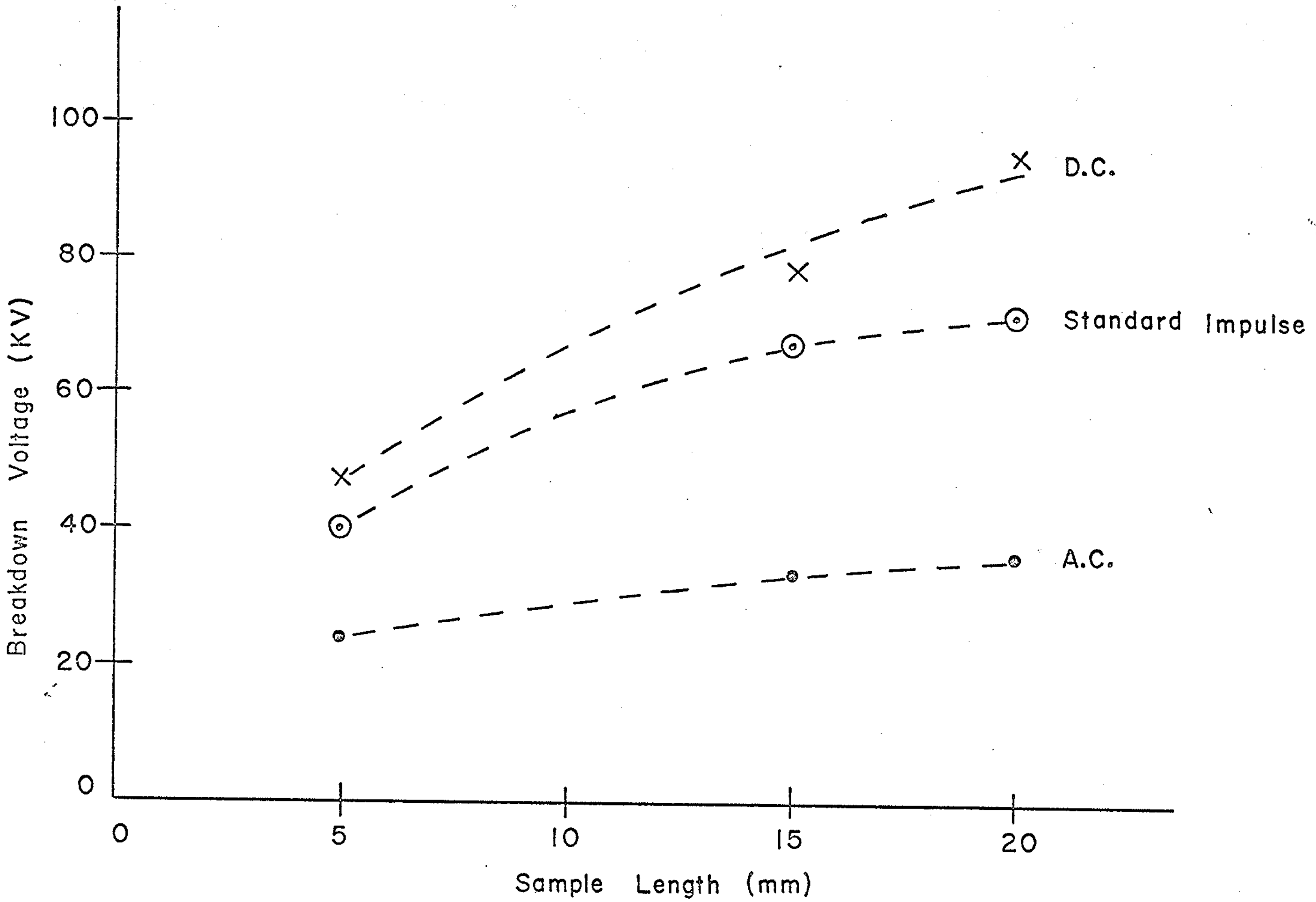

FIGURE 5.2 Comparison of D.C., A.C., and Standard Impulse Breakdown Characteristics For Teflon Samples (Pressure 10^{-6} torr, and D.C. Conditioning)

values. It is also apparent that the breakdown voltage-insulator length relationship is not linear but that as the length increases, the rate of rise of breakdown voltage decreases.

5.2 SURFACE BREAKDOWN OF TEFLON SAMPLES USING A.C. CONDITIONING

In the following sections, the results obtained on a.c.-conditioned Teflon samples are discussed. Factors considered are: the effect of surge front duration on the breakdown voltage; and the d.c., a.c., and standard impulse breakdown characteristics.

5.2.1 EFFECT OF SURGE FRONT DURATION ON THE BREAKDOWN VOLTAGE OF TEFLON SAMPLES

A study was made by applying surge voltages of various front durations (1.2, 40, 70, 100, 150, 300, and 500 μsec.) using a.c. conditioning (as described in § 4.3.3 and § 4.2.2) on Teflon samples of 5 and 15 mm. lengths. Tables 5.5 and 5.7 show typical values obtained for 5 and 15 mm. respectively. From these tables, it is clear that under all types of voltages used, independent of their front durations, the first three or four breakdown values were low and scattered but the subsequent breakdown values were higher and more consistent. This indicates a conditioning effect not observed when d.c. conditioning was used. It also can be seen that the sample did not deteriorate as quickly as under d.c. conditioning.

TABLE 5.5

SURFACE BREAKDOWN OF A 5 mm TEFLON SAMPLE UNDER DIRECT, ALTERNATING, AND SURGE VOLTAGES (Pressure 10^{-6} torr, and A.C. Conditioning)

D.C. Kv	1.2/50 Kv(Peak)	40/120 Kv(Peak)	70/350 Kv(Peak)	A.C. Kv(Peak)
42	42	52	48	28
45	47	58	52	29
47	50	58	46	29
45	50	56	50	30
45	52	60	52	30
47	58	54	52	30
45	58	60	55	30
	58	54	55	
	58	60	52	
	58	56	55	
	58	56	52	
	58	56	52	
	58	56	58	
	58	56	55	

TABLE 5.6

RELATION BETWEEN THE AVERAGE BREAKDOWN VALUE AND THE WAVE SHAPE OF THE APPLIED VOLTAGE FOR 5 mm TEFLON SAMPLES (PRESSURE 10^{-6}torr, AND A.C. CONDITIONING)

Sample No	Average Range	D.C. Kv	1.2/50 Kv(Peak)	40/120 Kv(Peak)	70/350 Kv(Peak)	100/700 Kv(Peak)	150/1800 Kv(Peak)	300/2000 Kv(Peak)	500/2500 Kv(Peak)	A.C. Kv(Peak)
1	Average	46	57.4	56.8	53.8	+ +	+ +	+ +	+ +	29.4
	Range	42-47	42-58	52-60	48-58	+ +	+ +	+ +	+ +	28-30
2	Average	46	56.2	+ +	+ +	+ +	+ +	48	46	29.2
	Range	38-47	40-58	+ +	+ +	+ +	+ +	40-50	38-47	28-30
3	Average	45	58.1	+ +	+ +	50.3	48.2	+ +	+ +	30.5
	Range	40-46	43-60	+ +	+ +	48-54	43-52	+ +	+ +	29-31
4	Average	50	58.2	+ +	+ +	+ +	49.1	+ +	+ +	30.3
	Range	46-52	45-60	+ +	+ +	+ +	45-54	+ +	+ +	29-31
Overall Average		47	58	57	54	50	49	48	46	30
Extreme Values		38-52	40-60	52-60	48-58	48-54	43-54	40-50	38-47	28-31

TABLE 5.7

SURFACE BREAKDOWN OF A 15 mm TEFLON SAMPLE UNDER DIRECT, ALTERNATING, AND SURGE VOLTAGES (PRESSURE 10^{-6}torr, AND A.C. CONDITIONING)

D.C. Kv	1.2/50 Kv(Peak)	40/120 Kv(Peak)	70/350 Kv(Peak)	100/700 Kv(Peak)	150/1800 Kv(Peak)	300/2000 Kv(Peak)	500/2500 Kv(Peak)	A.C. Kv(Peak)
75	78	78	80	67	60	76	58	45
88	100	84	92	90	88	84	66	49
88	90	96	90	80	92	75	70	49
90	115	96	90	80	76	75	68	51
90	110	92	96	88	88	80	84	51
85	110	96	96	94	94	89	80	51
85	110	92	94	90	102	80	80	52
	96	96	96	96	80	88	84	
	100	88	100	90	92	84	80	
	115	95	94	94	90	84	80	
	110	100	96	86	92	88	84	
	108	100	96	94	90	80	80	
	115	104	96	88	92	84	80	
	108	104	96	94	92	86	80	

TABLE 5.8

RELATION BETWEEN THE AVERAGE BREAKDOWN VALUE AND THE WAVE SHAPE OF THE APPLIED VOLTAGE FOR 15 mm TEFLON SAMPLES (PRESSURE 10^{-6}torr, AND A.C. CONDITIONING)

Sample No	Average Range	D. C. Kv	1.2/50 Kv(Peak)	40/120 Kv(Peak)	70/350 Kv(Peak)	100/700 Kv(Peak)	150/1800 Kv(Peak)	300/2000 Kv(Peak)	500/2500 Kv(Peak)	A.C. Kv(Peak)
1	Average	88	108.2	96.7	96	91.4	91.2	84.3	81.2	51
	Range	75-90	78-115	78-104	80-100	67-96	60-102	76-89	58-84	45-52
2	Average	85	105.3	94.5	93.2	92	90.3	88.6	84.1	50
	Range	78-90	80-110	82-102	78-102	82-97	76-100	80-93	70-90	46-51
3	Average	85	106.2	100.3	+ +	+ +	+ +	+ +	80.3	51
	Range	75-88	85-115	85-110	+ +	+ +	+ +	+ +	65-82	47-52
4	Average	90	110.4	+ +	+ +	+ +	+ +	+ +	85.4	51
	Range	85-95	80-117	+ +	+ +	+ +	+ +	+ +	73-90	45-52
Overall Average		87	108	97	95	92	91	86	83	51
Extreme Values		75-95	78-117	78-110	78-102	67-97	60-102	76-93	58-90	45-52

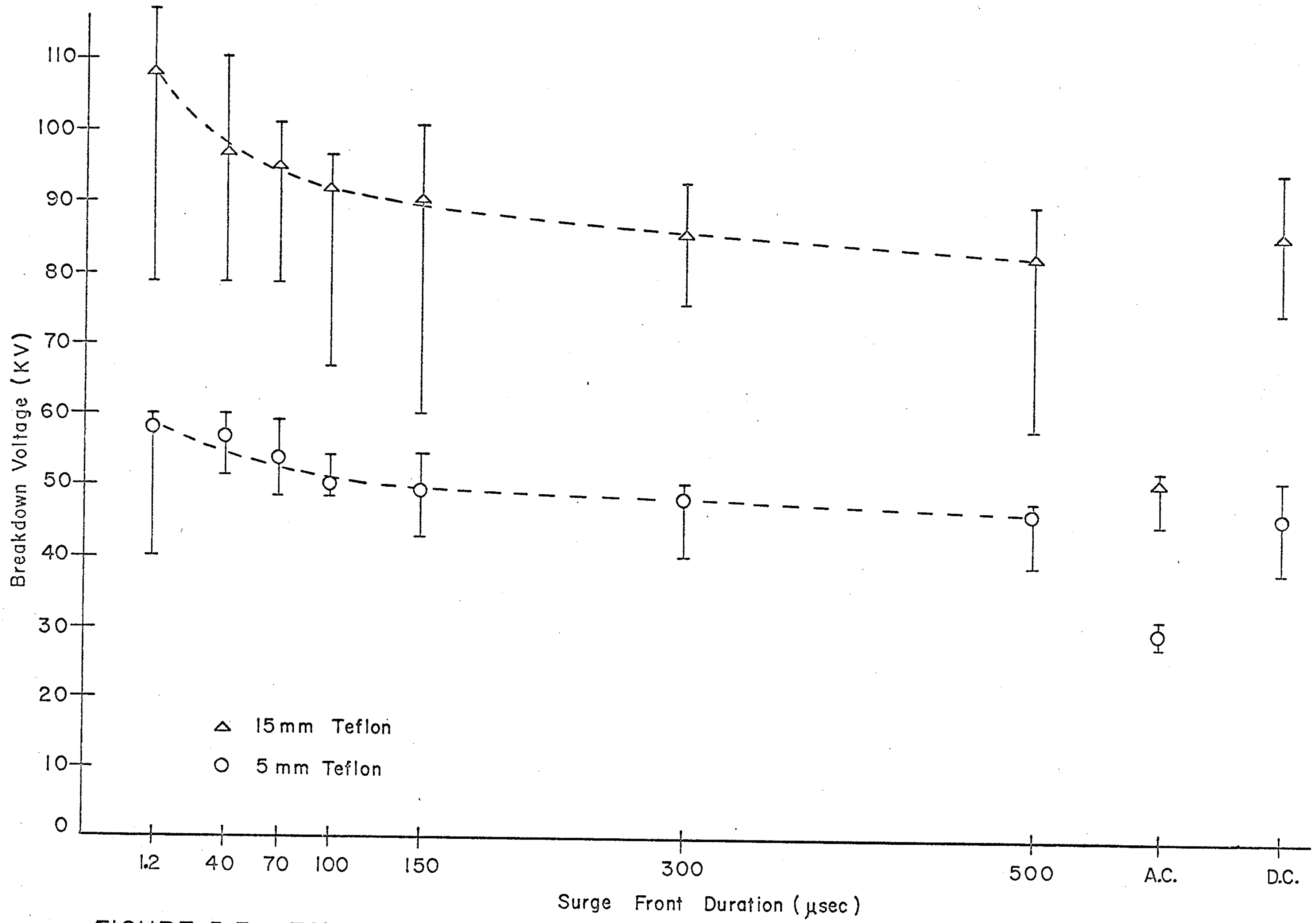

FIGURE 5.3 Effect of the Surge Front Durations on the Breakdown Voltage For Teflon Samples (Pressure 10^{-6} torr, and A.C. Conditioning)

Tables 5.6 and 5.8 include mean values and the range of scatter of surface breakdown values obtained for 5 and 15 mm Teflon samples respectively. The ranges of the surge voltages, in each column (Tables 5.6 and 5.8), represent the extreme values in a set of fourteen readings; while, the mean values are those of the last ten readings. In the cases of d.c. and a.c. voltages the ranges represent extreme values obtained in a set of seven readings and mean values are those of the last five readings. Under these conditions, results obtained were more consistent and there appeared no need for further testing. The overall averages and extreme breakdown values obtained on all samples are also included in both tables and are plotted in Figure 5.3. From these results it is seen that under surge voltages, the average breakdown values for each insulator length decreased slowly as the wave front duration was increased. The highest breakdown values were always observed under the standard impulse voltages which remained about 20% above the 500/2500 μsec breakdown values (the longest front duration used). The lowest breakdown values were always observed under a.c. power frequency voltages.

5.2.2 COMPARISON OF THE D.C., THE A.C. AND THE STANDARD IMPULSE BREAKDOWN CHARACTERISTIC OF TEFLON SAMPLES

To compare the d.c., a.c., and standard impulse breakdown characteristics of Teflon samples following a.c. conditioning, two additional Teflon samples of 10 and 20 mm

TABLE 5.9

SURFACE BREAKDOWN OF 10 mm AND 20 mm TEFLON SAMPLES UNDER DIRECT, ALTERNATING, AND 1.2/50 μsec. SURGE VOLTAGES (PRESSURE 10^{-6}torr, AND A.C. CONDITIONING)

a

10 mm Sample		
D.C. Kv	1.2/50 Kv(Peak)	A.C. Kv(Peak)
65	64	40
70	52	41
72	72	41
72	72	41
70	84	41
	84	
	80	
	80	
	84	
	84	
	84	

b

20 mm Sample		
D.C. Kv	1.2/50 Kv(Peak)	A.C. Kv(Peak)
104	127	?
100	106	
95	100	
	125	
	125	
	130	
	125	
	125	
	- -	
	- -	

- - Sample deteriorated.

? Supply Voltage Limitation Preventing Obtaining the A.C. Breakdown Voltage.

TABLE 5.10

RELATION BETWEEN THE AVERAGE BREAKDOWN VALUES (D.C., A.C., 1.2/50 μsec.) AND THE LENGTH OF TEFLON SAMPLES (PRESSURE 10^{-6} torr, AND A.C. CONDITIONING)

Sample Length mm	D.C. Kv	1.2/50 μsec. Kv(Peak)	A.C. Kv(Peak)
5	47	58	30
10	71	83	41
15	87	108	51
20	100	126	?

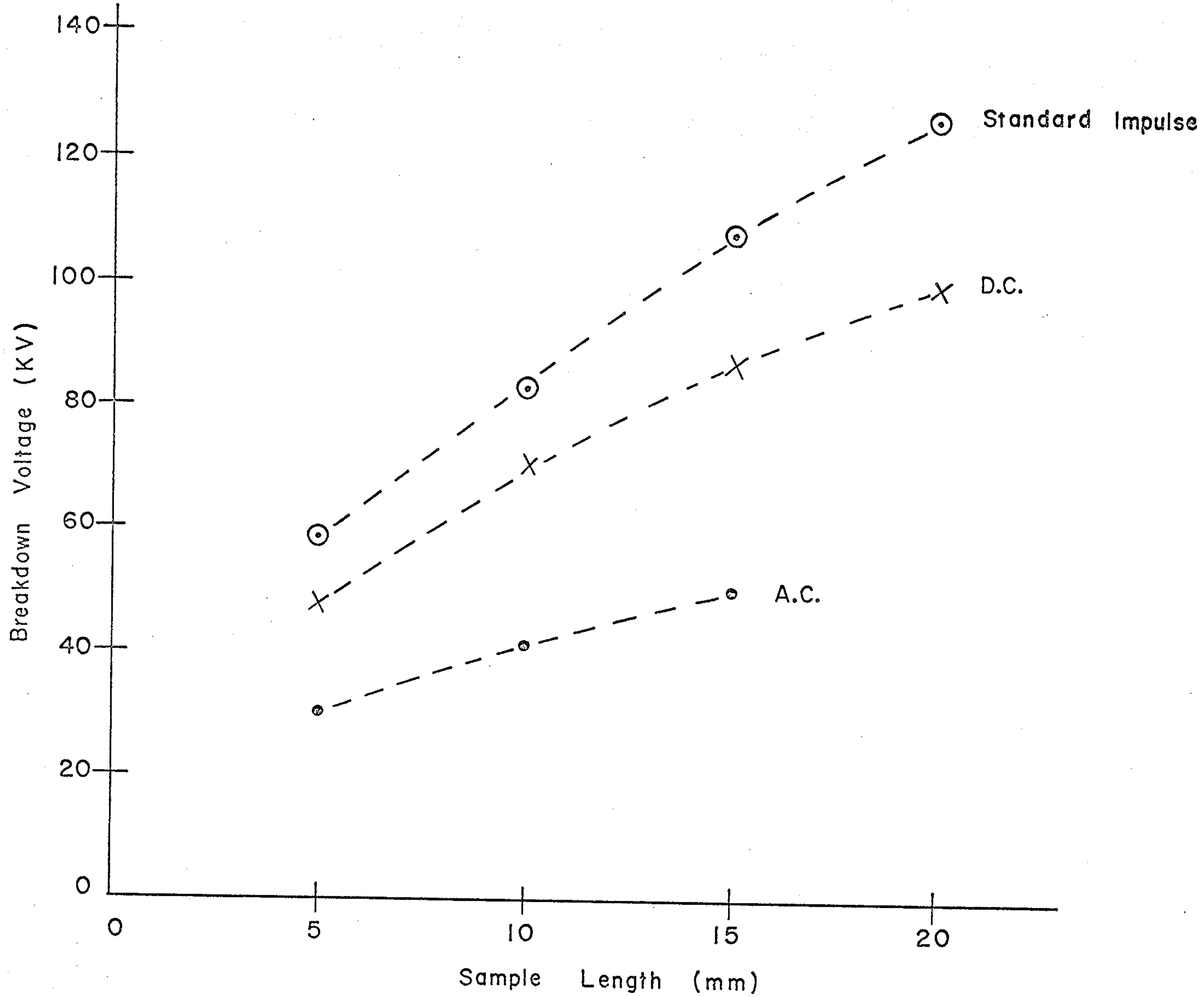

FIGURE 5.4 Comparison of D.C., A.C., and Standard Impulse Breakdown Characteristics For Teflon Samples (Pressure 10^{-6} torr, and A.C. Conditioning)

length were tested. The results obtained are presented in Tables 5.9a and 5.9b. The voltage supply limitations prevented the determination of the a.c. breakdown voltage for 20 mm long samples of Teflon. Average breakdown values of these samples, together with previous average values obtained for 5 and 15 mm samples are recorded in Table 5.10 and are plotted in Figure 5.4.

From these results it is clear that the standard impulse breakdown values were the highest for each sample length tested. These values remained about 20% higher than the corresponding d.c. breakdown values and about 50% above the a.c. breakdown values, which were the lowest values observed. It is also apparent that the breakdown voltage-insulator length relationship is not linear but that as the length increases, the rate of rise of breakdown voltage decreases.

5.3 SURFACE BREAKDOWNS OF POLYETHYLENE SAMPLES

In the following sections, the results obtained on polyethylene samples are discussed. Factors considered are: fluctuation of the d.c. breakdown voltage with successive breakdowns; the effect of conditioning on the standard impulse breakdown voltage; the effect of surge front duration on the breakdown voltage; the effect of plating sample ends on breakdown voltage; and the d.c., a.c., and standard impulse breakdown characteristics.

5.3.1 FLUCTUATION OF THE D.C. BREAKDOWN VOLTAGE WITH SUCCESSIVE BREAKDOWNS

The effect of successive breakdowns on the d.c. breakdown voltage was studied under d.c. voltages, using d.c. and a.c. conditioning, on a 5 mm long polyethylene sample. Breakdown values observed with d.c. conditioning are reported in Table 5.11a and Table 5.11b, and are plotted against the number of breakdowns in Figure 5.5. The results show that, as the test progressed, the breakdown voltage increased gradually but with a diminishing rate of rise. This phenomenon is best illustrated in the second series (numbers 11 to 20), which also shows the large fluctuation in breakdown voltages. It can further be seen that the breakdown voltages increased more rapidly in the second series (numbers 11 to 20) than in the first (numbers 1 to 10), indicating that a faster conditioning took place in the second series of measurements. Between the first and second series no voltage was applied and the sample was maintained in a vacuum of 1 x 10^{-6}torr for twenty hours. When tests were resumed, breakdown voltages were much lower than at the end of the first series, but higher than the first breakdown of the first series. These facts indicate that part of the conditioning gained during the first series of tests was lost during the rest period in vacuum. Similar results were observed earlier by Gleichauf[7] for glass and quartz insulators.

TABLE 5.11

SEQUENTIAL VARIATION IN D.C. BREAKDOWN OF A 5 mm POLYETHYLENE SAMPLE USING D.C., AND A.C. CONDITIONING (PRESSURE 10^{-6}torr)

a		b		c	
Using D.C. Conditioning		After 20 hour rest in Vacuum		Using A.C. Conditioning	
Breakdown No.	D.C. Voltage Kv	Breakdown No.	D.C. Voltage Kv	Breakdown No.	D.C. Voltage Kv
1	28	11	32	21	44
2	32	12	35	22	43
3	30	13	32	23	44
4	33	14	38	24	43
5	33	15	39	25	44
6	32	16	38	26	44
7	34	17	40	27	43
8	36	18	42	28	44
9	38	19	40	29	44
10	40	20	43	30	44

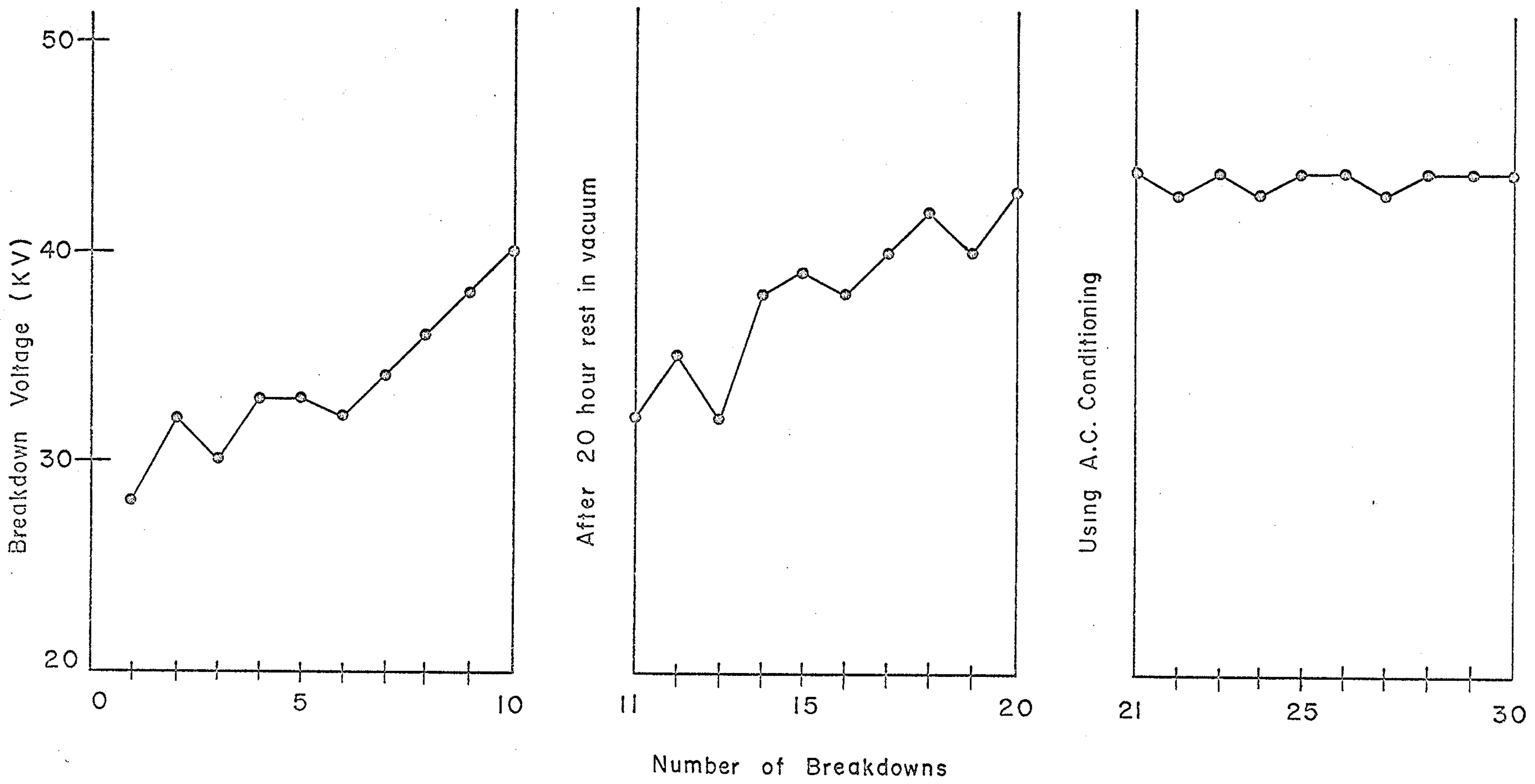

FIGURE 5.5 Effect of Successive Breakdowns on the D.C. Breakdown Voltage of a 5mm Polyethylene Sample (Pressure 10^{-6}torr, D.C., and A.C. Conditioning)

A third series of tests was carried out immediately after the second series but using a.c. conditioning instead of d.c. conditioning. The results obtained are presented in Table 5.11c and are also plotted in Figure 5.5 for comparison purposes. It can be seen that the extent of conditioning reached in the previous series was maintained, and further tests showed little variation in breakdown voltages.

5.3.2 EFFECT OF CONDITIONING ON THE STANDARD IMPULSE BREAKDOWN VOLTAGE

To study the effect of conditioning on the standard impulse breakdown voltage, four 5 mm long polyethylene samples were tested in a vacuum of 10^{-6}torr under the standard surge voltage. Three of the samples were tested using d.c., a.c., or pulse conditioning as described in § 4.2, and the fourth sample was tested without previous conditioning. The results of these tests are shown in Table 5.12 and are plotted against the number of breakdowns in Figure 5.6. These results show that independent of the conditioning technique used the electrical strength of the insulator increased with the number of breakdowns, reaching a maximum value. Further breakdown tests gave an electrical strength of approximately the same value. When the sample was tested without previous conditioning this maximum value was not reached in the eighteen readings taken, but a general trend toward this value was observed.

TABLE 5.12

EFFECT OF CONDITIONING ON THE STANDARD WAVE BREAKDOWN VOLTAGE FOR 5 mm POLYETHYLENE SAMPLES (PRESSURE 10^{-6}torr)

a

Without Conditioning	
Breakdown No	1.2/50 Kv(Peak)
1	32
2	32
3	35
4	35
5	35
6	38
7	46
8	40
9	40
10	42
11	42
12	46
13	48
14	48
15	50
16	56
17	50
18	58
A.C. Conditioning	
19	63
20	61
21	62
22	62
23	62

b

D.C. Conditioning	
Breakdown No	1.2/50 Kv(Peak)
1	42
2	42
3	45
4	47
5	47
6	52
7	55
8	58
9	60
10	63
11	57
12	62
13	60
14	62
15	60
16	62
17	60
18	62

c

Pulse Conditioning	
Breakdown No	1.2/50 Kv(Peak)
1	40
2	47
3	49
4	51
5	55
6	55
7	55
8	60
9	58
10	64
11	60
12	64
13	64
14	56
15	62
16	64
17	62
18	62

d

A.C. Conditioning	
Breakdown No	1.2/50 Kv(Peak)
1	52
2	57
3	58
4	62
5	62
6	61
7	63
8	62
9	61
10	62
11	62
12	62
Without Conditioning	
13	62
14	62
15	61
16	62
17	62
18	62

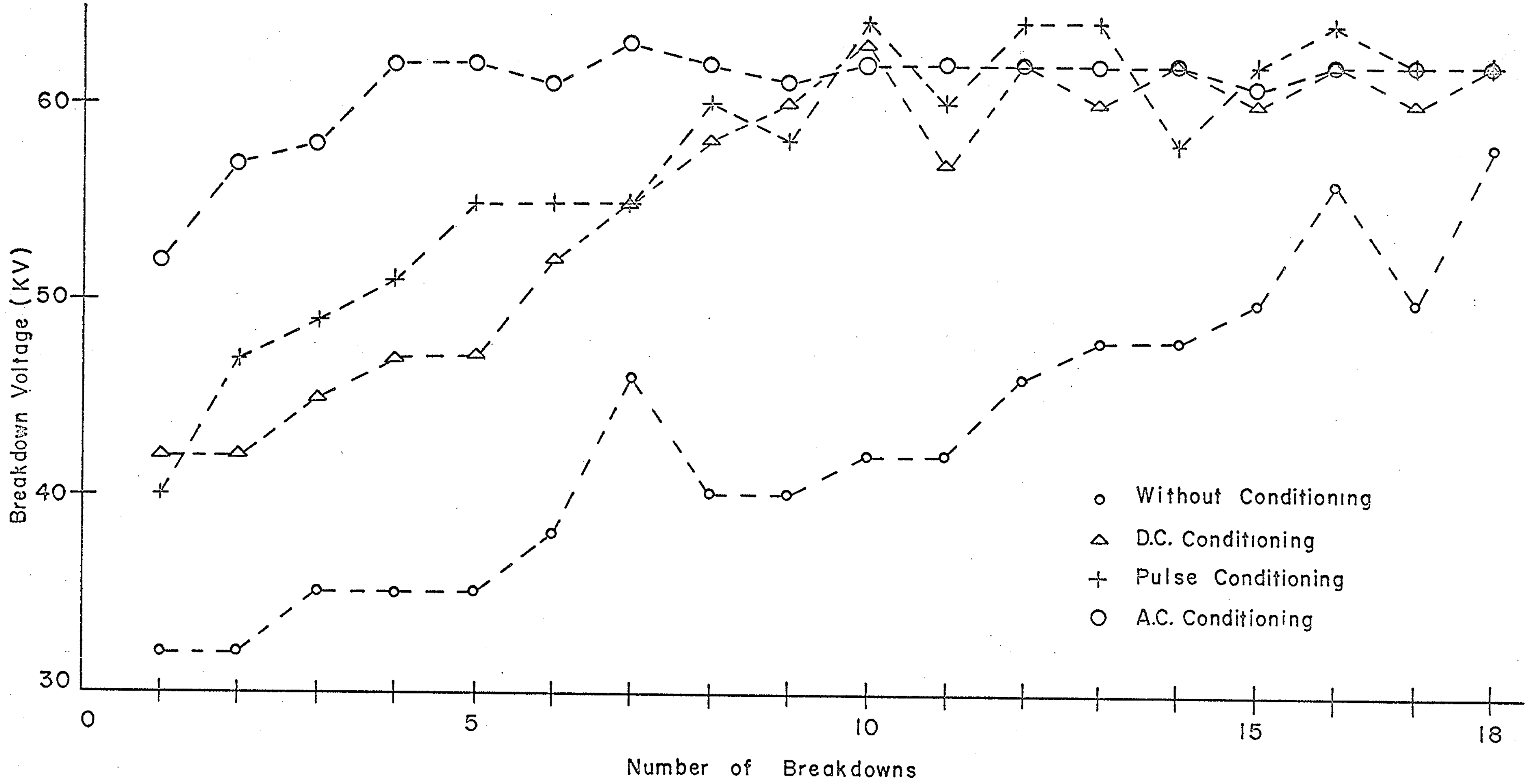

FIGURE 5.6 Effect of Conditioning on the Standard Impulse Breakdown Voltage for 5mm Polyethylene Samples (Pressure 10^{-6} torr)

Figure 5.6 also shows that the scatter of the results as well as the number of breakdowns needed to approach the steady range was strongly dependent upon the method of conditioning used. For example, when a.c. conditioning technique was used, the steady range was reached after only three breakdowns and the lowest reading observed was about 84% of the maximum. When d.c. and pulse conditioning were used, ten breakdowns were needed to reach the steady range and the first readings were about 70% of the maximum value. When the sample was tested without previous conditioning, readings as low as 50% of the maximum value were observed, and the eighteen applied breakdowns were insufficient to raise the level to the steady range. To check whether the behavior of this last sample was due to the absence of conditioning, the sample was subsequently conditioned under a.c. voltage and further tests were carried out. The results (5.12a, number 19 to 23) show that the effect was due to lack of conditioning.

It can also be seen that it is possible to reach a state of conditioning of the sample after which it is not necessary to use a conditioning treatment between breakdowns in order to obtain relatively consistent results. This is shown in Table 5.12d (numbers 13 to 18), where after nine consistent breakdowns using a.c. conditioning, the conditioning treatment was discontinued and subsequent results remained in the same range as before.

5.3.3 EFFECT OF SURGE FRONT DURATION ON THE BREAKDOWN VOLTAGE OF POLYETHYLENE SAMPLES

Applications of surge voltages of various front durations (1.2, 40, 70, 100, 150, 300, and 500 μsec) were made using a.c. conditioning on polyethylene samples of 5 and 15 mm length. Tables 5.13 and 5.15 show typical results obtained for 5 and 15 mm samples respectively. From these tables it is clear that for all types of voltages used in the tests, the first three or four breakdown values were low and scattered, but the subsequent breakdown values were higher and more consistent. This indicates that a conditioning process took place every time the front duration of the applied voltage was changed.

Tables 5.14 and 5.16 include the mean values and ranges of surface breakdown voltages obtained for 5 and 15 mm polyethylene samples respectively. Ranges of the surge voltages represent the extreme values obtained in a set of fourteen readings and the mean values are those of the last ten readings. In the cases of d.c. and a.c. voltages the ranges correspond to extreme values in a set of seven readings and the mean values were obtained from the last five readings. The breakdown values remained reasonably constant and there was no need for further tests.

Overall averages and extreme breakdown values for all samples tested are also included in both tables and the results are plotted in Figure 5.7. From these results it is clear that under surge voltages, average breakdown values observed are affected by the wave front duration.

TABLE 5.13

SURFACE BREAKDOWN OF A 5 mm LONG POLYETHYLENE SAMPLE UNDER DIRECT, ALTERNATING, AND SURGE VOLTAGES (PRESSURE 10^{-6} torr, AND A.C. CONDITIONING)

D.C. Kv	1.2/50 Kv (Peak)	40/120 Kv (Peak)	70/350 Kv (Peak)	100/700 Kv (Peak)	150/1800 Kv (Peak)	300/2000 Kv (Peak)	500/2500 Kv (Peak)	A.C. Kv (Peak)
40	59	52	47	44	37	37	41	27
45	59	53	48	58	42	37	51	28
42	50	53	53	46	49	49	51	28
45	66	55	49	46	49	37	42	28
44	60	57	53	46	51	46	47	28
45	63	61	55	50	50	46	55	28
45	66	58	57	50	55	55	48	28
	64	59	53	51	50	47	50	
	65	61	53	51	50	46	51	
	64	57	55	56	50	46	51	
	66	57	56	54	51	47	50	
	64	59	57	52	50	46	53	
	64	61	58	52	51	46	51	
	65	59	55	51	50	46	51	

TABLE 5.14

RELATION BETWEEN THE AVERAGE BREAKDOWN VALUE AND THE WAVE SHAPE OF THE APPLIED VOLTAGE FOR 5 mm POLYETHYLENE SAMPLES (PRESSURE 10^{-6}torr, AND A.C. CONDITIONING)

Sample No	Average Range	D. C. Kv	1.2/50 Kv(Peak)	40/120 Kv(Peak)	70/350 Kv(Peak)	100/700 Kv(Peak)	150/1800 Kv(Peak)	300/2000 Kv(Peak)	500/2500 Kv(Peak)	A.C. Kv(Peak)
1	Average	44	64.1	58.9	55.2	51.3	50.8	47	50.7	28
	Range	40-45	50-66	52-61	47-58	44-58	37-55	37-55	41-55	27-28
2	Average	44	62.3	58.5	57.5	52	49.5	46	49	28
	Range	41-45	52-65	50-60	48-59	46-56	38-51	35-49	35-54	25-28
3	Average	43	62	+ +	+ +	+ +	+ +	+ +	+ +	27
	Range	39-45	50-64	+ +	+ +	+ +	+ +	+ +	+ +	25-27
4	Average	44	62.5	+ +	+ +	+ +	+ +	+ +	+ +	28
	Range	41-45	49-64	+ +	+ +	+ +	+ +	+ +	+ +	27-28
Overall	Average	44	63	59	56	52	50	47	50	28
Extreme	Values	39-45	49-66	50-61	47-59	44-56	37-55	35-55	35-55	25-28

TABLE 5.15

SURFACE BREAKDOWN OF A 15 mm POLYETHYLENE SAMPLE UNDER DIRECT, ALTERNATING, AND SURGE VOLTAGES (PRESSURE 10^{-6}torr, AND A.C. CONDITIONING)

D.C. Kv	1.2/50 Kv(Peak)	40/120 Kv(Peak)	70/350 Kv(Peak)	100/700 Kv(Peak)	150/1800 Kv(Peak)	300/2000 Kv(Peak)	500/2500 Kv(Peak)	A.C. Kv(Peak)
96	90	92	92	70	82	92	88	44
115	93	102	102	91	72	78	92	46
112	105	95	93	90	95	92	96	48
110	105	105	100	98	92	90	96	48
112	112	102	102	96	92	100	96	47
110	110	100	95	104	99	90	100	48
112	104	100	104	102	100	92	94	48
	112	103	108	96	92	88	92	
	110	104	98	96	100	92	96	
	112	100	98	100	96	92	97	
	104	106	100	104	90	94	94	
	110	102	102	98	100	92	100	
	110	105	100	98	96	88	96	
	112	105	100	100	96	92	100	

TABLE 5.16

RELATION BETWEEN THE AVERAGE BREAKDOWN VALUE AND THE WAVE SHAPE OF THE APPLIED VOLTAGE FOR 15 mm POLYETHYLENE SAMPLES (PRESSURE 10^{-6}torr, AND A.C. CONDITIONING)

Sample No	Average Range	D. C. Kv	1.2/50 Kv(Peak)	40/120 Kv(Peak)	70/350 Kv(Peak)	100/700 Kv(Peak)	150/1800 Kv(Peak)	300/2000 Kv(Peak)	500/2500 Kv(Peak)	A.C. Kv(Peak)
1	Average	112	109.6	102.7	100.7	99.4	96.1	92.0	96.5	48
	Range	96-115	90-112	92-105	92-108	70-104	72-100	78-100	88-100	44-48
2	Average	112	117.2	112.4	112.0	107.3	106.1	100.3	104.2	51
	Range	105-117	100-122	100-115	102-116	90-109	92-109	85-105	90-108	44-52
3	Average	112	110.7	104.3	98.5	95.4	92.1	88.2	94.2	49
	Range	100-115	100-115	95-110	90-107	88-102	80-95	81-95	88-98	43-50
4	Average	105	100.4	95.2	95.7	92.1	88	88.3	90	47
	Range	95-109	88-105	90-104	89-104	89-100	81-90	80-90	86-95	40-47
Overall Average		110	110	104	102	99	96	92	96	49
Extreme Values		95-117	88-122	90-115	89-116	70-109	72-109	78-105	86-108	40-52

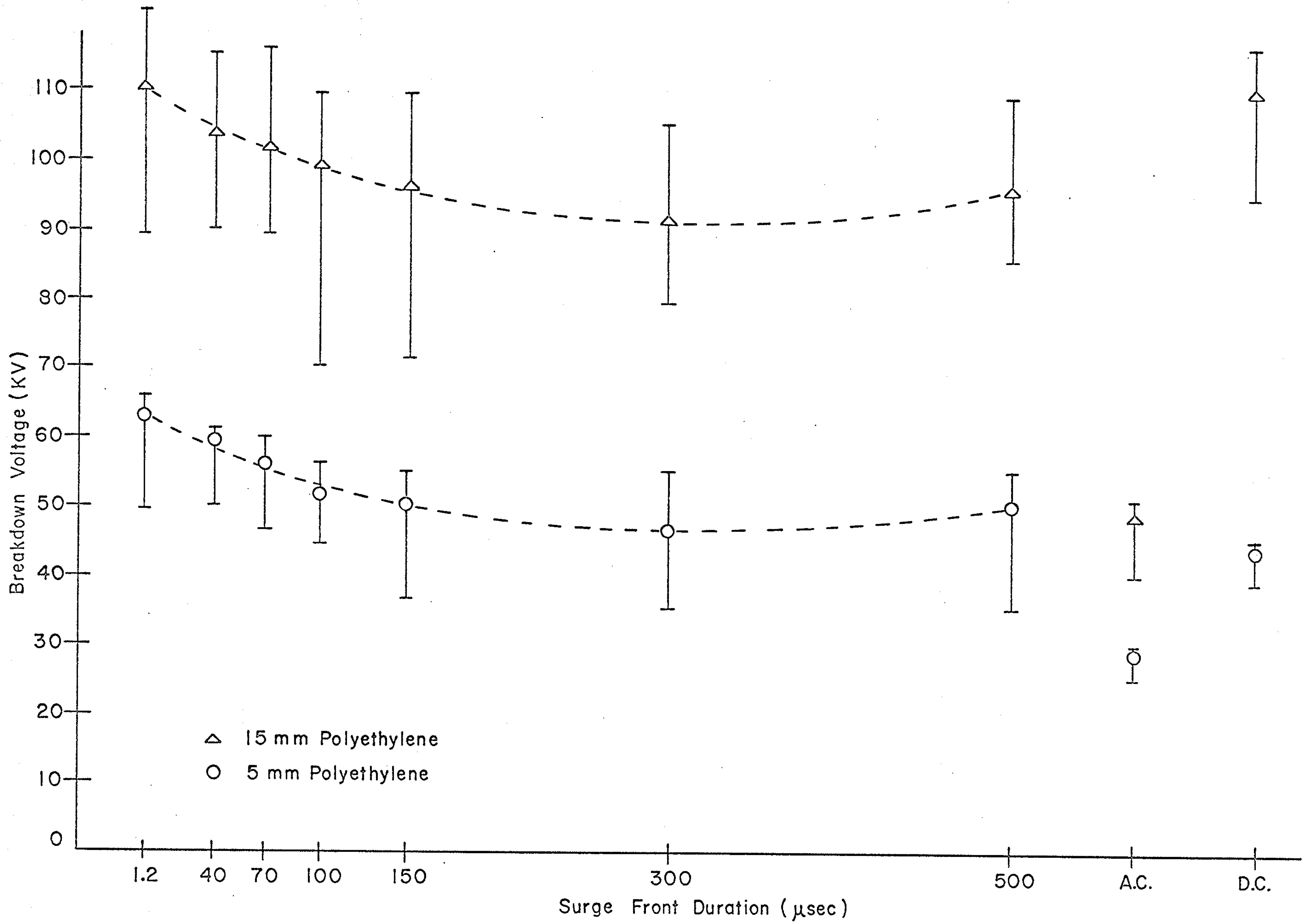

FIGURE 5.7 Effect of the Surge Front Durations on the Breakdown Voltage For Polyethylene Samples (Pressure 10^{-6} torr, and A.C. Conditioning)

The standard impulse voltage gave the highest values and as the wave front duration was increased the breakdown values decreased and reached a minimum for a surge of front duration somewhere in the range between 150 μsec and 500 μsec, thereafter, the values increased with further increase in the wave front duration. The minimum average breakdown values under surge voltages were obtained with 300 μsec front surge and their values were of about 80% of the average breakdown values for the standard impulse voltage. The lowest breakdown values were always observed under a.c. power frequency voltages.

5.3.4 EFFECT OF PLATING SAMPLE ENDS ON BREAKDOWN VOLTAGES

To study the effects on breakdown voltages of plating the sample ends, a 15 mm polyethylene sample without plated ends was tested in a vacuum of 10^{-6}torr under d.c., a.c., and surge voltages. The results obtained are shown in Table 5.17. It is seen that the breakdown values are fairly consistent, and that their average values are a little higher than the overall average values obtained for samples with plated ends (Table 5.16). The values are of the same magnitude as the average values obtained for the second sample (Table 5.16). Therefore, it may be concluded that plating the sample ends has little effect- if any- on the breakdown value of polyethylene samples. Little significance should be attached to this conclusion as it is based on only one sample.

TABLE 5.17

SURFACE BREAKDOWN OF A 15 mm LONG POLYETHYLENE SAMPLE UNDER DIRECT, ALTERNATING, AND SURGE VOLTAGES (PRESSURE 10^{-6}torr, A.C. CONDITIONING, AND SAMPLE WITHOUT PLATED ENDS)

	D. C. Kv	1.2/50 Kv(Peak)	70/350 Kv(Peak)	100/700 Kv(Peak)	150/1800 Kv(Peak)	300/2000 Kv(Peak)	500/2500 Kv(Peak)	A.C. Kv(Peak)
	112	117	103	108	101	92	78	50
	115	119	103	108	101	88	73	51
		119	110	114	100	99	88	
		119	110	112	101	92	104	
		117	114	114	100	99	100	
			119			99	104	
Average	114	118	113	113	100	97	99	51
Range	112-115	117-119	103-119	108-114	100-101	88-99	73-104	50-51

5.3.5 COMPARISON OF THE D.C., THE A.C., AND THE STANDARD IMPULSE BREAKDOWN CHARACTERISTICS OF POLYETHYLENE SAMPLES

To compare the d.c., a.c., and standard impulse breakdown characteristics of polyethylene samples following a.c. conditioning, samples of 10, 20 and 25 mm in length were also tested. The results obtained are presented in Table 5.18. The available voltage supply limitations prevented measurements of a.c. breakdown voltages for samples of 20, and 25 mm lengths. Average breakdown values of these samples, together with previous average values obtained for 5 and 15 mm samples, are recorded in Table 5.19 and are plotted in Figure 5.8.

These results indicate a different insulator length-breakdown voltage relationship for d.c. than for standard impulse voltage. Thus, for lengths of less than 15 mm, the standard impulse breakdown voltages were higher than the corresponding d.c. average breakdown values; at 15 mm both were equal; and for samples longer than 15 mm, d.c. average breakdown voltages were higher than corresponding standard impulse average breakdown values.

Figure 5.8 also shows that the lowest break - down values were obtained under a.c. power frequency voltages. These were about 45% of the standard impulse breakdown voltages.

5.4 A COMPARISON OF CHANGES IN ELECTRICAL STRENGTH OF TEFLON AND POLYETHYLENE WITH SUCCESSIVE BREAKDOWNS

Comparison was made of the results obtained for Teflon and polyethylene samples 5 mm in length, under d.c.

TABLE 5.18

SURFACE BREAKDOWN OF 10 mm, 20 mm, AND 25 mm LONG POLYETHYLENE SAMPLES UNDER DIRECT, ALTERNATING, AND STANDARD SURGE (PRESSURE 10^{-6}torr, AND A.C. CONDITIONING)

	a			b			c		
	10 mm Sample			20 mm Sample			25 mm Sample		
	D.C. Kv	1.2/50 Kv(Peak)	A.C. Kv(Peak)	D.C. Kv	1.2/50 Kv(Peak)	A.C. Kv(Peak)	D.C. Kv	1.2/50 Kv(Peak)	A.C. Kv(Peak)
	70	62	39	90	82	?	130	90	?
	85	80	39	115	110		135	92	
	80	92	40	125	120		135	110	
	85	95	40	125	116			130	
	85	92	40	130	130			130	
	83	100	40	125	124			132	
	85	97	40	125	119			130	
		96			119			--	
		92			123			--	
		95			124				
		90			123				
		96			123				
Sample No.	Average Values			Average Values			Average Values		
1	84	95	40	126	122	?	135	130	?
2	80	90	39	125	123	?			
Overall Average	82	93	40	126	123	?	135	130	?
Extreme Values	70-85	62-100	38-40	90-130	82-130		130-135	90-132	

TABLE 5.19

RELATION BETWEEN THE AVERAGE BREAKDOWN VALUES (D.C., A.C., 1.2/50 μsec) AND THE LENGTH OF POLYETHYLENE SAMPLES

(PRESSURE 10^{-6} torr, AND A.C. CONDITIONING)

Sample Length mm	D. C. Kv	1.2/50 Kv (Peak)	A.C. Kv (Peak)
5	44	63	28
10	82	93	40
15	110	110	49
20	126	123	?
25	135	130	?

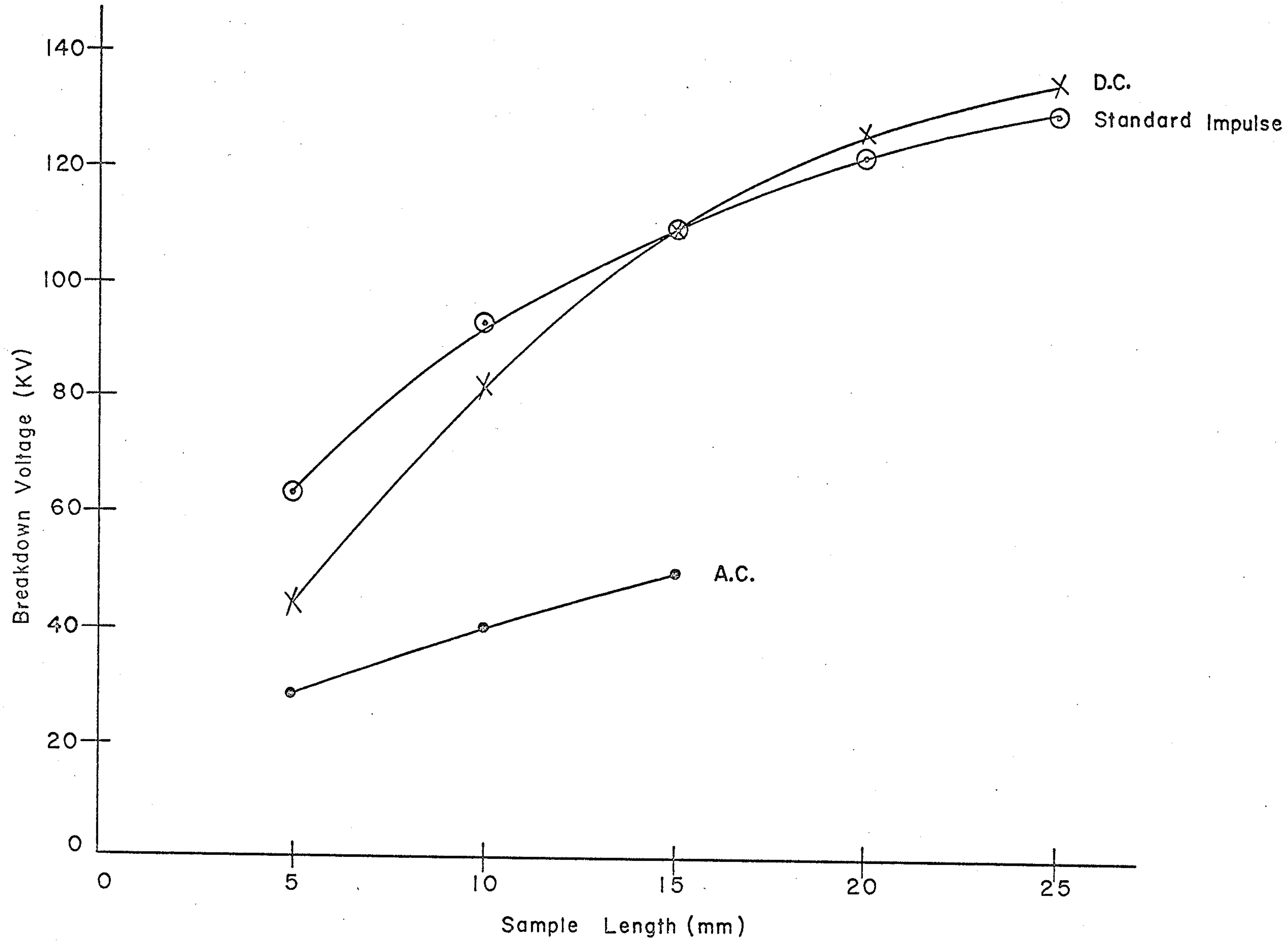

FIGURE 5.8 Comparison of D.C., A.C., and Standard Impulse Breakdown Characteristics For Polyethylene Samples (Pressure 10^{-6} torr, and A.C. Conditioning)

voltages and using d.c. conditioning (Fig. 5.1 and Fig. 5.5). The breakdown voltages of polyethylene samples increased gradually as the number of breakdowns increased but for Teflon samples the breakdown voltages fluctuated around the first breakdown value or a little lower until surface deterioration took place. A decrease in breakdown voltage was also noted when a polyethylene sample remained for twenty hours in vacuum with no application of voltage. In the case of Teflon samples an increase in breakdown voltage occurred. The Teflon sample also deteriorated faster than the polyethylene, and all breakdowns of Teflon followed the same path across the insulator. In polyethylene, the location of the path resulting from breakdowns on the insulator surface changed with successive breakdowns.

5.5 EFFECT OF D.C. AND A.C. CONDITIONING ON TEFLON AND POLYETHYLENE BREAKDOWN VOLTAGES

During the present study a strong dependence of the breakdown voltage of Teflon samples on the method of conditioning was observed. Figure 5.9 presents the a.c., d.c., and standard impulse breakdown characteristics of Teflon samples following d.c., and a.c. conditioning. The average breakdown voltages increased, independently of the wave shape of the applied voltage, when a.c. conditioning was used. The effect of this a.c. conditioning was more noticeable in the standard impulse and a.c. breakdown characteristics than in the d.c. breakdown

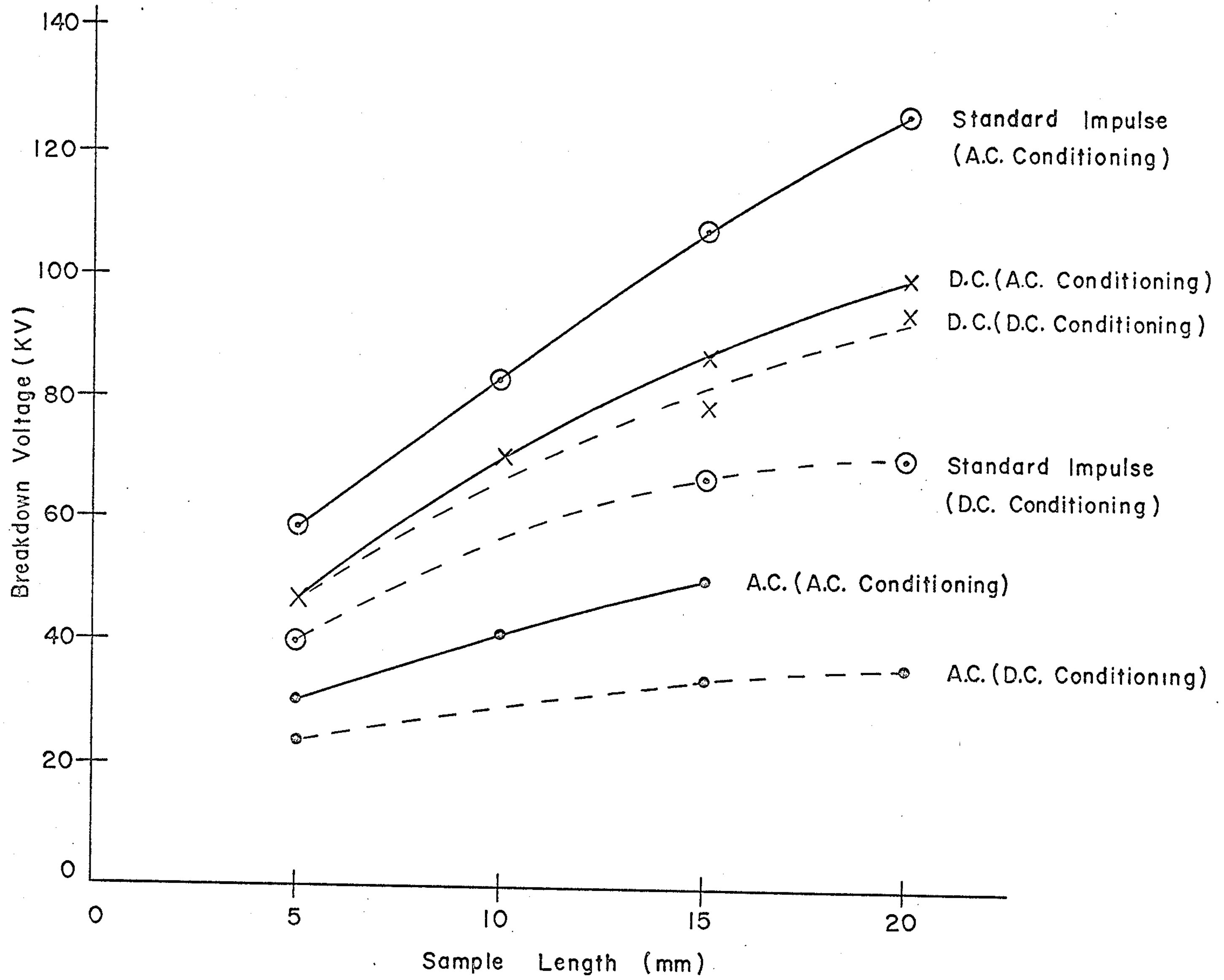

FIGURE 5.9 Comparison of D.C., A.C., and Standard Impulse Breakdown Characteristics For Teflon Samples under D.C., and A.C. Conditioning

characteristic. For example, following a.c. conditioning, increments between 45% and 77%, depending upon the insulator length, can be observed in the standard impulse breakdown characteristic, and increments between 25% and 55% in the a.c. breakdown characteristic, while increments of only 10% were seen in the d.c. breakdown characteristic.

It was also noted that when d.c. conditioning was used, all breakdowns followed the same path across the insulator surface, but when a.c. conditioning was used, the path associated with successive breakdowns frequently changed from one to the next, and the sample did not deteriorate as quickly as when d.c. conditioning was used.

This strong dependence of the magnitude of the breakdown voltage on the conditioning method was not observed in polyethylene samples, but Figure 5.6 shows that when a.c. conditioning was used, the sample was conditioned faster and the results were less scattered than the results obtained when d.c. conditioning was used.

The phenomena observed with a.c. conditioning suggest that changes of surface charge distribution with each voltage reversal accelerated the conditioning process, and therefore affected the breakdown voltages of the insulator. However, much more work will be necessary before a general understanding of the mechanism of breakdown across insulation surfaces in vacuum is available.

5.6 COMPARISON OF THE BEHAVIOR OF TEFLON AND POLYETHYLENE UNDER SURGE VOLTAGES

The relationship between the breakdown voltage and surge front duration detected for Teflon and polyethylene samples in a vacuum of 10^{-6}torr and under a.c. conditioning is demonstrated in Figure 5.10. From this figure it can be seen that the breakdown voltages changed about 20% within the range of surge front duration investigated (1.2 to 500 μsec) for both lengths and materials. It is also clear that changes in breakdown values with changes of surge front duration were more rapid in the 1.2 to 150 μsec range than in the 150 to 500 μsec range. Insulator length also had an effect on the relationship between breakdown voltages of different materials under the same surge voltage.

Figure 5.10 also shows that in the range of surge front duration investigated, the average breakdown voltages measured for polyethylene samples decreased as the wave front duration increased, and reached a minimum somewhere between 150 μsec and 500 μsec, and that further increase in the wave front duration increased the breakdown value. When Teflon samples were tested, a similar decrease of breakdown voltages with the increase of wave front duration was observed, but a minimum was not reached.

It can also be seen that for the insulator lengths and surge front durations investigated, the average breakdown values obtained for polyethylene samples were a little higher than for Teflon samples, with the minor

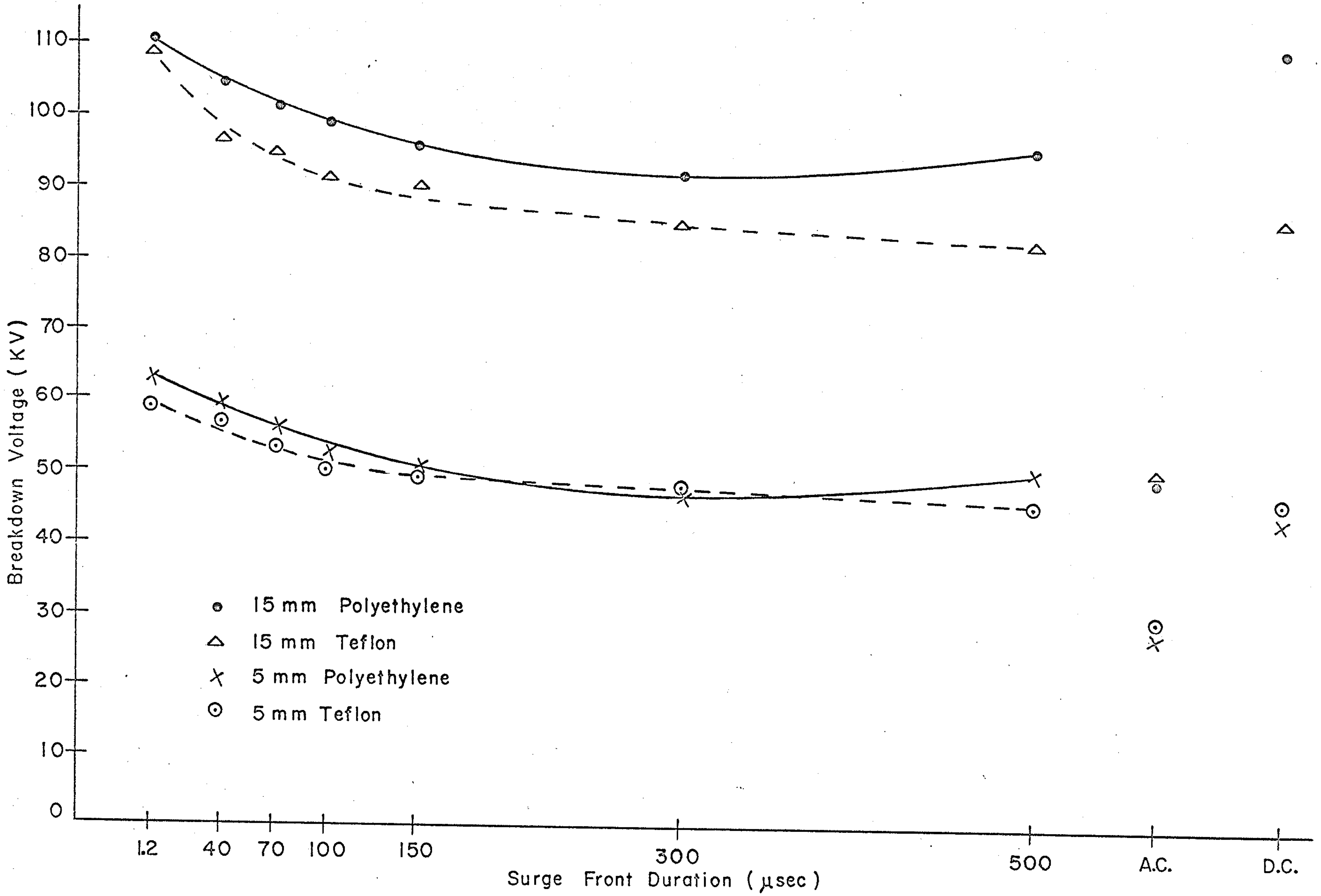

FIGURE 5.10 Comparison between Teflon and Polyethylene Behaviour under Surge Voltages (Pressure 10^{-6} torr, and A.C. Conditioning)

exception of the average breakdown value of 5 mm polyethylene samples under a front surge of 300 sec., which was 2% lower than the corresponding value for Teflon.

5.7 COMPARISON OF THE D.C., THE A.C., AND THE STANDARD IMPULSE BREAKDOWN CHARACTERISTICS OF TEFLON AND POLYETHYLENE

The d.c., a.c., and standard impulse breakdown characteristics obtained for Teflon and polyethylene samples in a vacuum of 10^{-6}torr and using a.c. conditioning are presented in Figure 5.11.

The lowest breakdown values were obtained under a.c. power frequency voltages for both materials, but a.c. breakdown values for the Teflon samples were up to 7% higher than the corresponding a.c. breakdown voltages for polyethylene.

The highest breakdown voltages observed for Teflon were recorded under standard impulse voltages. These values remained about 20% above the corresponding d.c. breakdown voltages and about 50% above the corresponding a.c. breakdown values.

The highest breakdown voltages observed for polyethylene were recorded under standard impulse voltages or d.c. voltages, depending upon the insulator length. Thus for insulators shorter than 15 mm, the standard impulse voltages gave the highest breakdown values, but for insulators longer than 15 mm, the d.c. voltages gave the highest breakdown values. These values were about 55% higher than the corresponding a.c. breakdown voltages.

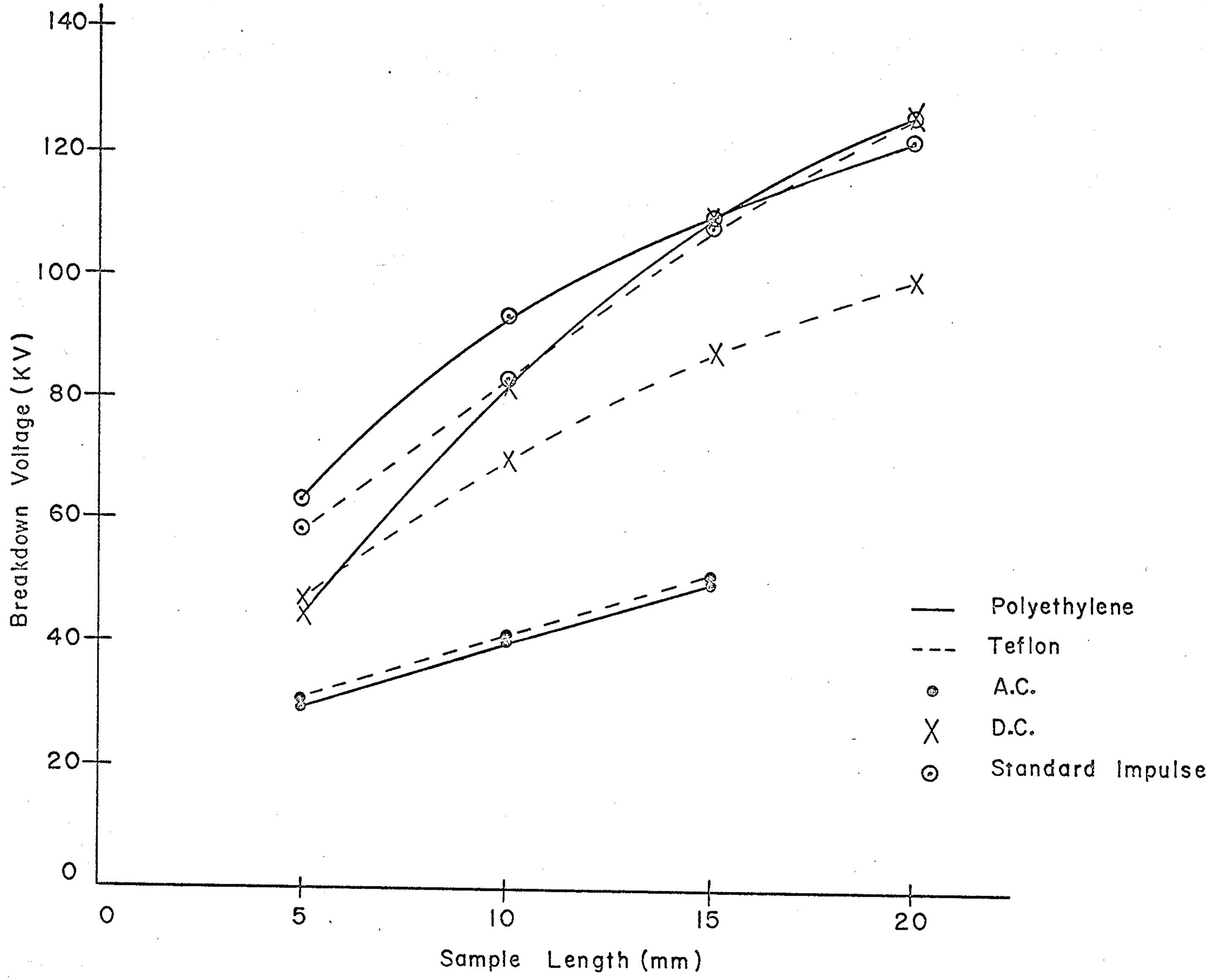

FIGURE 5.11 Comparison of D.C., A.C., and Standard Impulse Breakdown Characteristics of Teflon and Polyethylene (Pressure 10^{-6} torr, and A.C. Conditioning)

A comparison of the d.c. breakdown characteristics shows that except for the results of 5 mm long samples (where the d.c. average breakdown value for Teflon was 6% higher than for polyethylene), the d.c. breakdown voltages of polyethylene samples were higher than those of Teflon.

A comparison of the standard impulse breakdown characteristics shows that for sample lengths less than 15 mm, the average breakdown voltages of polyethylene were higher than the corresponding breakdown voltages of Teflon, but for insulator lengths greater than 15 mm, the breakdown voltages of Teflon were higher than those of polyethylene.

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CHAPTER VI

SUMMARY OF RESULTS

The studies presented in this thesis provide new and additional information about the surface breakdown phenomena of a solid insulator in vacuum. They also indicate that the surface breakdown voltages of a solid insulator in vacuum depend upon the length of the insulator, the front duration of the applied voltage, the conditioning technique used, and the material of the insulator.

Breakdown voltages across insulation surface in a vacuum of 10^{-6}torr were measured under direct, alternating, and surge voltages of front durations extending from 1.2 μsec to 500 μsec using cylindrical samples of Teflon, and polyethylene placed between uniform field electrodes.

In the range of surge front durations investigated, the average breakdown voltages measured for polyethylene samples decreased as the wave front duration of the applied voltage was increased, and reached a minimum value somewhere between 150 μsec and 500 μsec. Further increase in the wave front duration increased the breakdown value. When Teflon samples were tested, a similar decrease of breakdown voltages with the increase of wave front duration was observed, but a minimum was not reached. In both materials, the breakdown voltage decreased about 20% when the wave front duration was changed from 1.2 μsec to 500 μsec. Changes of breakdown values with changes of surge front duration occurred more rapidly in the 1.2 to 150 μsec range than in the 150 to 500 μsec range.

The highest breakdown voltages observed for Teflon samples were recorded under standard impulse voltages. These values remained about 20% above the corresponding d.c. breakdown values and about 50% above the corresponding a.c. breakdown values. When polyethylene samples were tested, the highest breakdown values were recorded under standard impulse voltages or d.c. voltages, depending upon the insulator length. Thus, for insulators shorter than 15 mm, the standard impulses gave the highest breakdown values, but for insulators longer than 15 mm, the d.c. voltages gave the highest breakdown values. These values were about 55% higher than the corresponding a.c. breakdown voltages.

Most investigators have stated that their measured breakdown voltages depended strongly on the pre-conditioning of the samples, but no standard conditioning technique has yet been suggested. During the present work, three different conditioning techniques (d.c., a.c., and pulse) were investigated. When d.c.

conditioning was used, the d.c. voltage applied to a new unconditioned sample was increased at a rate of 2 Kv/min. until seventy per cent of the anticipated d.c. breakdown value was reached. At this value, the voltage was maintained constant for one hour before the sample was tested to breakdown. After the first and subsequent breakdowns the sample was conditioned at the same voltage as before but the time of conditioning was reduced to 30 minutes.

When a.c. conditioning was used, the a.c. voltage was again increased at a rate of 2 Kv/min up to about seventy per cent of the anticipated a.c. breakdown value. The voltage was maintained constant at this value for 30 minutes before the sample was tested to breakdown. After the first and subsequent breakdowns, the sample was conditioned at the same voltage as before but the time of conditioning was reduced to 15 minutes.

When pulse conditioning was used, the unconditioned sample was repeatedly pulsed at intervals of one minute with a standard impulse voltage whose amplitude was fifty per cent of the anticipated standard impulse breakdown value. One hour later the voltage was increased until breakdown occurred. After the first and subsequent breakdowns, the sample was conditioned at the same voltage as before but the time of conditioning was reduced to 30 minutes. Preliminary measurements showed that the breakdown values were appreciably scattered when the conditioning times of the investigated conditioning techniques were reduced.

The present investigation showed that the breakdown voltages of Teflon samples in vacuum were strongly dependent upon the conditioning technique applied. When a.c. conditioning was used, the breakdown values were less scattered and the sample did not deteriorate as quickly as when d.c. conditioning was used. The average breakdown voltages increased, independently of the wave shape of the applied voltage when a.c. conditioning instead of d.c. conditioning was used. For example, following a.c. conditioning, increments between 45% and 77%, depending upon the insulator lengths, were observed in the standard impulse breakdown voltages, and increments between 25% and 55% were observed in the a.c. breakdown voltages.

This strong dependence of the breakdown voltage magnitude on the conditioning technique was not observed in polyethylene samples, but when a.c. conditioning was used, the sample was conditioned faster and the results were less scattered than the results obtained when d.c. conditioning was used. The consistency of the results, and the time saving following a.c. conditioning showed that its use in conditioning is most efficient.

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