SPARKPLUG COATING ENHANCEMENT OF THE FLASHOVER POTENTIAL OF LEXAN

by

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ABSTRACT

An increase in surface flashover potential was observed to occur in the organic polymer Lexan after it was exposed to the by-products of a vacuum sparkplug discharge. Previous analysis of the treated surfaces using Electron Spectroscopy for Chemical Analysis (ESCA) showed the insulator to be coated with a thin hydrocarbon/metal oxide layer. The formation of this high flashover potential coating is strongly dependent on the amount of water vapor in the chamber during treatment. Earlier studies have shown that insulator surfaces treated with the special coating produced secondary electrons with lower energy levels than the untreated samples. It has also been proposed that the monoenergetic nature of this secondary electron avalanche is destroyed due to electron-gas molecule collisions before the onset of breakdown, thus inhibiting the breakdown process.

This thesis will show how varying experimental parameters, and exposing an insulator to the by-products of a jet engine sparkplug, can increase the breakdown voltage of insulators. First, an introduction on surface flashover will be discussed. Next, several suggestions will be made regarding how to choose the material and geometry when selecting an insulator for a particular application.

The arrangement of the high voltage system that was used to implement the experiment will be discussed. Finally, the experimental results will be evaluated and conclusions presented.

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CHAPTER 1

INTRODUCTION OF THEORY OF SURFACE FLASHOVER IN A VACUUM

The breakdown field strength of a system made up of an unbridged spark gap, separated by a certain distance, is considerably higher than the breakdown field strength of the same spark gap, if the distance between the electrodes is replaced with a solid dielectric. Usually, the breakdown of a gap, bridged by a solid dielectric, occurs along the surface of the insulator, and is initiated at the interface between the insulator, the electrode, and the surrounding medium. The breakdown of an insulator along its surface is referred to as surface flashover.

While there is general agreement on the initiating mechanism of surface flashover, there is disagreement concerning the mechanism of the intermediate stage of the discharge. The initiation of a surface flashover is usually brought on by the emission of electrons from the triple junction (the interface where the insulator, metal electrodes, and vacuum come into contact). The final stages of surface flashover are thought to occur in desorbed surface gas or in vaporized insulator material [1].

The most accepted mechanism for the intermediate stage is the secondary electron emission avalanche (SEEA). Some of the electrons emitted from the triple junction impact the surface of the insulator, producing additional electrons by secondary emission. Some of the secondary electrons will again strike the surface producing tertiary electrons. Continuation of this process results in the development of an SEEA, which will result in surface charging of the insulator [2].

Given an insulator in a vacuum, the surface of the insulator will be covered with a layer of absorbed gas. The SEEA electrons bombarding the surface of the insulator desorb some of this absorbed gas, forming a gas cloud which then is partially ionized by the electrons in the SEEA. Then some of the resultant positive charge on the surface of the dielectric enhance the electron emission from the triple junction and thus increase the current along the insulator surface. Consequently, a regenerative process occurs that leads quickly to surface flashover of the insulator [3].

Another postulated mechanism for the intermediate phase of surface flashover is the propagation of electrons in a conduction band of the insulator. The electrons are accelerated by the electric field within the insulator. The electrons gain energy and begin making inelastic collisions, thus creating an electron cascade along the surface as soon as their energy exceeds the band gap of the insulator. A fraction of these cascading electrons will be emitted into the vacuum, whereupon the external electric field drives them toward the anode. From an external point of view, one sees a steadily increasing flow of electrons along the insulator. The cascade of ionized electrons will produce a number of holes in the valence band and stimulate desorption of surface gases. The electrons cascading just inside the insulator surface make inelastic collisions with absorbed gases that are trapped at the surface. This process transfers enough energy to liberate the adsorbed gas molecules. Final flashover then occurs in the desorbed surface gas [4]. It seems quite probable that no single theory is capable of explaining all cases of surface flashover in vacuum, but rather that depending upon specific experimental conditions (geometry, dielectric material, voltage waveform) a particular mechanism could dominate the surface flashover [2].

It will be shown in this thesis that when a polished insulator, coated with the by-products of a jet engine spark plug flash, is inserted between two electrodes, the flashover potential is increased. The insulator surface, the electrodes and the experimental conditions all play roles in the breakdown process.

CHAPTER 2

EXPERIMENTAL CONDITIONS OF INSULATOR FLASHOVER

2.1 Conditioning

It has been found that after a surface flashover has occurred, subsequent flashovers occur at higher voltages. This process of conditioning involves gradually applying higher voltages to the electrodes connected to the insulator. It has also been found that if a conditioned insulator is left unstressed by voltage for a long enough time, its flashover voltage will be less than the fully conditioned value. Thus, applications where an unstressed insulator has to suddenly withstand a voltage usually cannot depend on the conditioned value of voltage, but must adopt a more conservative rating. Conversely, applications where the insulator is under continuous voltage stress, or where it is allowed to recondition itself, can utilize the conditioned value. Conditioning has been attributed to either the removal of emission sites, removal of surface gas, or removal of surface contaminants. Conditioning can also occur without actual flashover. This type of conditioning is obtained via stepped voltage increases, but without flashover. The insulator is polarized by the electric field, thus decreasing its instantaneous response to a subsequent increase in electric field.

Conditioning under such circumstances is slower than when flashovers are allowed to occur. However, such nonbreakdown conditioning offers the advantage that it is much less likely to damage the surface of the insulator [5].

2.2 Geometric Shapes of Insulators

The exact shape of an insulator can have a strong effect upon its surface voltage. Some insulator geometries are shown in Figure 2.1. The simplest shape, a cylinder, generally has a lower breakdown voltage than do more complex shapes. The poorest insulator performance seems to be for cones with slight negative angles [2].

One method of changing the fields near the insulator, especially at the triple junctions, is to put metal inserts into the ends of an insulator [6]. A related method of reducing the fields at the triple junctions is by shaping the electrodes so that the ends of the insulators are recessed into the electrodes [7]. Similar field reductions can be obtained by the use of shields, which also can prevent particles (ultraviolet, soft X-rays, etc.) from striking the surface of the insulator [8]. Chamfering (removing the sharp edge by sloping it 45 degrees) the metal electrodes and/or the cathode end of the insulator can be effective in increasing the voltage breakdown performance. This probably occurs because electrons accumulating

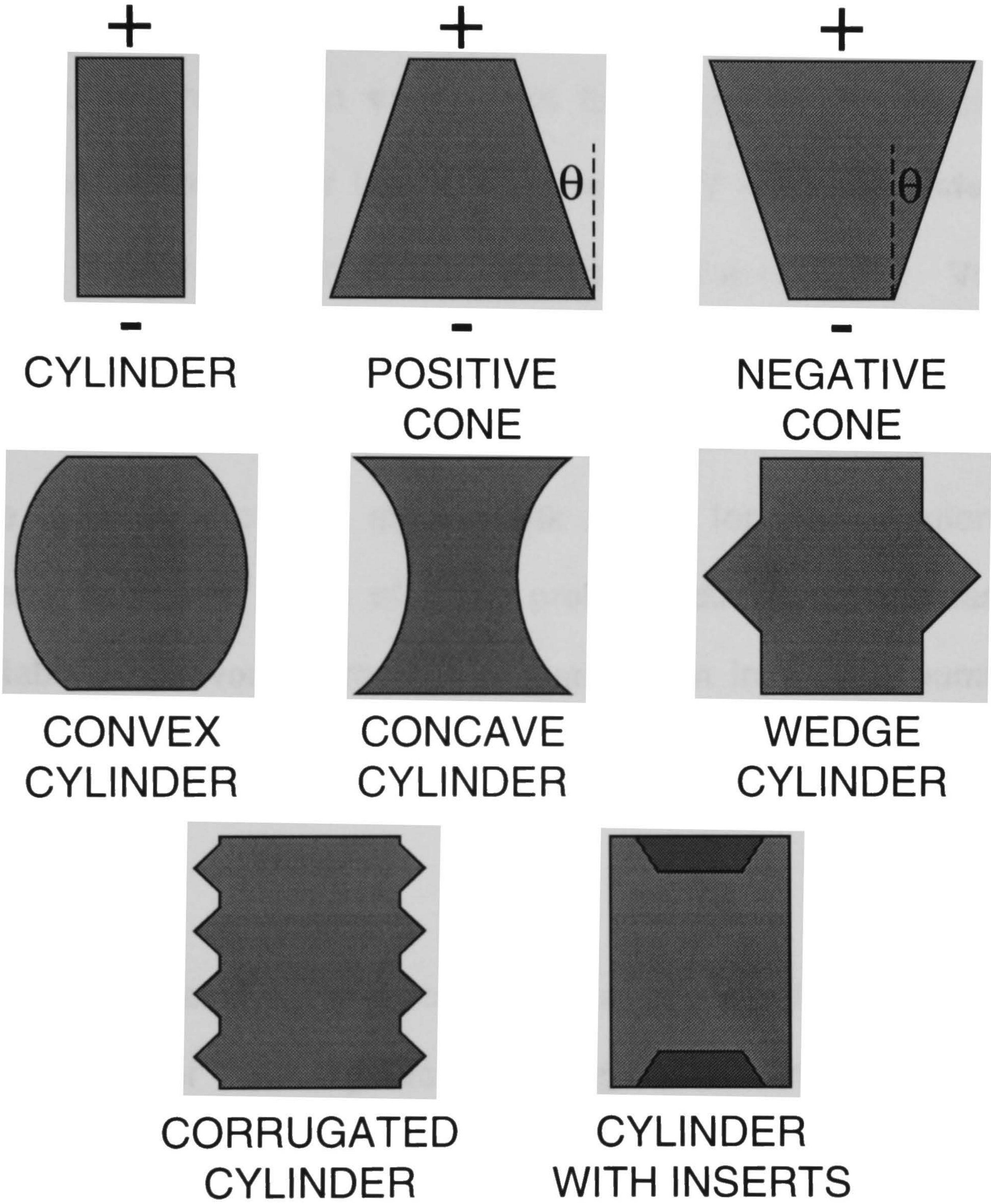


Figure 2.1 Insulator Geometries [2].

on the surface of the chamfer reduce the electric field at the cathode triple junction [9].

Voltage breakdown varies with the length of the insulator according to the power law $V \propto L^{\alpha}$, where V is the breakdown voltage, L is the length of the insulator and $\alpha \approx 0.5$ [10]. Voltage breakdown of insulators decreases with increasing insulator diameter. This reduction occurs because the increasing length of the triple junction provides more weak points for the initiation of surface flashover. This effect is probably due to an increase in available flashover energy rather than to an increased number of potential flashover sites [11].

2.3 Materials

The insulator material can have a strong effect on surface flashover. For both organic and inorganic materials, the best insulator is made of a material that has a high degree of homogeneity [2]. An inverse relationship between the relative permittivity (κ) of a material and its flashover voltage has been observed. Relative permittivity is defined as the ratio of the permittivity of the material (ε) to the permittivity of vacuum (ε_0), i.e., ($\kappa = \varepsilon / \varepsilon_0$) [12].

The probable reason for the relationship between the relative permittivity of an insulator and its surface flashover voltage in vacuum are voids at the triple junction. Figure 2.2 illustrates this theory. Figure 2.2(a) shows the equipotential lines for an ideal triple junction. The equipotential lines run parallel to the electrode and are uniformly spaced. Because the insulator completely fills the gap between the electrodes, the κ of the insulator has no effect on the equipotential lines. Figure 2.2(b) shows a triple junction for a practical case, where very small voids can exist at the junction between the insulator and the electrode. The presence of a small void strongly concentrates the equipotential lines and greatly increases the local electric field. In regions where materials with different κ factors meet, the equipotential lines are shifted from the region of higher κ towards the lower κ region. The amount of equipotential shifting depends upon the ratio of the κ values, ($\kappa_{high}/\kappa_{low}$). Thus the degree of field intensification caused by a void (κ=1) depends mainly upon the κ of the insulator, with the actual size of the void having much less effect. Figure 2.2(c) shows the effect of a graded relative permittivity at the triple junction. The grading was modeled by increasing κ in the layer of insulator including the void and gradually reducing κ throughout the rest of the insulator.

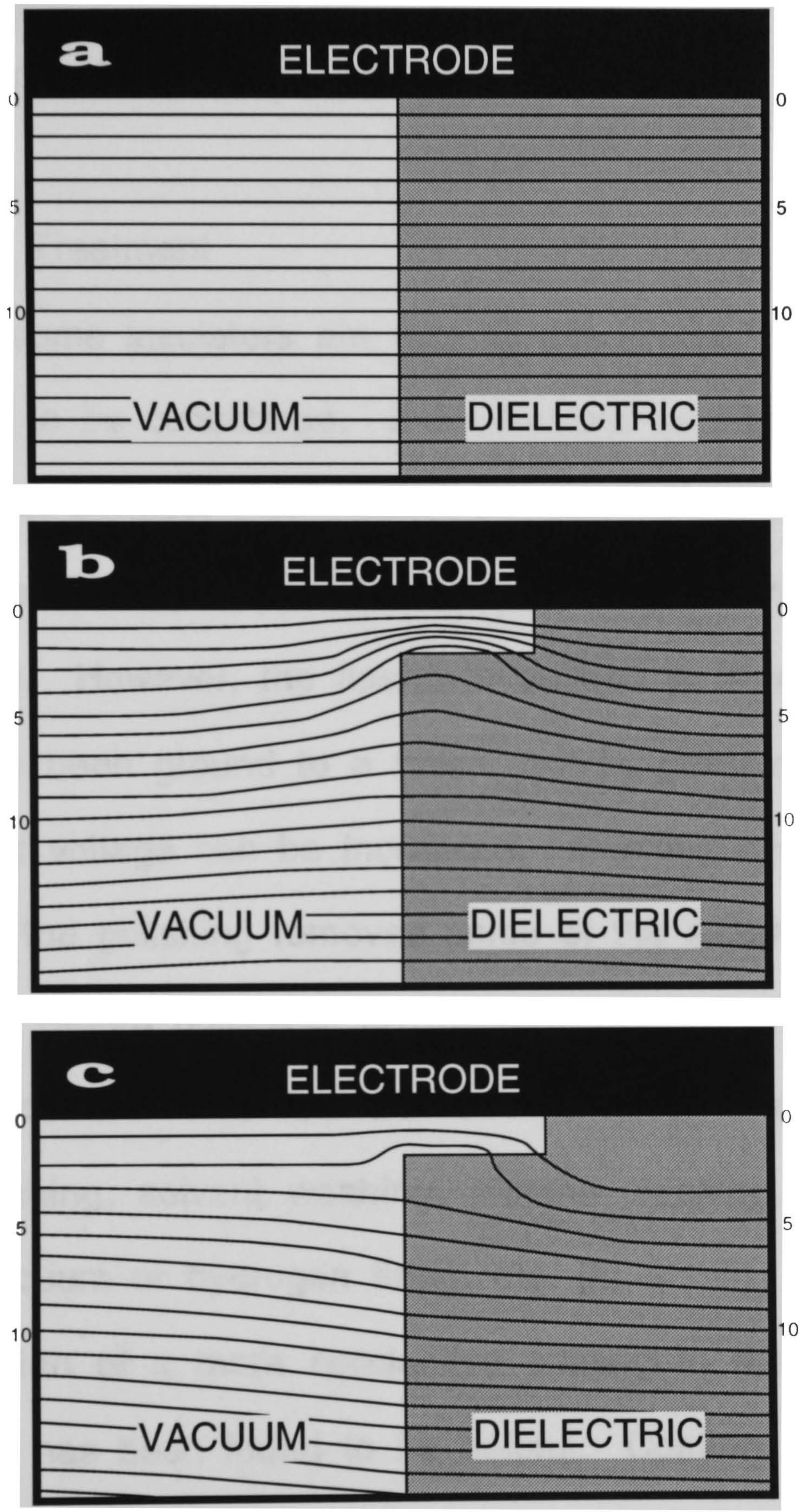


Figure 2.2 Equipotential plots - Triple Junction region. (a) Ideal Contact, (b) with small void, (c) with small void and graded relative permittivity.

By doing this the equipotential lines are shifted away from the void and their concentrated effect is negated [13].

2.4 Surface Treatment

Since some insulators are ground into shape, the effect of such grinding has to be considered. If an insulator is made of a material with a smooth surface, then usually roughening the surface of the insulator can raise the breakdown voltage significantly for dc voltages [14]. However, the flashover voltage is lowered when an insulator has been ground to a finish, but by polishing the insulator, the flashover voltage can be increased. Grinding creates surface defects and the polishing removes some of the severely damaged layers [15]. Before polishing, an insulator surface should be cleaned to remove possible contaminants. Such cleaning may include chemical etching, solvent washing, plasma cleaning, glow discharge cleaning, vacuum or hydrogen firing, etc. [2].

Application of a more conductive coating to the insulator surface also has been found to be helpful. Coatings which penetrate into the outer layers of the insulator are often preferable to those which remain on the surface, since insulators with such doped surface layers are more resistant to surface damage. Most surface coating treatments have involved inorganic materials (usually ceramics), but recent studies are now being performed on organic materials [2].

The effectiveness of surface treatment is dependent on the coating materials and technique, the insulator material, and the condition of the surface to which the coating is applied. Several possible mechanisms by which surface treatment could increase the surface flashover voltage have been postulated: (1) decrease the secondary electron emission coefficient of the surface; (2) make the surface dielectrically more uniform; (3) decrease the surface resistivity; (4) decrease the amount of gas adsorbed onto the surface [16].

2.5 Surface Gases

Most theories of surface flashover predict that the final stage of flashover involves gas desorbed from the surface of the insulator. These quantities of small bursts of gas can be produced by dc flashovers [17].

In order to remove excess gas from an insulator, the insulator can be baked in a low temperature oven or placed under high vacuum for 24 hours. Table 2.1 shows that while there is a large difference between baked and unbaked insulators in the quantities of gases desorbed by voltage pulses which did not cause breakdown, the

Table 2.1 Total Gases - Prebreakdown and Breakdown

(Quantities of gas, 10^{12} molecules) [2].

	Flashover	No flashover
Baked	25-32	~0.07
Unbaked	48	1.8-8

quantities desorbed by surface flashovers on baked or unbaked insulators were within a factor of two. This suggests that the quantity of adsorbed surface gas which must be desorbed for surface flashover to occur is relatively independent of the amount of gas present. For example, assume that for a particular insulating system a quantity of gas (assumed to be desorbed surface gas, but could include vaporized surface material) had to be released from the surface for a surface flashover to occur. Now consider an identical insulator, but with less gas (or more tightly bound gas) on its surface. Then to release the same amount of gas, a higher voltage would have to be applied. Thus, the insulator with more easily released surface gas would have the lower surface flashover voltage [2].

This would explain why treatments which reduce the amount of adsorbed surface gas on an insulator (treatments such as baking it, cleaning it with UV or glow discharge, or just pumping on it for longer periods before applying voltage), can improve its breakdown voltage significantly [18]. Therefore, if originally a particular voltage would release enough gas to induce surface flashover, after treatment an increased voltage would be required to release the same quantity of gas [2].

2.6 Temperature

Decreasing the temperature of an insulator has been shown to increase its flashover voltage [19]. Experiments with cooling one end of the insulator suggest that the temperature effect is mainly at the cathode end. The increase in flashover voltage was attributed to the effect of the lowered temperature on the adsorbed surface gas. Heating an insulator lowers its flashover voltage. The decrease is attributed to the change in surface resistivity of the insulator with temperature [19].

CHAPTER 3

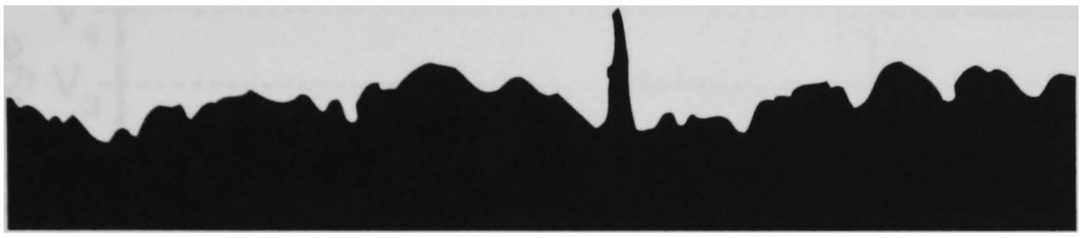
MECHANISMS WHICH LEAD TO VOLTAGE BREAKDOWN IN VACUUM

Under ideal conditions, the breakdown field level for vacuum exceeds that of all other media including liquids and solids, and may be 10 MV/cm or higher [20].

Conductive whiskers form in high-field regions on electrodes in vacuum. These whiskers can result from the migration of debris or they can grow from metallic surfaces subjected to high electric fields. The whisker shown in Figure 3.1 was produced by subjecting an optically flat stainless steel surface to a field of somewhat less than 200 kV/cm [21].

The field-enhancement factor at the tip of a whisker can be extremely high and can produce field emission of electrons. The current flow through the tip of a whisker coupled with ion bombardment (ions are produced when the field-emitted electrons strike gas atoms) may lead to a low voltage breakdown between electrodes [20].

In order to "clean up" the whiskers on electrodes, a voltage conditioning process can be applied in which a high voltage is gradually applied to the electrodes as shown in Figure 3.2. In a high



304 Stainless Steel

Aluminum

Figure 3.1 Whiskers on Stainless Steel and Aluminum Produced by Electric Field [2].

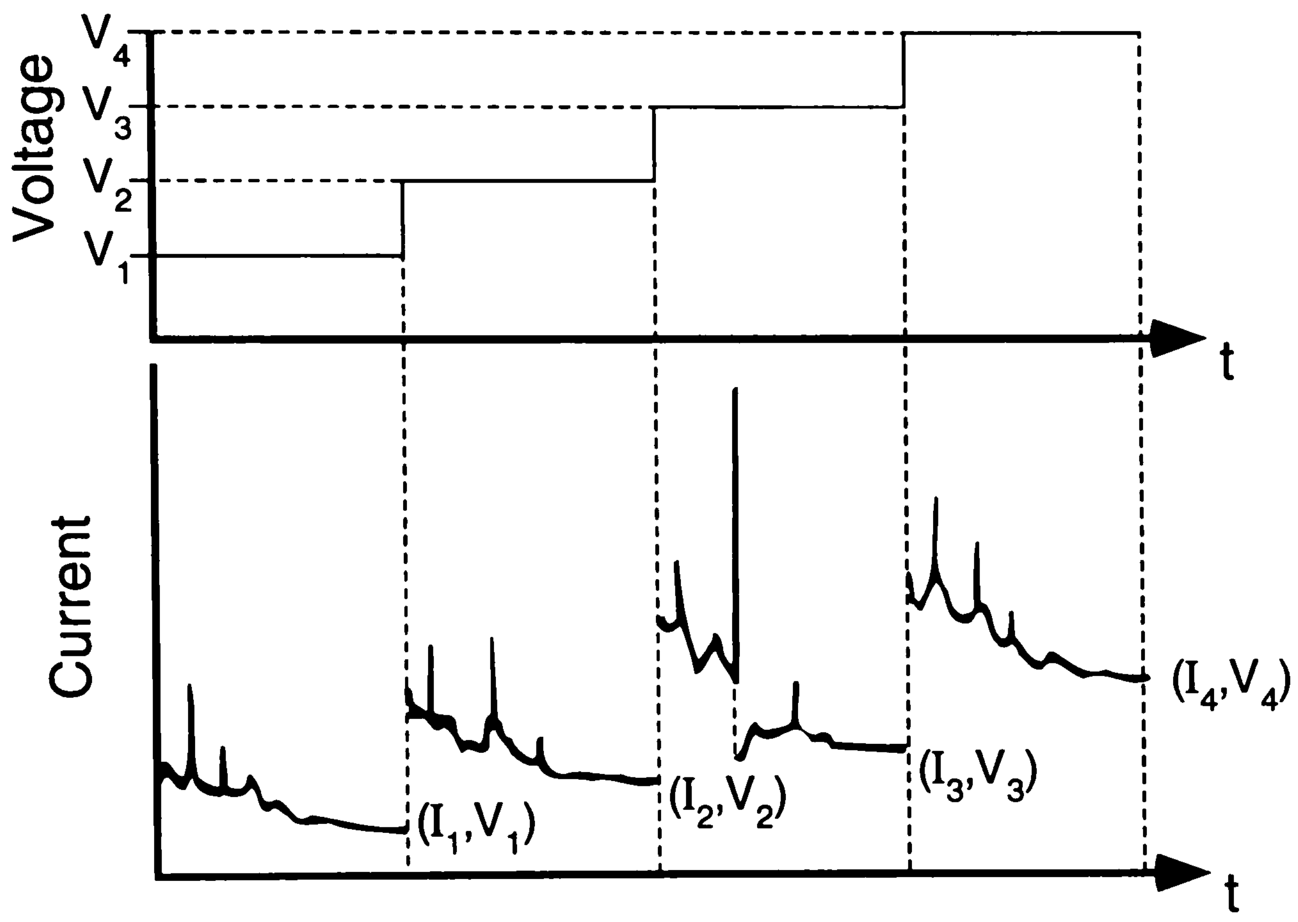


Figure 3.2 Typical Voltage and Current During Conditioning [20].

voltage device, this process must be carried out when voltage is first applied and then must be repeated in an accelerated manner each time the device is turned on after being off for even relatively short periods [20]. It has been established that loose particles in the interelectrode region can result in voltage breakdown. Some examples of this are listed below [20].

1. When voltage is applied, a surface charge density is induced on the electrodes and on particles on the surfaces of the electrodes. The particles may be drawn across the gap by the electric field as shown in Figure 3.3. If sufficient vapor is generated when the particles strike the opposing electrodes, breakdown occurs.
2. For large particles, breakdown may occur between a particle in transit and the electrode surface that it approaches.
3. When a particle strikes a surface, a crater is produced. The splash rim of material surrounding the crater may have sharp protrusions that field emit and result in breakdown.

In addition to the effect of loose particles, it has been demonstrated that insulating particles, as shown in Figure 3.4, (partly embedded in the electrode surfaces) are sites for the initiation of breakdown [20].

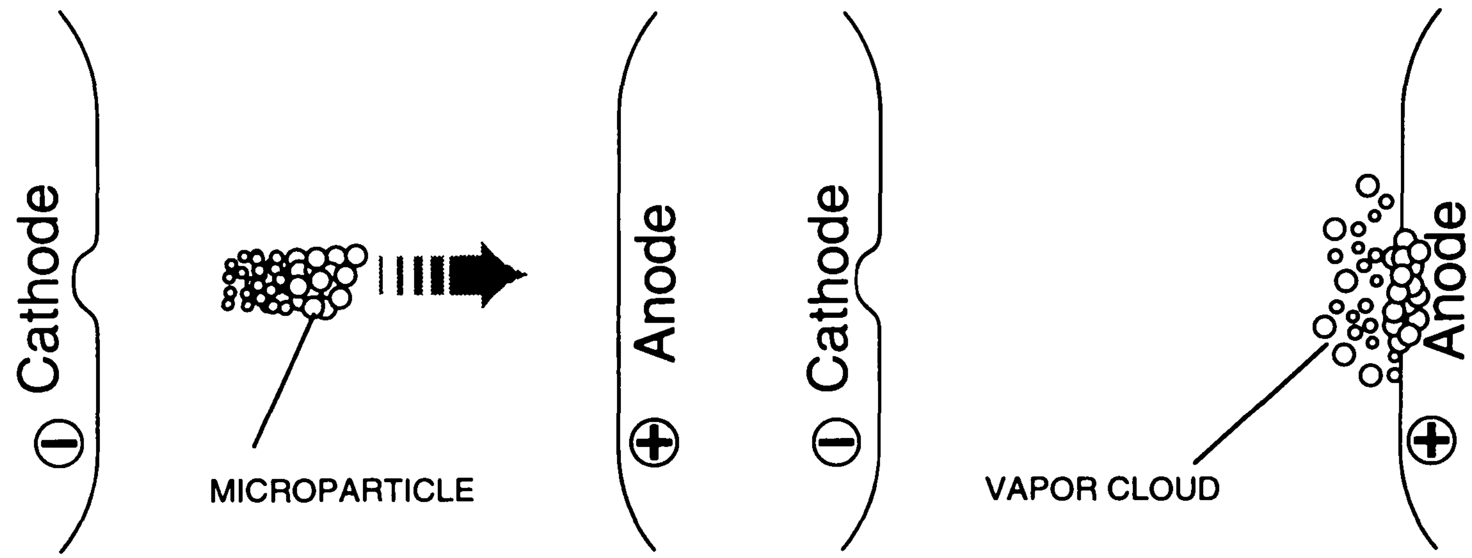


Figure 3.3 Breakdown Initiation by a Microparticle [20].

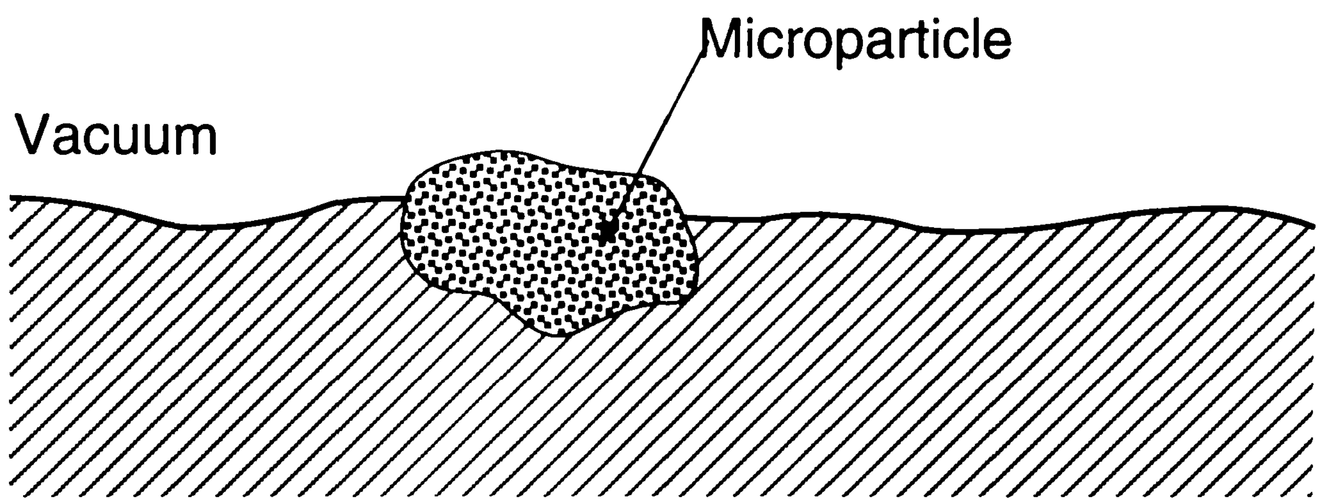


Figure 3.4 Partially Embedded Dielectric Microparticle [20].

Some examples of sources of particles that can lead to breakdown are:

1. Debris in electrodes from the manufacturing process.
2. Careless assembly procedures that cause chipping of insulators.
3. Dust from inadequate cleanliness.
4. Debris from a previous arc.

One of the weakest points in a vacuum device is the interface between a metal, insulator, and vacuum. This interface is called the "triple junction" and is illustrated in Figure 3.5. Because of electron launching mechanisms at the triple junction and surface effects on the insulator, the breakdown strength of the insulator surface is well below that of a vacuum gap or solid insulator of equivalent length [22].

When an insulator is mechanically held in place, there are voids between the insulator and the metal along the triple junction. The field enhancement factor in these voids may be as high as the relative dielectric constant of the insulator. This field-enhancement factor, coupled with those of whiskers, is thought to lead to field emission and microparticle generation [20].

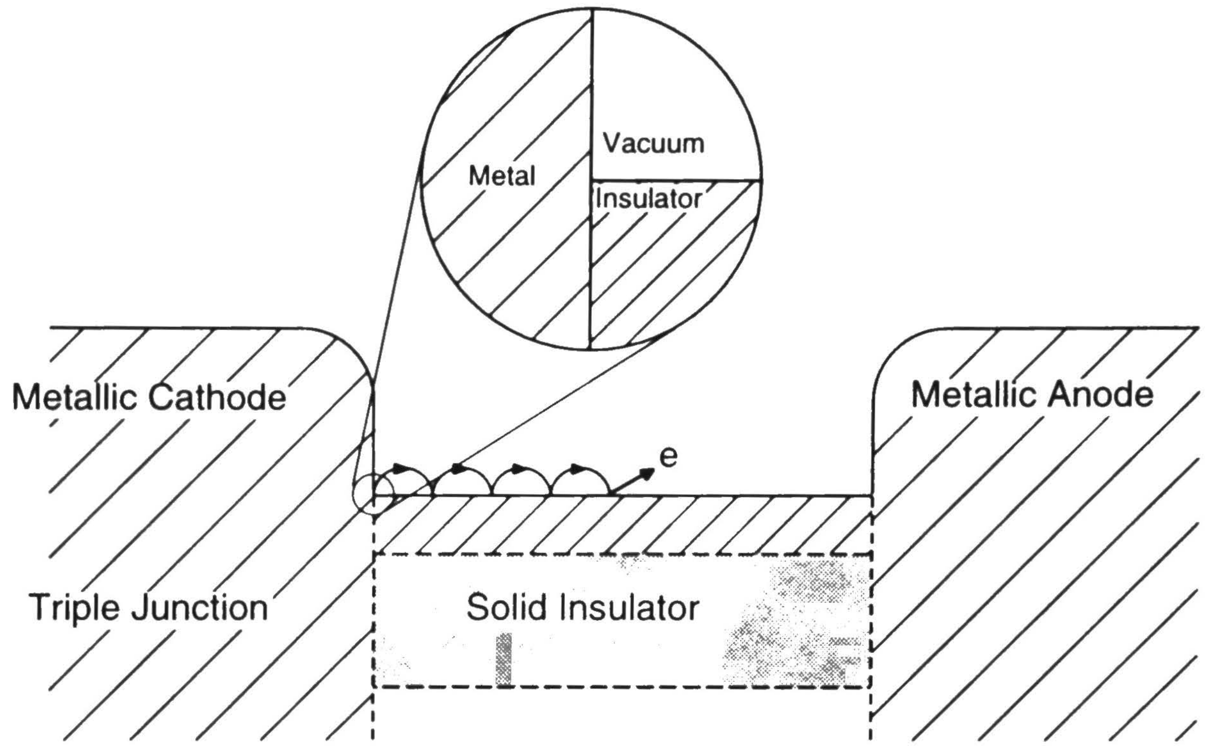


Figure 3.5 Triple Junction and Hopping Mode of Electron Travel [25].

Another factor in insulator flashover is thought to be the positive charging of the insulator in the vicinity of the triple junction. This occurs, as indicated in Figure 3.6, because field-emitted primary electrons from the triple junction strike the insulator surface causing secondary emission to occur. The secondary emission coefficient for most insulating materials is relatively high (especially if the primary electrons strike the surface at a grazing angle). The secondary emission process is regenerative in that the secondary electrons produced are accelerated by the field at the surface to produce additional secondaries [20].

The result of the secondary emission process is that the insulator surface becomes positively charged in the triple-junction region, and this increases the field and the rate of electron emission at the triple junction [20].

The final phase in the flashover process is thought to be the desorption of gas molecules from the insulator surface and subsequent ionization by the hopping electrons. These processes are indicated in Figure 3.7. The positive ions are accelerated toward the cathode and further enhance the field and increase the electron emission [20].

Some techniques used to suppress insulator flashover at the triple junction are:

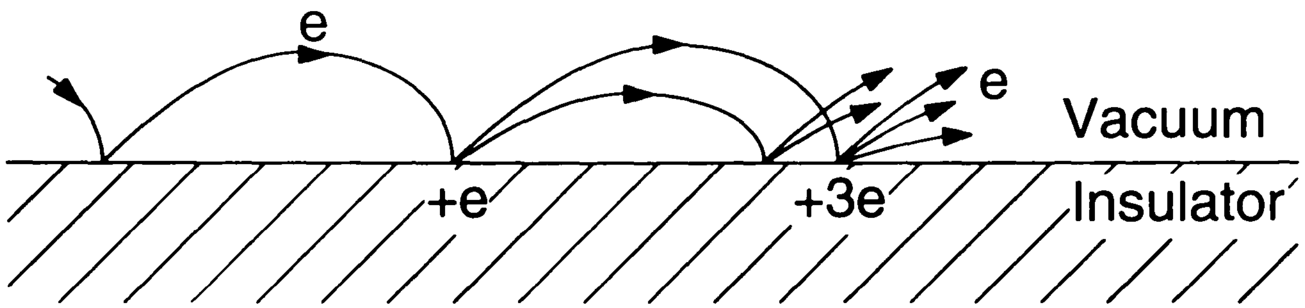


Figure 3.6 Insulator Charging by Hopping Electrons [20].

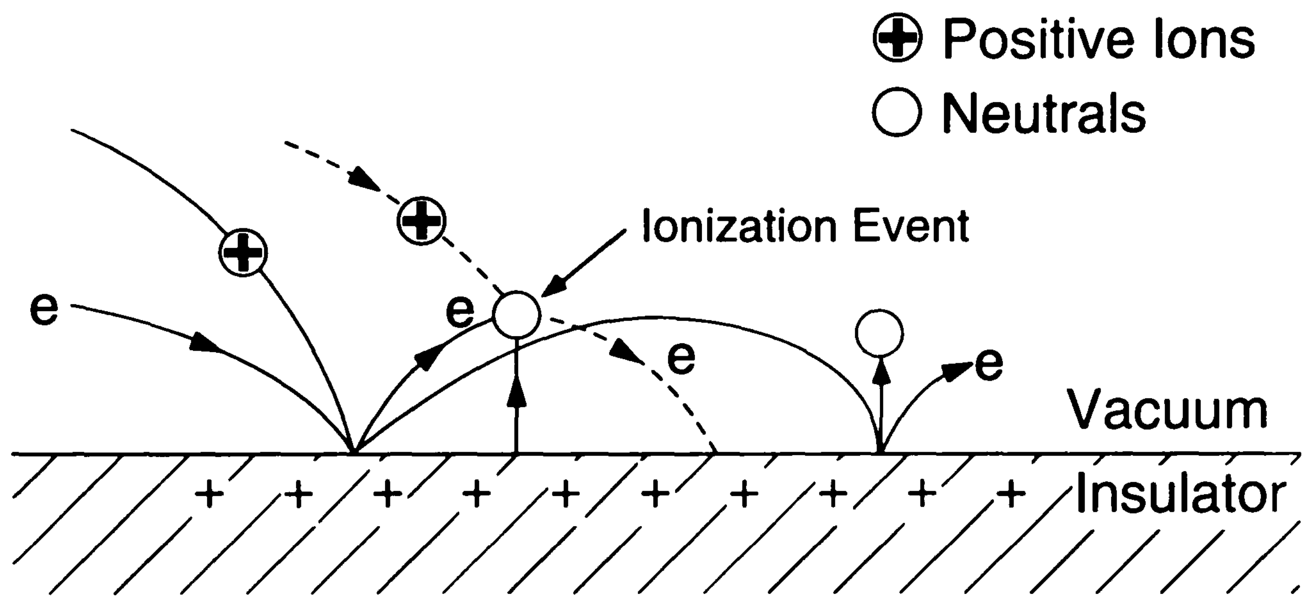


Figure 3.7 Desorption and Ionization of Gas Molecles by Hopping Electrons [20].

1. Circular shaping of the metal electrodes in order to reduce the electric field at the triple junction.
2. Shaping the angle that the insulator surface makes with the metal electrodes, in order to control the trajectories of secondary electrons.
3. Coating the insulator surface with a material that has a low secondary electron yield.

CHAPTER 4

EXPERIMENTAL SETUP

4.1 Vacuum System

Figure 4.1 shows the block diagram of the flashover system. The flashover tests were carried out in the vacuum chamber. The resistor tank was lifted so that the sample could be placed inside the chamber between the top and bottom electrode. The chamber is then mechanically pumped down to a pressure of about 0.1 Torr. A 6-inch diffusion pump filled with DC-704 silicon oil was then used to pump the chamber down to the range of 10^{-6} Torr.

The backstreaming rate of the silicon oil into the vacuum chamber was controlled by a cold trap. Backstreaming of pump oil molecules arises because, in the vapor stream from the topmost nozzle of a diffusion pump, oil molecules do not only travel in the direction of streaming to the cooled pump wall, but receive backward components of velocity due to intermolecular collisions and therefore can stream in the direction of the flashover chamber [24].

On top and out to the side of the diffusion pump is the chevron-type cold trap filled with methanol. A refrigerator with a helical

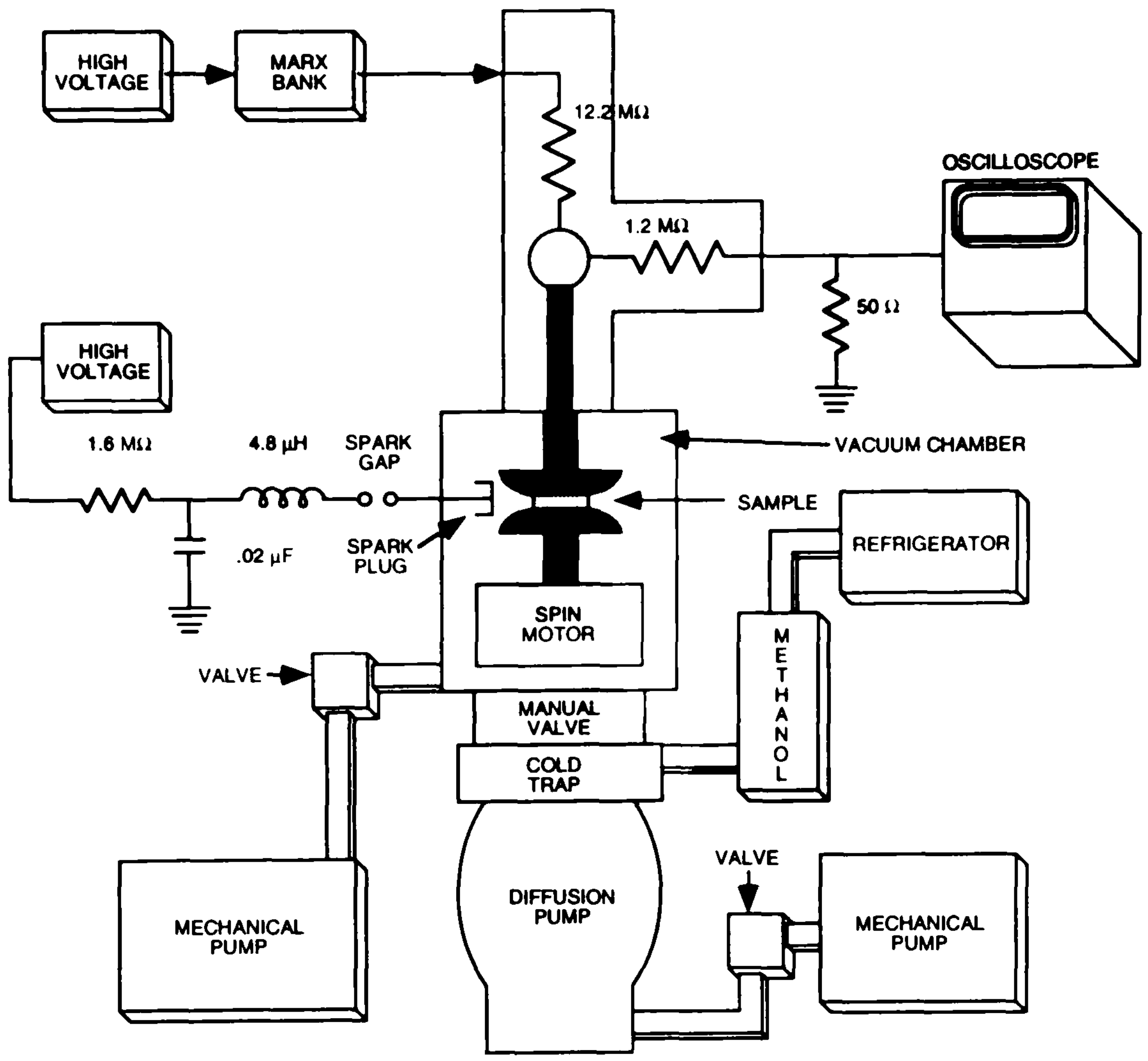


Figure 4.1 Box Diagram of the Flashover System

probe is used to cool a copper reservoir, also filled with methanol, to -40°C. This cooled methanol then flows downward replacing the warmer methanol in the cold trap and forcing it into the top of the reservoir [26]. The cold trap temperature is monitored by a thermocouple gauge.

The operating pressure obtained in this vacuum system was about 4×10^{-6} Torr. This particular pressure was used because many other investigations have shown that the vacuum flashover potential appears to be independent of pressure in the range from 10^{-4} to 10^{-7} Torr [25]. The flashover chamber was separated from the diffusion pump by a 6 inch gate valve. Use of this gate valve made it possible to replace samples easily after the flashover tests were completed.

The chamber is 10 inches in inside diameter and 12 inches high. There are four equally spaced ports located at a height of 6 inches on the chamber. Each port has a different function and is listed below.

1st port - used to observe visually the flashover inside the chamber.

2nd port - used as an inlet for the spark plug circuit cable.

3rd port - used as an inlet valve for the mechanical pump.

4th port - used as an inlet for the ion gauge tube.

A high voltage feed-through used to supply the flashover pulse to the sample is located on the lid of the chamber. This feed-through is made from a segment of RG-17 coaxial cable. The cable is approximately 1 m long and connected to the test stand via a spring loaded rotatable fixture on the end of the cable.

The pressure in the range from 10^{-4} Torr to 10^{-6} Torr is measured by means of an ionization gauge. Pressures in the range from .1 to 100 Torr are measured by a thermocouple gauge.

4.2 Sample Preparation

A Lexan insulator sample was machined from bar stock into cylinders with a diameter of 6.35 cm and a height of 1 cm. The sample circumference surface was then rinsed with distilled water, polished with Crest toothpaste (regular flavor), rinsed again with distilled water, and then polished with 1 micron size grit of alumina. Cyclohexane was used to clean the surface of the insulator because it removes most of the remnants of the polishing procedures, does not chemically attack the polymer, and does not leave any residual contamination [23].

After a sample had been polished and washed, it was inserted between two polished, uniform field, chamfered brass electrodes. The electrodes were polished with a German compound paste called "Pol." As each electrode rotated on a lathe machine, the paste was applied to remove scratches and pits. Inside the bottom electrode is an o-ring (diameter of 3.5 cm) that was formerly used to keep the sample centered on the bottom electrode. The o-ring was later glued to the sample in order to keep the sample centered. Figure 4.2 shows a sketch of the aluminum device used to center the o-ring onto the sample.

It was stated previously in this thesis that the method of joining the insulator to the electrode has a large effect on the flashover potential. Many investigators have coated the ends of the insulator with some type of conducting material (silver or carbon) and then inserted the insulator between the electrodes applying a constant pressure to the electrodes [23]. In this experiment, a pressure fit was used to insure physical contact between the electrodes and the insulator sample. However, the bottom electrode had to be machined until it was perfectly flat in order to eliminate all of the voids between the insulator and the bottom electrode.

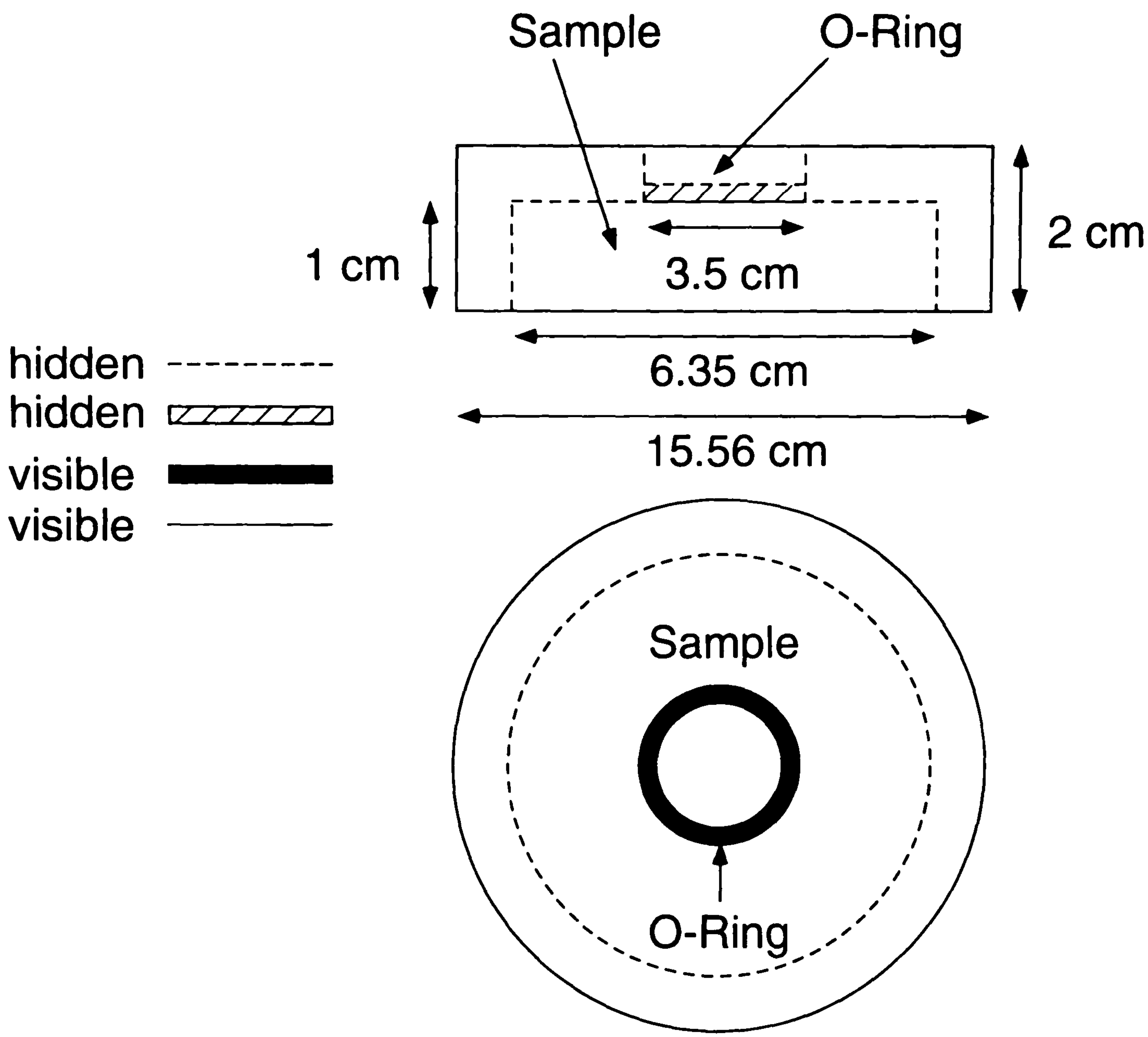


Figure 4.2 Device used to center O-Ring on sample

4.3 Control Panel

A schematic of the control panel is shown in Figure 4.3. Applying power to L1 and L2 and flipping the B switch to ON, enables the red light, which confirms that power has been applied to the circuit. Now that power has been provided, flipping the reset switch (toggle switch) will enable the yellow light which confirms that the panel relay coils have been energized. At this time, the red light will be disabled because the relay arm switches position.

In order for the mechanical pumps to pump both the flashover and the diffusion pump chambers down to a value of 0.1 Torr, valves 1 and 2 must be opened. This is done by flipping switches C and D. Whenever switches C or D are flipped to either ON or OFF, a yellow light is enabled (ON) or disabled (OFF) for each.

As soon as the diffusion pump chamber has reached a pressure of 0.1 Torr, power to its heater coil can be applied safely. Flipping the E switch to ON will energize the relay coils of both the diffusion pump and the cold trap. A yellow light will also be enabled to confirm that power has been applied to both the diffusion pump and the cold trap. If switch E is flipped to OFF, then the yellow light is disabled and no power is supplied to either the diffusion pump or the cold trap.

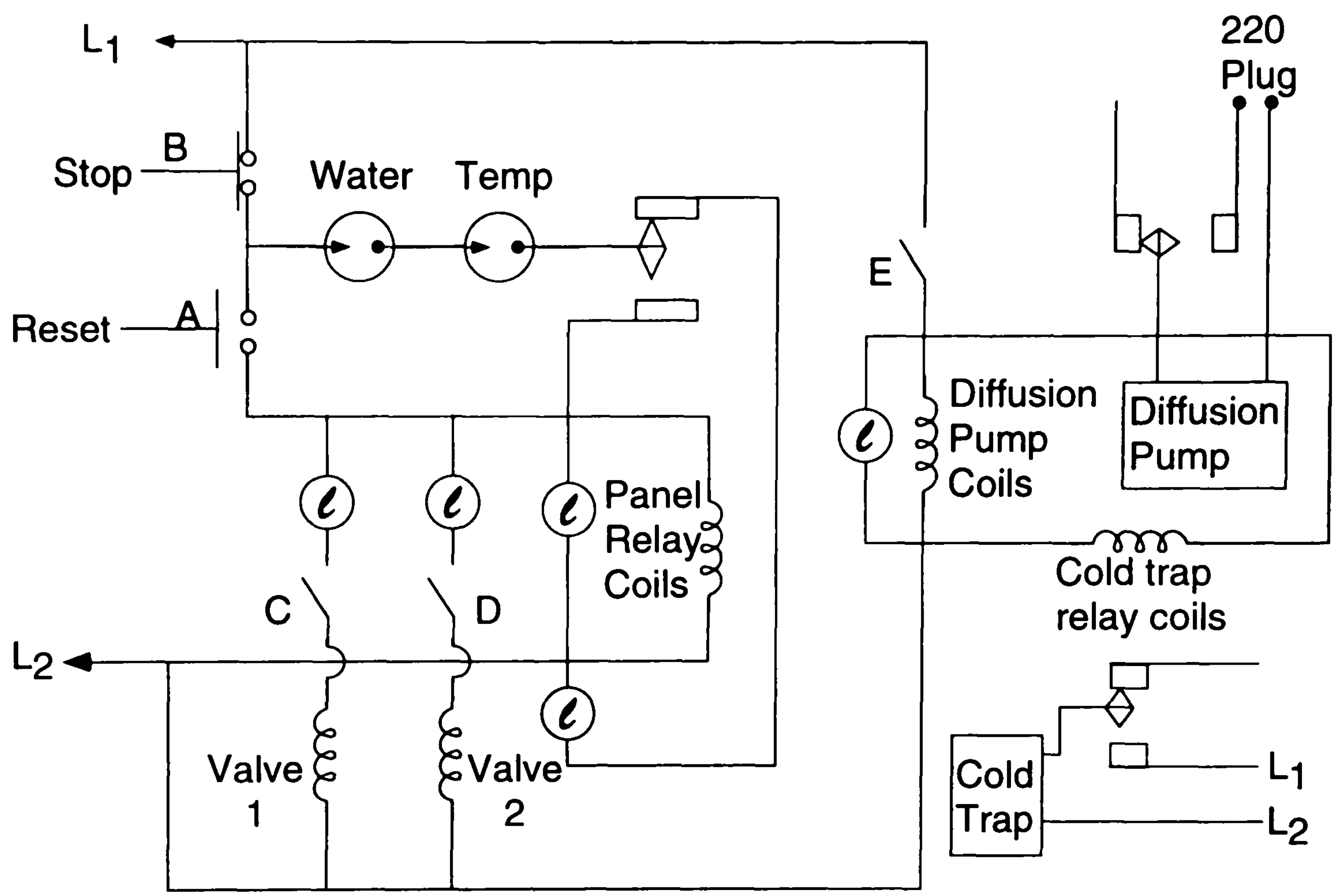


Figure 4.3 Schematic of the Control Panel

The diffusion pump and cold trap will be disabled if there is a power failure, if the diffusion pump's heater coil overheats, or water pressure becomes too low. If the diffusion pump and cold trap become disabled, then the yellow indicator light is disabled and the red indicator light is enabled.

4.4 Sparkplug Circuit

Figure 4.4 shows the schematic of the 36 kV power supply which supplies power to the sparkplug circuit shown in Figure 4.5. The power supply is made up of a transformer, high voltage diodes, capacitors and resistors. When the transformer produces a positive voltage, D1 conducts, and enables C3 and C2 to charge in series to a total voltage of V_{C1}. When the transformer produces a negative voltage, D2 conducts, and enables C1 to become charged to a voltage value of V_{C2}. The total rectified d.c voltage is :

$$V_{out} = V_{C1}+V_{C2}.$$

The sparkplug circuit is made up of a capacitor, an inductor, a resistor, a sparkgap and a sparkplug. The capacitor charges up to a specified voltage value (14 kV). The sparkgap breaks down at this voltage and the circuit delivers about 1 kA of current to the spark-plug. The inductor limits the current entering the sparkgap. The RC

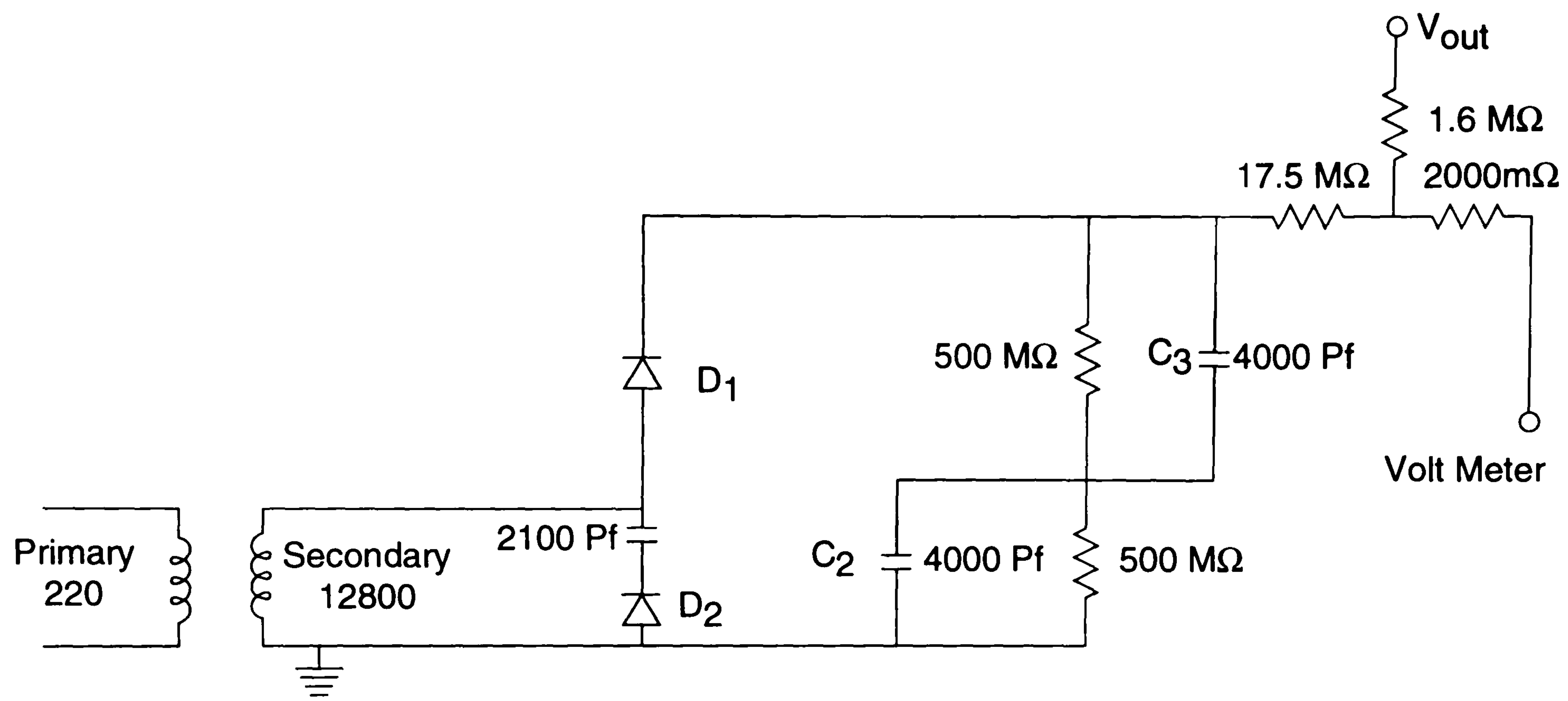


Figure 4.4 36 KV Power Supply for the Sparkplug Circuit

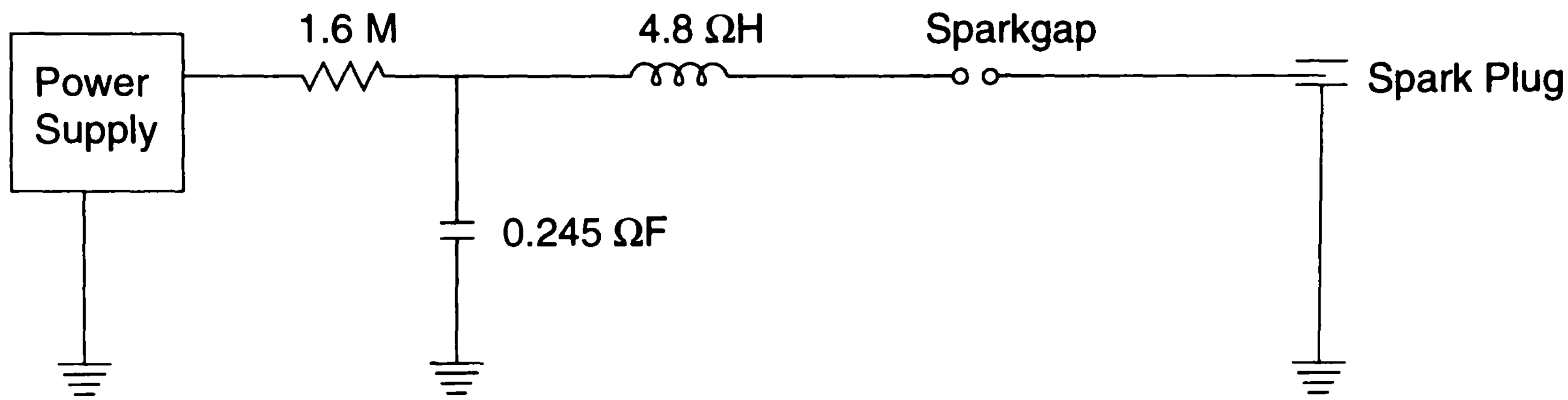


Figure 4.5 Sparkplug Circuit

charging time is about 0.4 seconds, which allows for a sparking rate of 150 sparks a minute.

4.5 Marx Bank Generator

The high voltage delivered to the sample was supplied by erecting the eight stage Marx Bank shown in Figure 4.6. The eight capacitors are first charged in parallel to the desired voltage (each capacitor is rated to withstand 40kV) and then discharged in series through an array of spark gaps to achieve a much higher voltage. A typical output voltage pulse from the Marx bank is shown in Figure 4.7.

The voltage supply for the Marx bank is shown in Figure 4.8. The transformer, diodes, capacitors and resistors are all housed inside an oil filled casing. A safety switch allows the coil of the relay to be energized. Once the relay coil has been energized, its arm changes position and power is applied to the transformer. As the transformer swings positive, D1 conducts and C1 is charged. As the transformer swings negative, D2 conducts and C2 is charged.

The total rectified d.c. output voltage is:

$$V_{out} = VC_1 + VC_2.$$

In order for the spark gaps to fire, an Ealing brand spark source is used to generate the initial spark on a sparkplug. The sparkplug

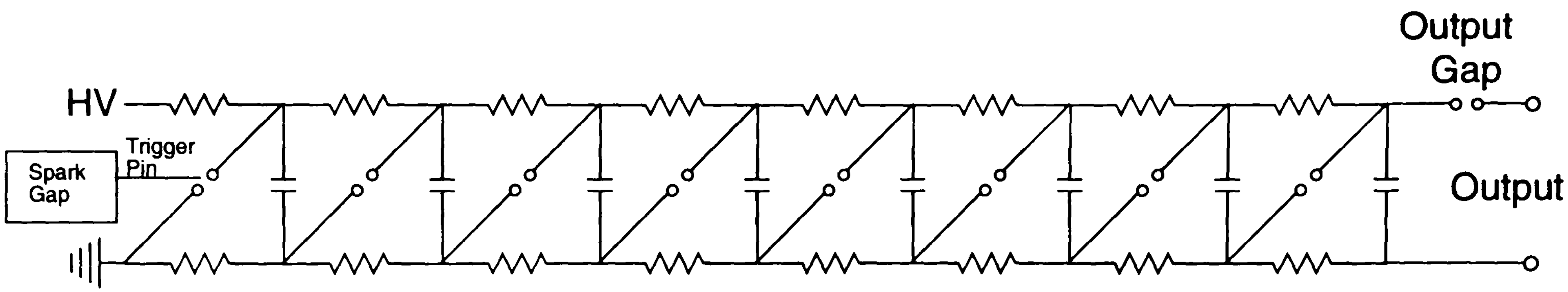


Figure 4.6 Schematic of Marx Bank Generator

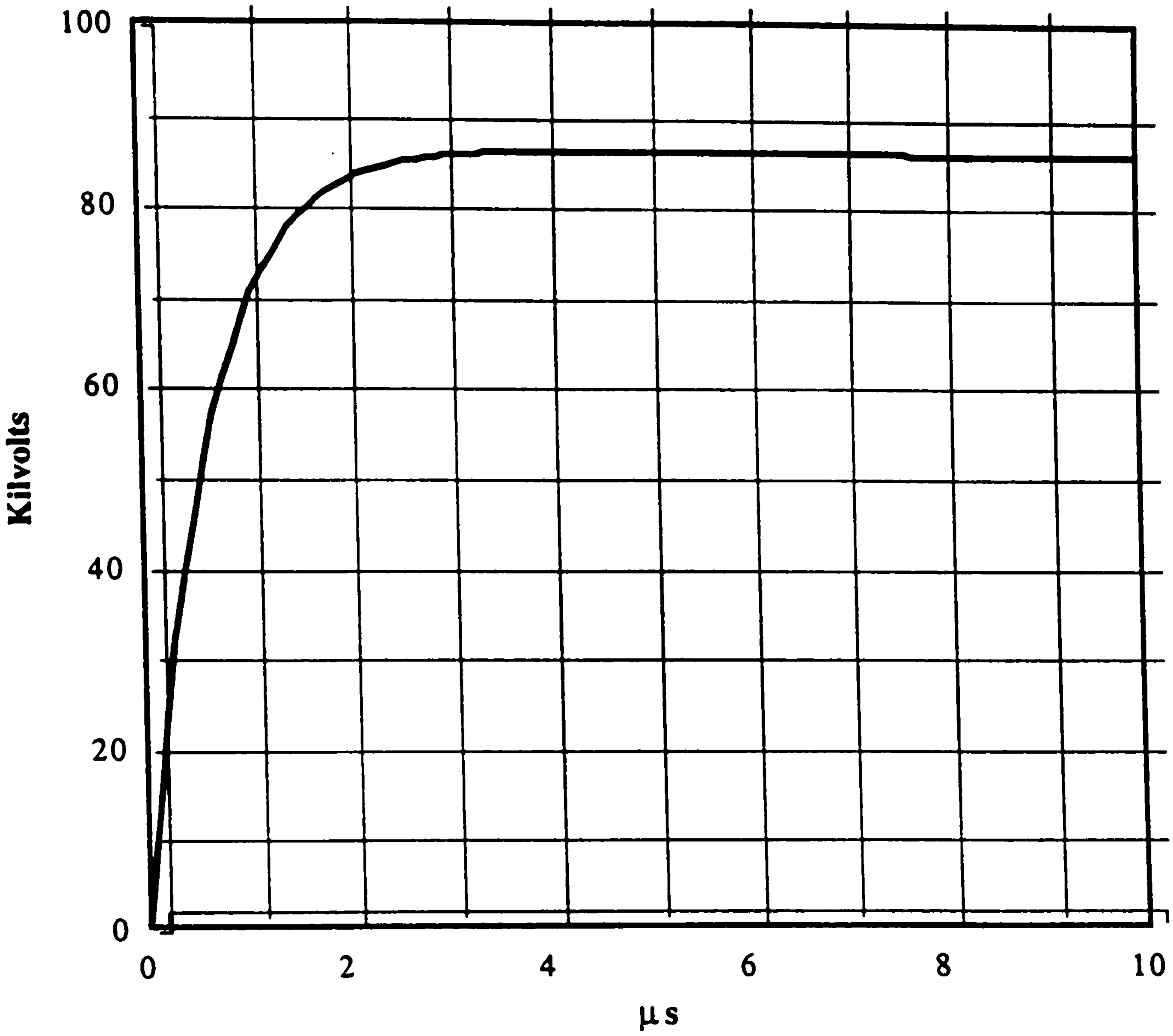


Figure 4.7 Output Voltage Pulse of the Marx Bank

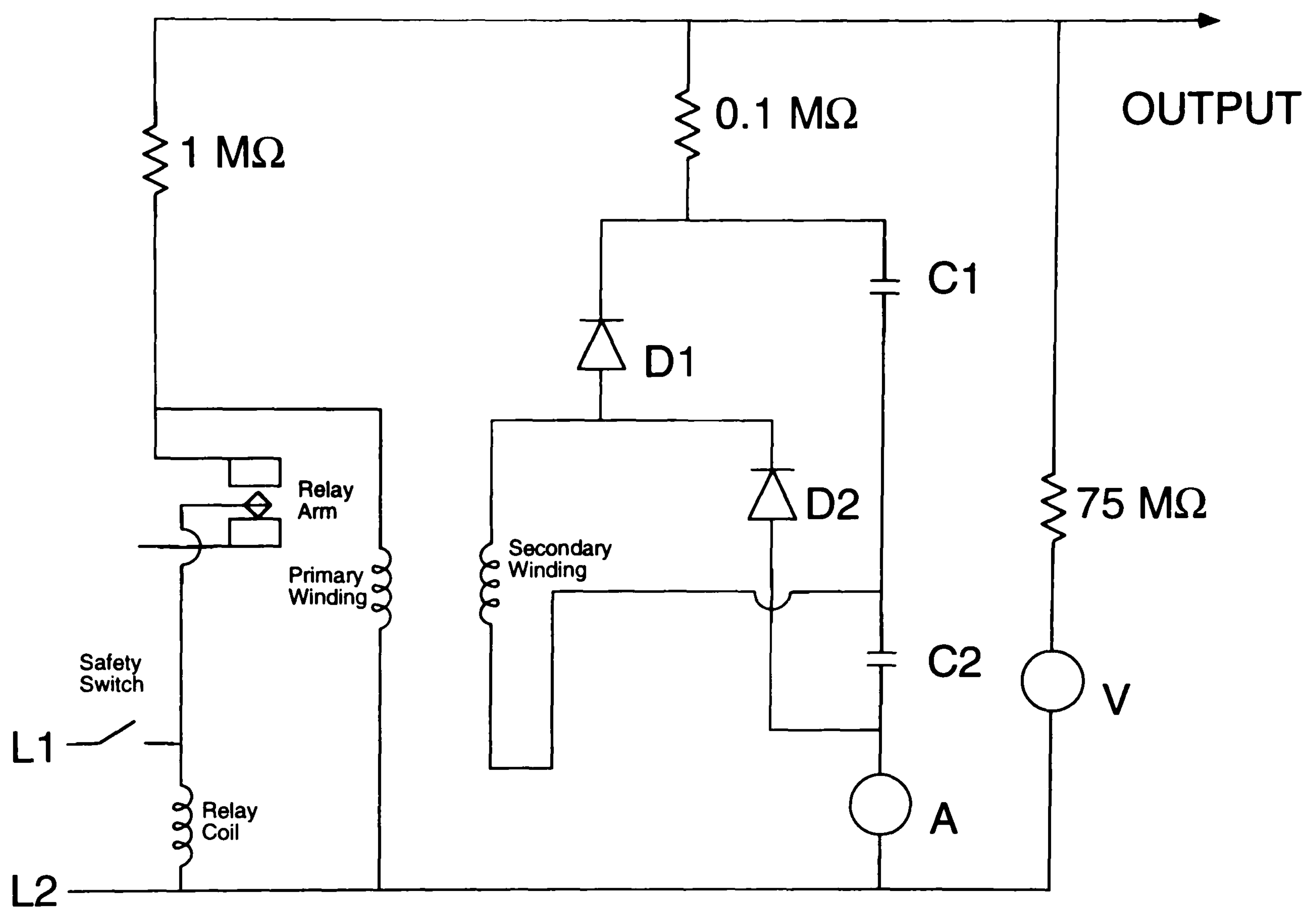


Figure 4.8 Voltage supply for the Marx Bank Generator

is then used to trigger the first sparkgap. Once the first gap has been triggered, the voltage across the next gap will double. This increase in voltage across the second sparkgap is enough to cause an arc through it, which creates a bigger voltage across the next gap. Each succeeding sparkgap will also arc in this manner. The resulting voltage for an N-stage Marx bank is almost N times the charging voltage.

The Marx bank is housed in an aluminum cylinder with a lucite tube inner lining. Eight ceramic capacitors are fitted vertically between two parallel lucite plates and held in place by rubber grommets. The capacitors expand and contract slightly when discharged and would eventually crack if mounted rigidly. Electrical contact with the capacitors is provided by brass screws connected to threaded holes in the sides of the capacitors. These screws also provide the connection points for the charging resistors and spark-gaps. The sparkgaps are aligned vertically such that the UV radiation produced by the arc from one gap will help to trigger the next gap [26].

The effective capacitance of an n-stage Marx bank is :

$$C_n = C/n \ ,$$

where C is the capacitance of each of the n capacitors. For this particular Marx bank C= 4700 pF which gives an effective capacitance of C_8 = 587 pF. For a charging voltage of 40 kV, the Marx bank could theoretically produce 320 kV; however, about 20% of the voltage is lost in the transfer circuit [26]. For this experiment, the Marx bank was only charged to produce approximately 180 kV.

4.6 Voltage Divider Circuit

Figure 4.9 shows the voltage divider circuit that is used to measure high voltages with an ordinary oscilloscope. The capacitance of the sample was measured to be 60 pF and the effective capacitance of the 8-stage Marx bank is 587.5 pF. The 1.2 MΩ resistor in series with the 50 Ω terminating resistor gives a divider ratio of 24000 to 1. The 12.2 kΩ resistor is used to set the risetime of Marx bank output voltage. The voltage that is displayed on the oscilloscope is shown in Figure 4.10.

The resistor strings are housed in a 10 inch diameter aluminum tube and backfilled with 80% N_2 and 20% SF_6 during flashover test. The N_2 is allowed to slowly flow through the tube to replace air and water vapor, then a small amount of SF_6 added. SF_6 has a high electron attachment cross section and suppresses electrical breakdown from the resistor strings through the intervening gas to the outer wall [26].

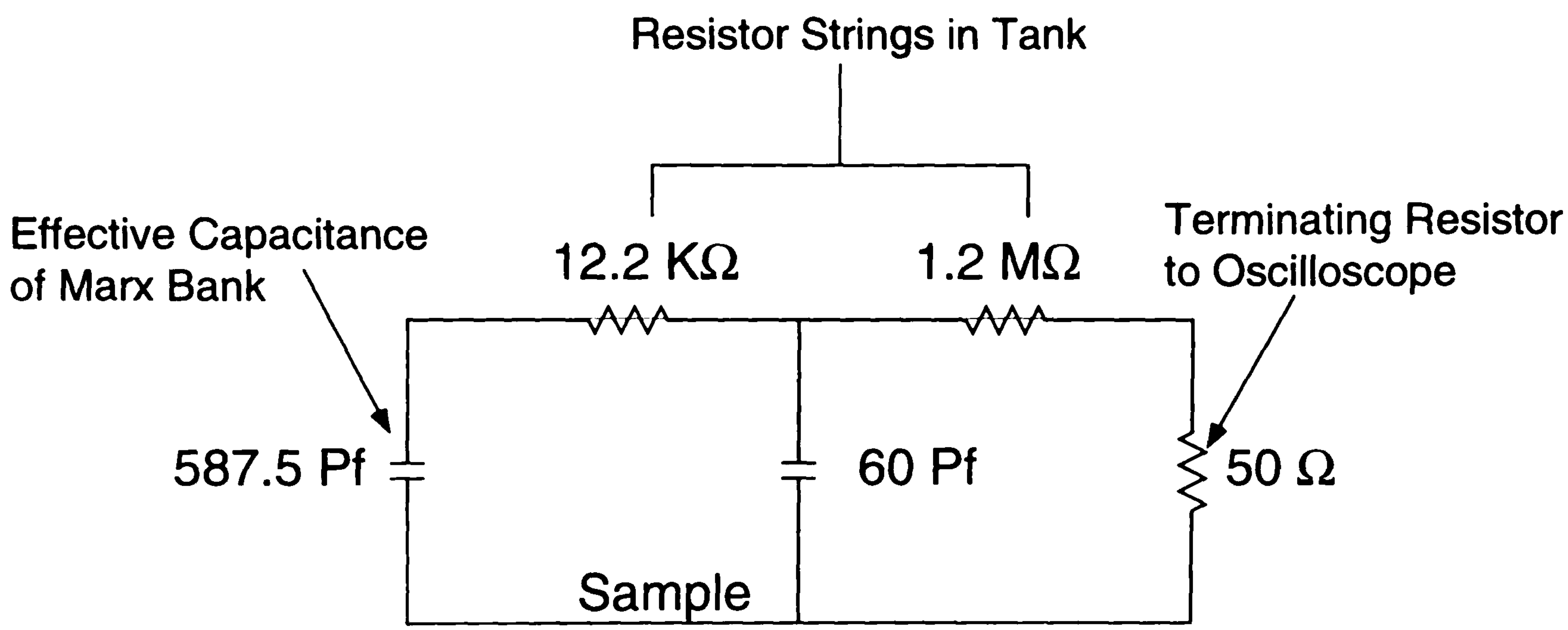


Figure 4.9 Equivalent circuit of flashover system
(including the voltage divider circuit)

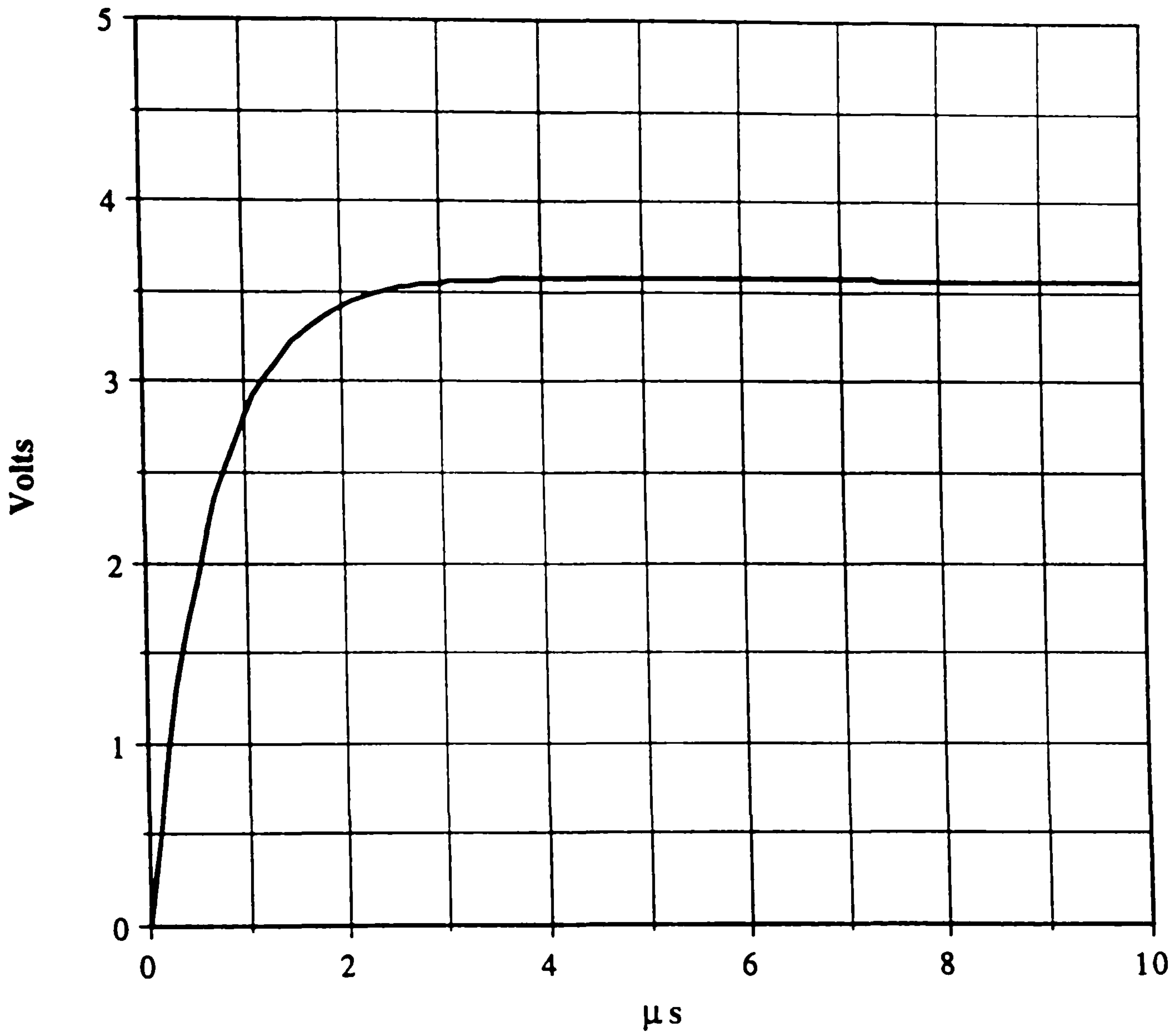


Figure 4.10 Output Voltage Waveform on the Oscilloscope

The resistor strings are made from standard 2 watt carbon composition resistors. They are soldered together to form long strings and wrapped in plastic tubing to minimize breakdown along the chain. At the junction of the resistor strings and the feed through cable to the flashover chamber there is a round 3 inch in diameter aluminum ball. This ball minimizes the electric field that is usually generated from electrical wire forming a corner.

CHAPTER 5

EXPERIMENTAL RESULTS

The results of this experiment have shown that an uncoated Lexan insulator sample (1 cm in thickness and .637 cm in diameter) has a lower breakdown voltage than a similar sample coated with the by-products of a jet engine sparkplug.

Figure 5.1 shows that an uncoated Lexan sample will break down at about 24 kV. If the same sample is exposed to the by-products of an airplane sparkplug as it discharges approximately 200,000 times, the breakdown voltage increases to approximately 140 kV (Figure 5.2).

The exact number of discharge shots were hard to count because the sparkplug had a varying discharge rate. If the sample was exposed to less than 100,000 discharges from the sparkplug, the breakdown voltage varied linearly according to the amount of coating on the sample. The highest breakdown voltage after about 100,000 discharges from the sparkplug was approximately 96 kV (Figure 5.3).

After the sample had been coated and its breakdown voltage recorded, an additional sample was placed in the bottom of the chamber. This additional sample had been exposed to the outside air

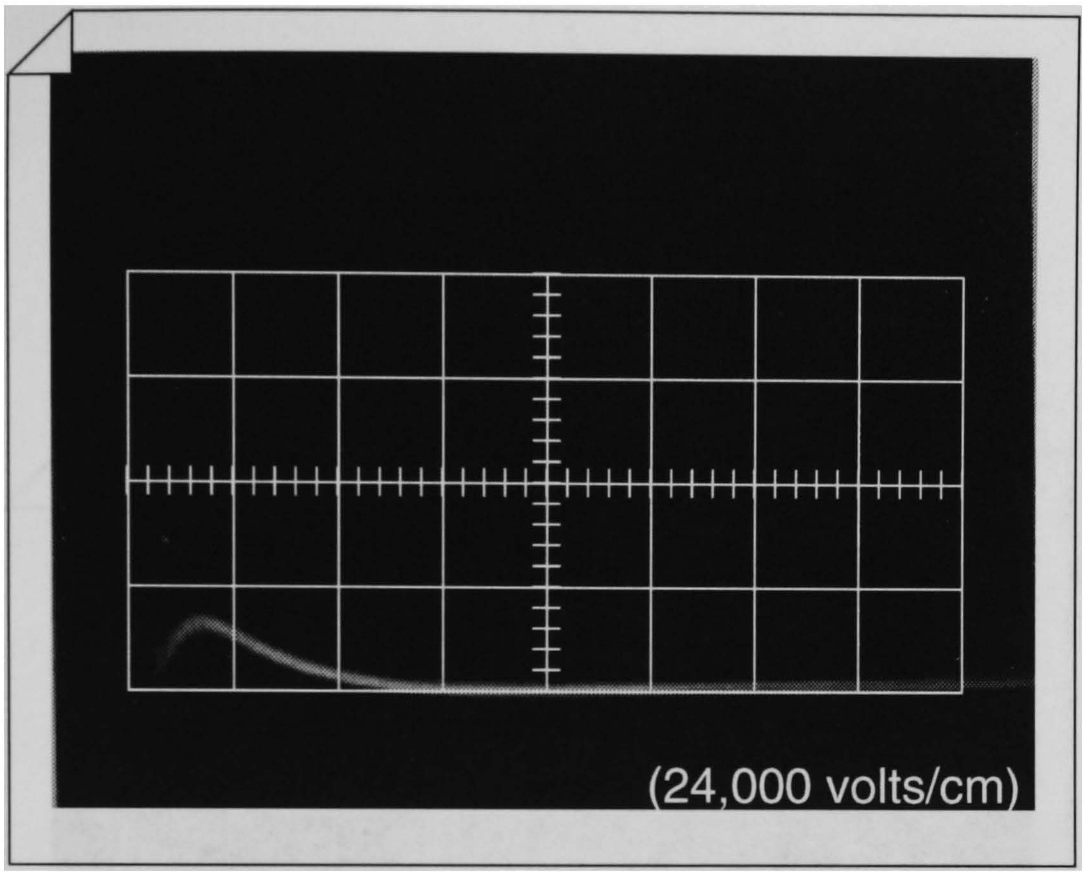


Figure 5.1 Breakdown voltage of an uncoated sample.

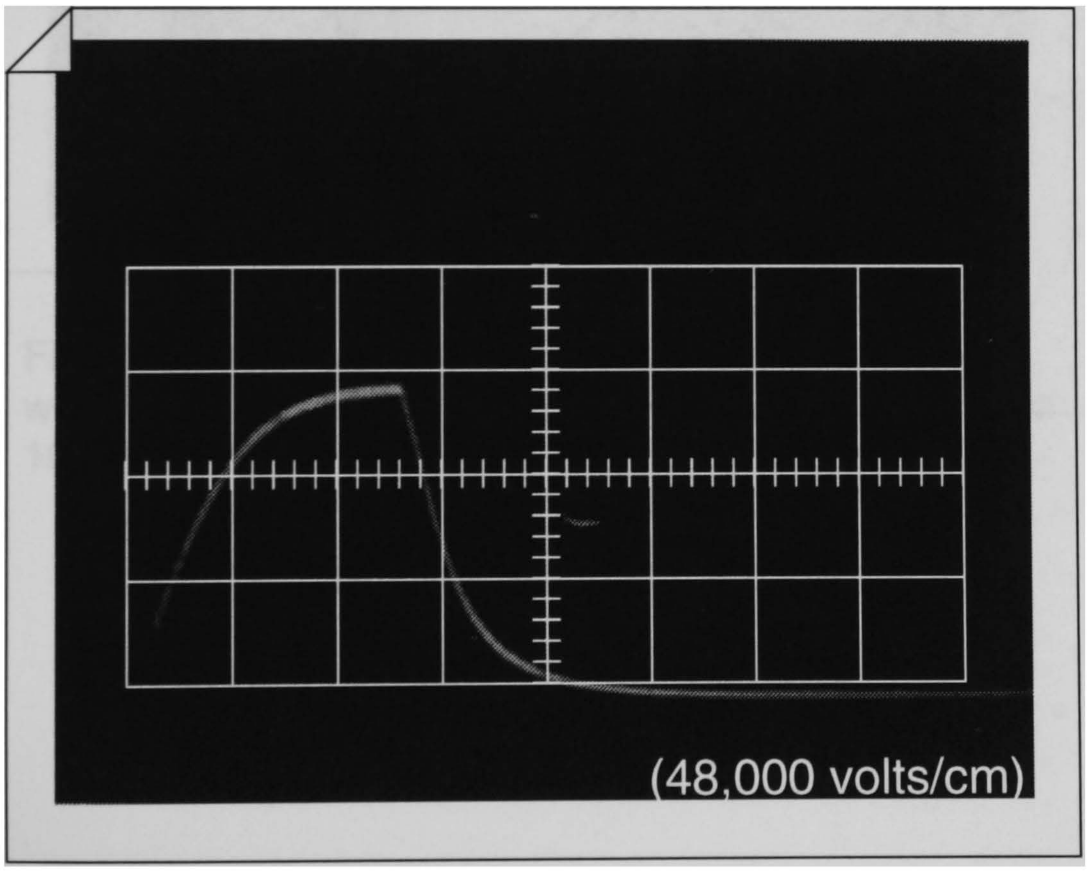


Figure 5.2 Maximum Breakdown voltage of a sample exposed to 200,000 spark plug discharge shots.

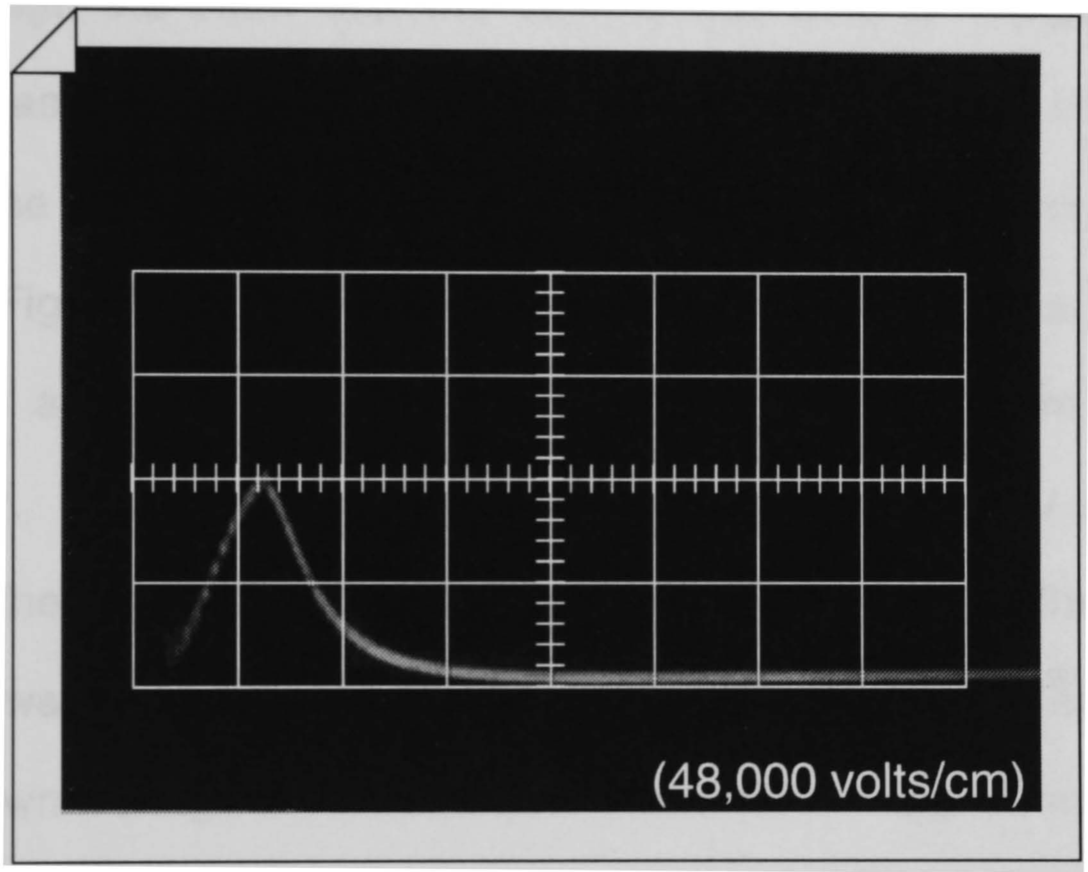


Figure 5.3 Voltage breakdown of a sample coated with the by-products of a sparkplug that has discharged 100,000 times.

and would provide the proper amount of moisture that was needed in order for the second coating to adhere. It has already been discussed that the sample that had been coated would have dried out in the vacuum chamber [26]. During the second coating, the sample was exposed to another 100,000 discharges from the sparkplug. Figures 5.4 through 5.8 show that the sample was able to withstand voltages as high as 130 kV before finally breaking down at 140 kV (Figure 5.2). The next sequential shots continuously broke down at about 96 kV (Figure 5.9). The sample was coated a third time, but this time the additional sample was not placed in the bottom of the chamber. The sample continued to break down at 96 kV (Figure 5.10). During the coating of the sample for the fourth time, the additional sample was again placed in the bottom of the chamber and the breakdown voltage of the sample increased to approximately 130 kV (Figure 5.11). Table 5.1 shows a summary of the experimental results.

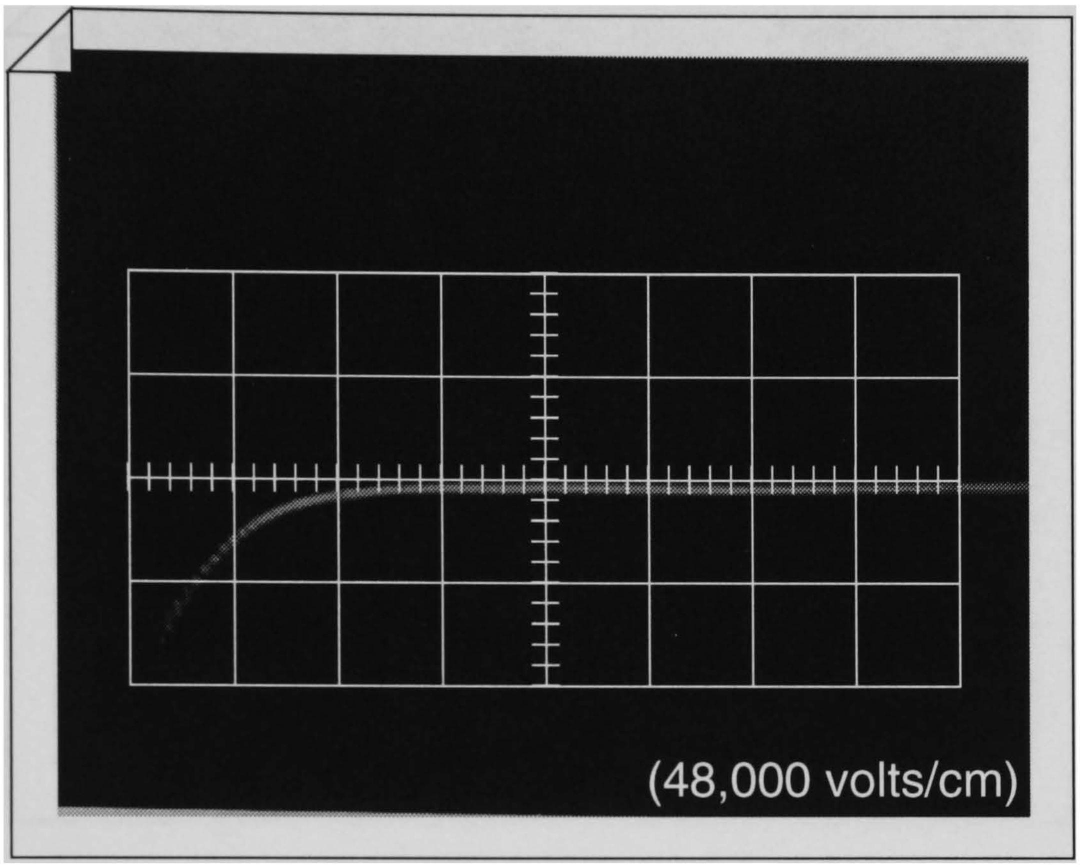


Figure 5.4   96 KV Across a twice coated sample.

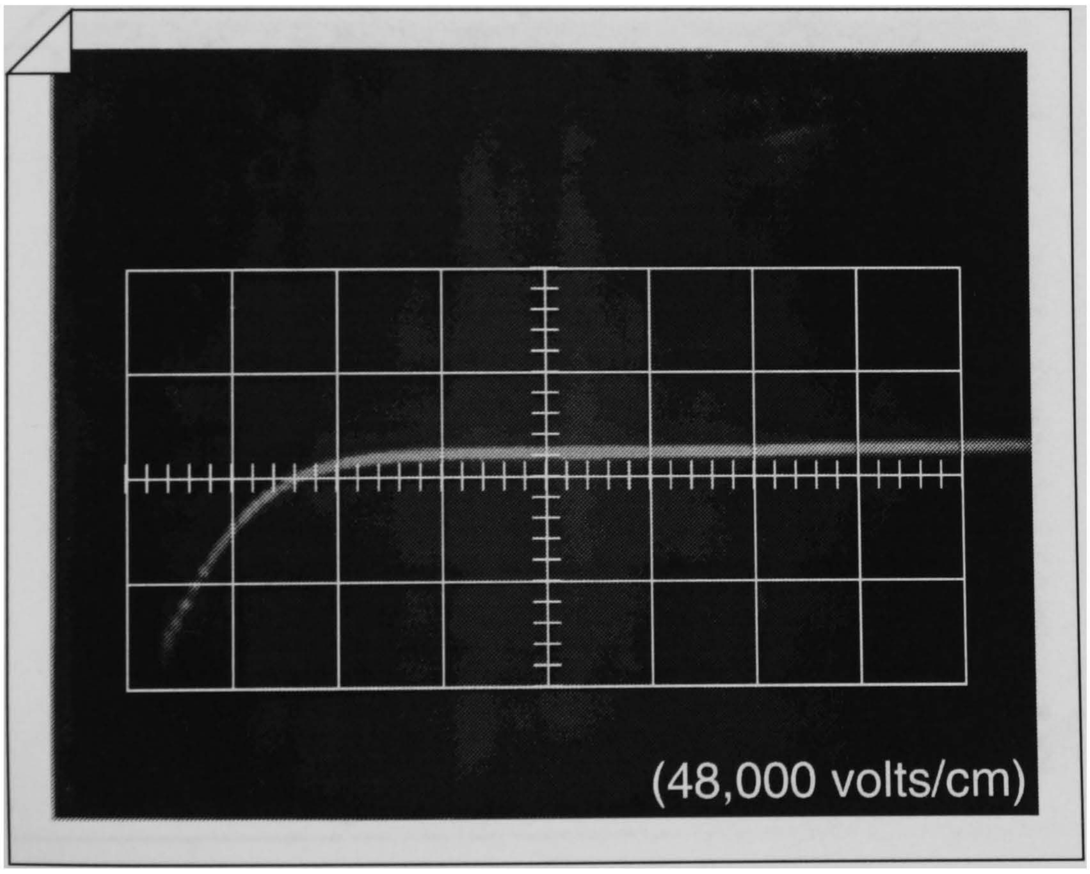


Figure 5.5   105.6 KV Across a twice coated sample.

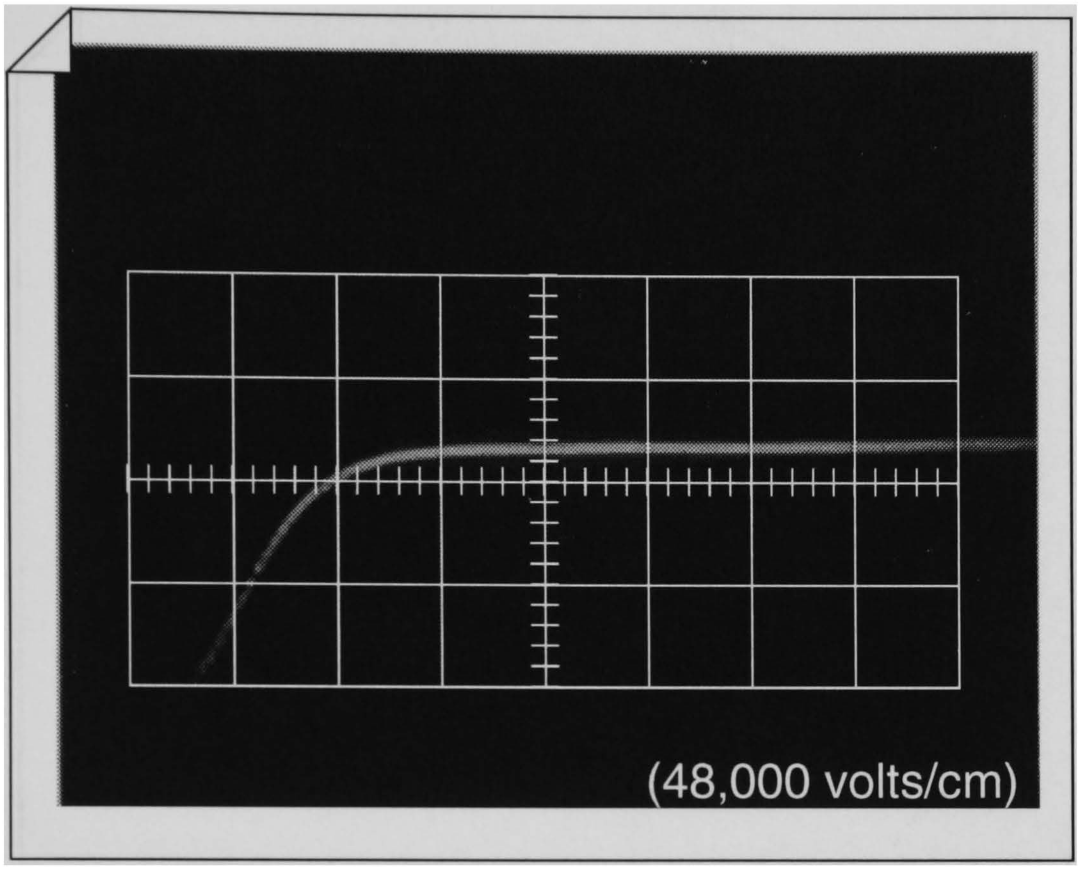


Figure 5.6 108 KV Across a twice coated sample.

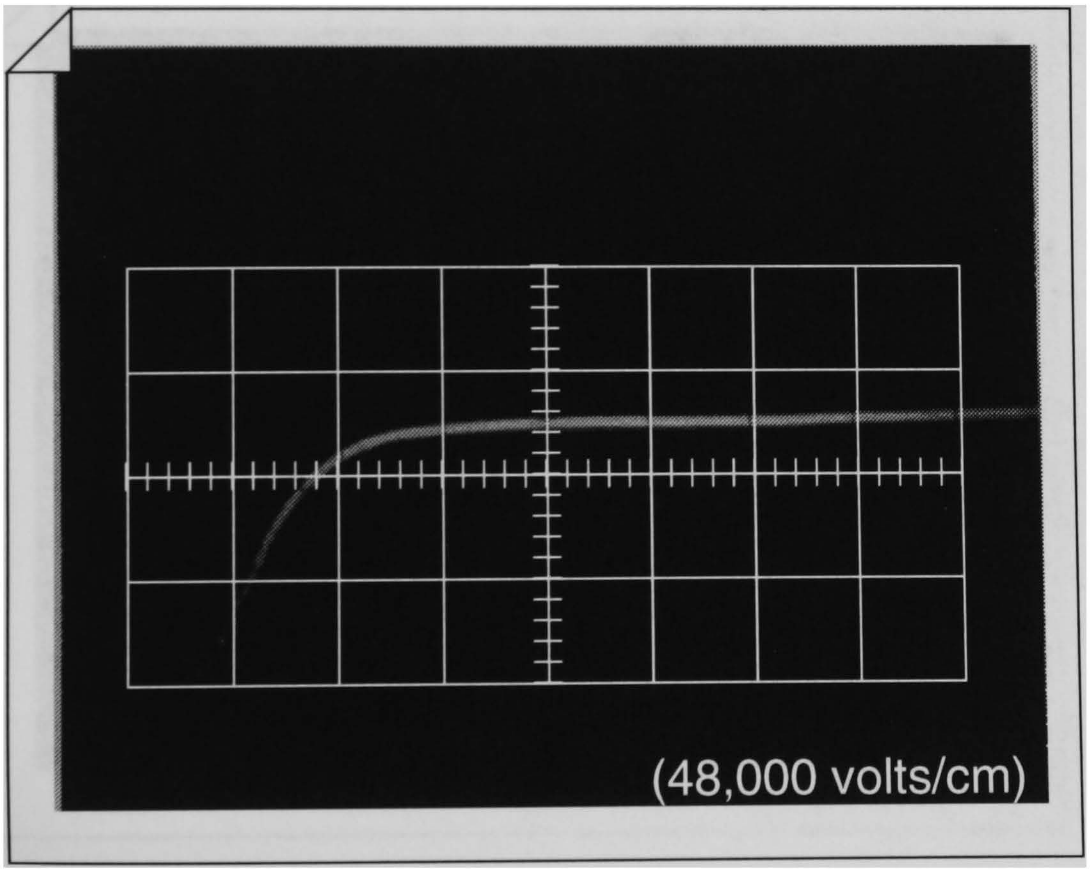


Figure 5.7 120 KV Across a twice coated sample.

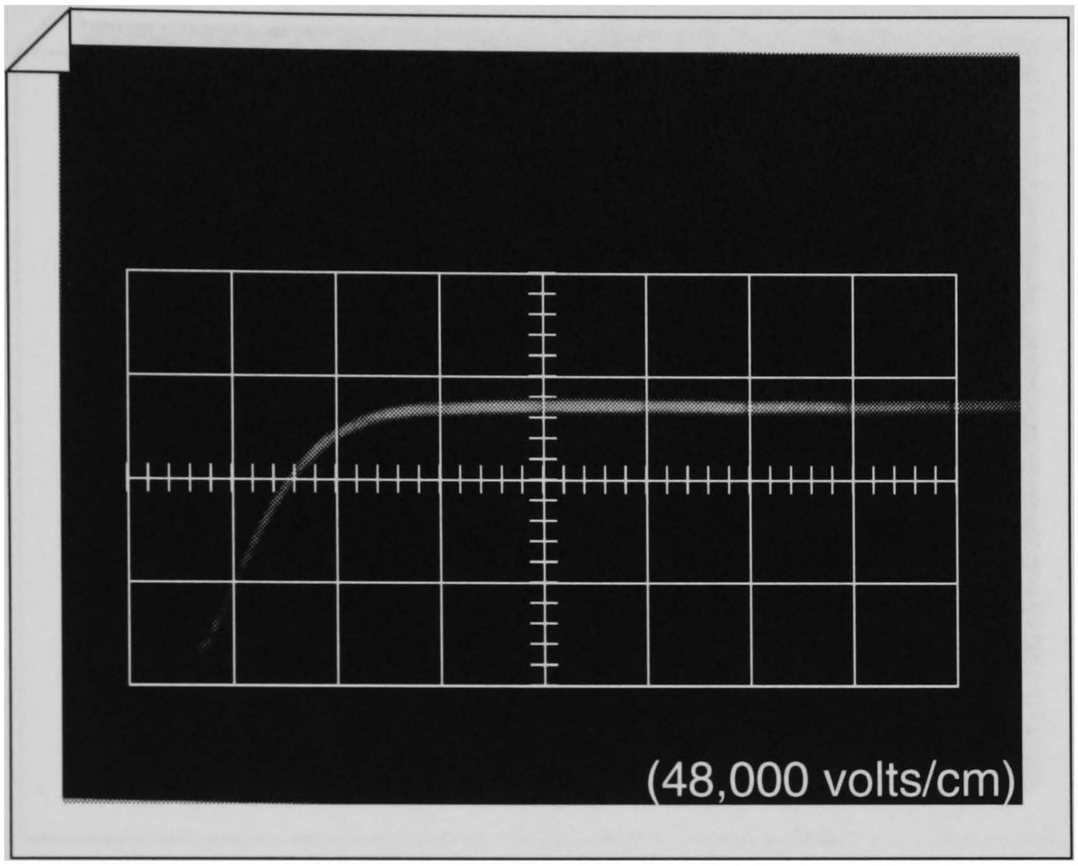


Figure 5.8 130 KV across a twice coated sample.

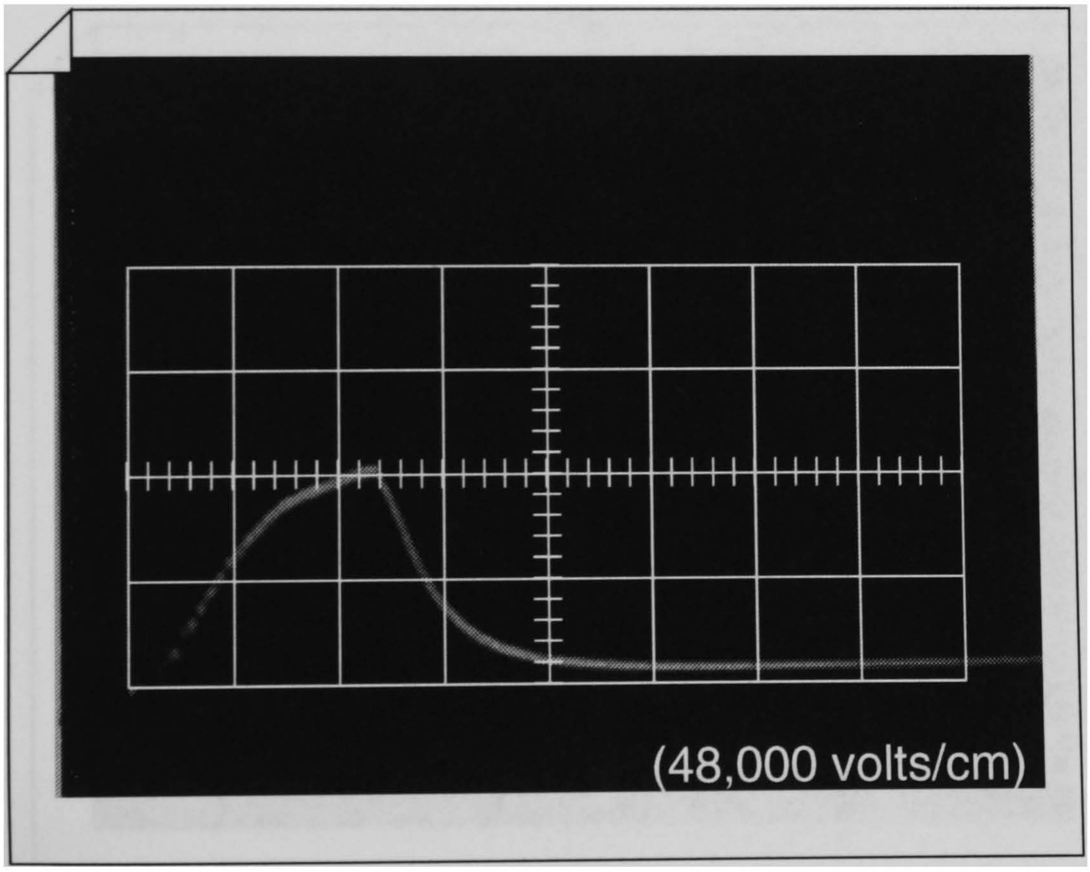


Figure 5.9 Typical Breakdown Voltage of a twice coated sample after previously breaking down at 140 KV.

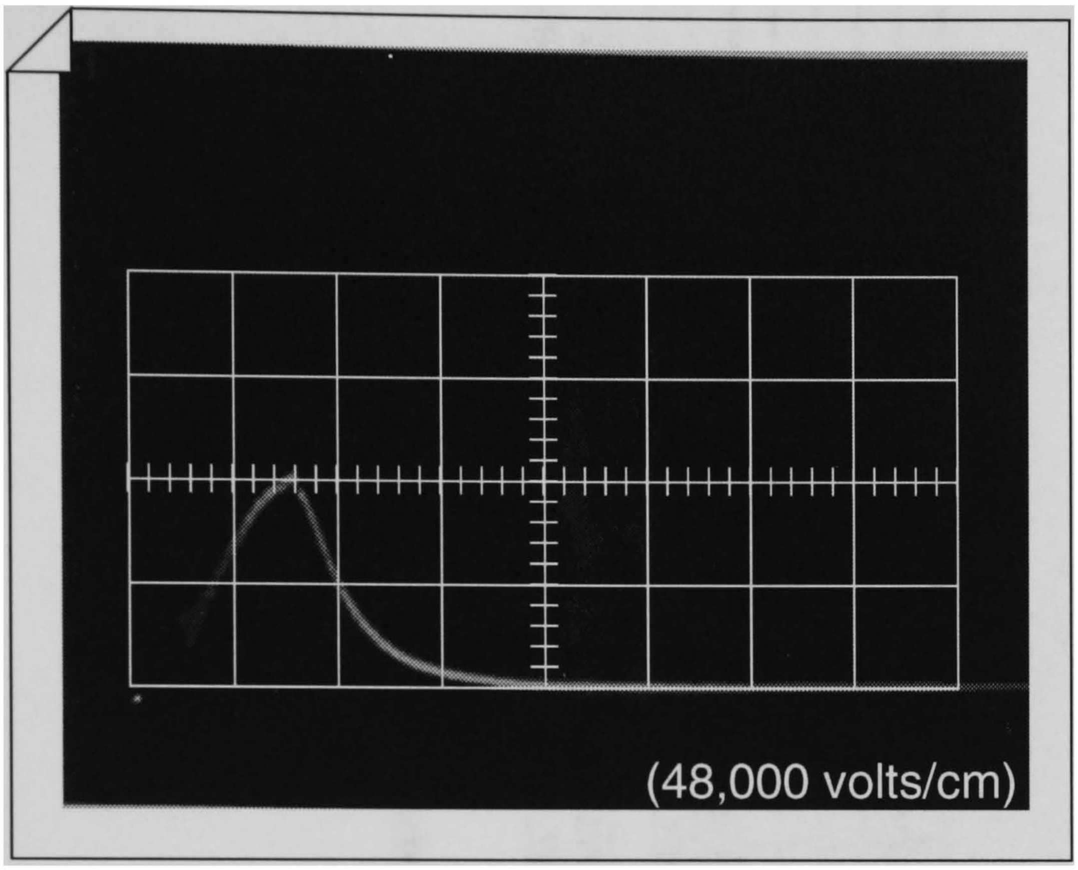


Figure 5.10 Voltage Breakdown of a sample coated without moisture.

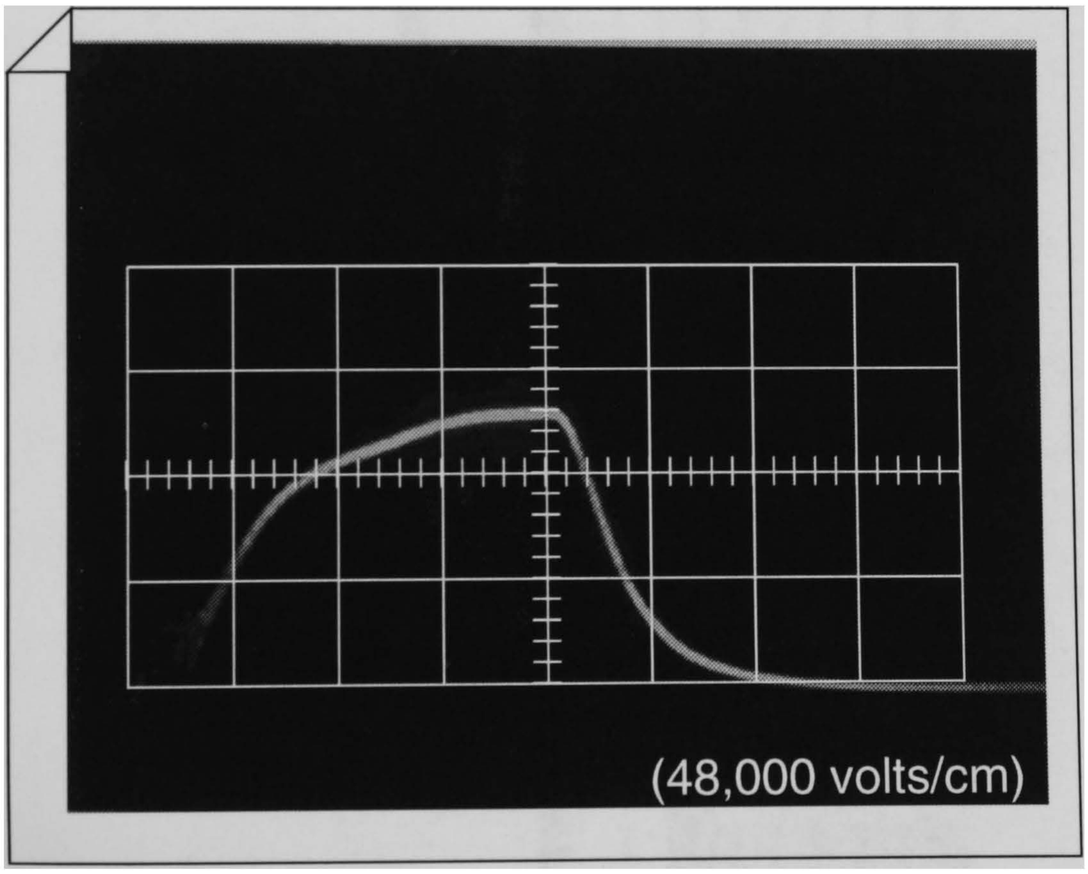


Figure 5.11 Voltage Breakdown of a sample coated 4 times with moisture.

Table 5.1 Summary of experimental results

SAMPLE TYPE	MOISTURE	NO. OF SPARKPLUG DISCHARGE SHOTS PER COATING	TOTAL NO. OF COATINGS	NO. OF COATINGS AFTER PREVIOUS BREAKDOWN	BREAKDOWN VOLTAGE
conditioned	doesn't matter	N/A	N/A	N/A	98 KV
polished	no	doesn't matter	doesn't matter	doesn't matter	24 KV
polished	yes	less than 180,000	1	doesn't matter	96 KV
polished	yes	greater than 250,000	1	doesn't matter	96 KV
polished	yes	200,000	1	none	140 KV
polished	yes	200,000	2	1	133 KV
polished	yes	200,000	3	2	133 KV

CHAPTER 6

CONCLUSIONS

This thesis has not only shown that the flashover potential of a lexan insultor in vacuum will increase if it is exposed to the by-products of a jet engine sparkplug, but it has also shown that even after the lexan insulator has broken down, the same sample can be coated again and again and will reach about 95% of its flashover potential before finally breaking down.

In order to show that the coated sample has a higher breakdown voltage than the uncoated sample, many factors have to be taken into consideration. The first factor is that the sample and the top and bottom plates of sample holder must be completely cleaned and polished until they are void of any scratches or indentions. The sample must also lie completely flat between the top and bottom plates of the sample holder. There must not be any small spaces between the sample and the two plates. After the sample holder is placed inside the chamber, great concern must be made to make sure that the discharge of the sparkplug will actually illuminate the sample. The sample holder should also be checked to ensure that it will rotate the sample continuously.

After the chamber is isolated and sealed, the pressure has to reach 10^{-6} Torr and the sample must be allowed to outgas, but not to the point that all of the sample's moisture is removed. There has to be a certain amount of moisture in the chamber in order for the coating to adhere.

Next the exact amount of coating must be applied to the sample. Too little or too much coating will cause the sample to break down at a lower voltage. After the exact amount of coating is applied to the sample, the entire system must be checked to ensure that only the sample is breaking down and not the resistor strings, the top plastic frame of the sample holder or some other part of the system that is capable of breaking down at high voltages. The voltage pulses fired from the Marx bank have to be executed at 15 minute intervals in order to allow excess surface charge produced by the surface flashover to diminish. The Marx bank has to be flushed out after each execution in order to clear out residue created from the firing.

There were not many difficulties in constructing this experiment, but there were many factors that lead to difficulties in the execution of the experiment. For example, if even one of the actions listed above were not completed, the experiment would not have yielded good results. The coating generated from the sparkplug yielded results similar to the conditioning process, but when using the conditioning process, the results are not dependent on the amount of moisture in the chamber and are permanent. The sparkplug coating is not only moisture dependent, but it is not practical because it can be easily destroyed from the surface of the sample. Suggested future work should include an experiment that would show whether a coated sample is capable of absorbing the proper amount of moisture while being exposed to atmospheric air.

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