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PULSED HIGH-VOLTAGE FLASHOVER OF VACUUM DIELECTRIC INTERFACES

by

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ABSTRACT

A general overview of the mechanism involved in the pulsed, high voltage flashover of vacuum-dielectric interfaces is given and, in some cases, modified in the light of observed experimental evidence.

Flashover was observed across cylinders and truncated cones of lucite in a vacuum of about 10^{-4} torr with voltage pulse amplitudes greater than 500 KV, risetimes of 6 nanoseconds, and pulse durations of about 60 nanoseconds. Diagnostic equipment included streak and integrated photography along with time synchronized voltage and current waveforms of the flashover event. Magnetic fields of several kilogauss and intense ultraviolet irradiation were employed to see the effects, if any, on the breakdown voltage.

Experimental data are presented to support the following:

1) The initiatory electrons for the discharge are born at the intersection at the cathode, dielectric and vacuum by field emission.

2) A mechanism leading to a positive surface charge on the insulator, perhaps due to a type of modified, thermionic emission, plays a significant role in determining the breakdown voltage for positively angled, truncated cones.

3) Streak photography shows a roughly constant streamer velocity of 6×10^8 cm/sec for a 1.78 cm thick sample.

4) Magnetic fields of several kilogauss play no significant role in altering the breakdown voltage.

5) Ultraviolet irradiation studies show a definite decrease in breakdown voltage and point the way to the possible development of a fast, high current, triggered ultraviolet switch.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

INTRODUCTION

A. General

Workers in the field of high voltage have always been faced with the problem of separating high potentials between conductors or electrodes. In many cases, the problem is specially acute where dielectric interfaces exist, for example, flashover across an insulator supporting an EHV transmission line. In Van de Graff generators , electrostatic separators, high voltage X-ray machines or in just about any physical device that depends on high voltage for its operation, flashover across supporting dielectric structures is a definite problem. These dielectric members must provide adequate mechanical strength, yet protect against flashovers which may interrupt service or cause severe damage.

In recent years, design engineers in the relatively new field of pulse-power devices have had to face these problems squarely as operating voltages have leaped from kilovolts to megavolts. Operating potentials of several megavolts are common with various types of pulse transformers, Marx generators, and stacked transmission line arrays. Flash X-ray machines built by industrial laboratories such as Sandia and Physics International are designed for use above 10 megavolts. At the High Voltage Laboratory in Cornell's Laboratory of Plasma Studies, two electron accelerator-diodes have been designed for greater than a megavolt and have been operated routinely at half a megavolt.

Typical pulsed, high-voltage devices, such as the ones mentioned above, require the insulation of high voltage across many media; solid, liquid, gas, and vacuum. Considerable pressure to advance state-of-the-art insulation techniques in all these media has been exerted as pulse-power equipment has undergone a quantum jump in operating voltage. The purpose of this study, however, is to investigate only a small subset of these insulation problems; namely the factors affecting flashover across vacuum-dielectric interfaces for pulsed, high voltages. In particular, experimental results are advanced that clarify the breakdown process across insulators in vacuum. This work is then combined with that of previous experimenters in proposing a unified theory of the breakdown mechanism. An excellent overview of the related phenomena of breakdown across meltalic vacuum gaps given by Charbonnier (1) and also by Rao (2). It is hoped that a fundamental understanding of the breakdown process of insulators in vacuum will enable the design engineers of the next generation of pulse power devices to better cope with the sophisticated insulation problems that will surely arise.

This research follows Smith's (3) work with J. C. Martin's group at A. W. R. E. in that the dielectric specimens tested were either cylindrical disks or truncated cones. These test insulators (Figure 1) were several inches in diameter and up to .70" thick with sides that had been smoothed to a high polish. Not only are these general shapes of interest, but they provide considerable convenience in testing.

The exclusive test material for the insulators was chosen as the plastic, polymethyl methacrylate, more commonly known as lucite or plexiglas. Lucite was chosen because: 1) it showed some of the best flashover properties of all the materials Smith tested; 2) the Cornell accelerator-diodes, which use lucite as envelope insulators, have withstood hundreds of shots successfully without failure; 3) lucite is readily available, and 4) it is easily shaped, drilled, machined, or hot formed.

The breakdown process was observed with the help of integrated and high-speed streak photography as well as time synchronized current and voltage waveshapes detailing the electrical history of the test insulator. In addition to general observations of the breakdown process, particular emphasis was placed on the effects, if any, of 1) strong ultraviolet irradiation of the sample, and 2) presence of a high magnetic field. Impetus for the magnetic field experiment was provided by J.C. Martin who suggested that a high magnetic field might possibly lower the flashover voltage by a drastic amount. As a set of field coils were available from the Cornell relativistic electron beam experiments, it was felt that an investigation into any deleterious magnetic field effects, would be quite timely. A further incentive for the magnetic field study arose from the planned use of high magnetic fields near the accelerator-diodes which might have been rendered inoperable if any significant magnetic field effects were present. The ultraviolet irradiation studies were made with the hope that a fast, ultraviolet-triggered switch could be developed. Both this author and Smith (3) have observed that the passage of large current pulses have no harmful physical effects on the lucite test insulator and that the breakdown is accomplished within a few nanoseconds. These are, of course, necessary prerequisites for a fast, reliable switch. The ultraviolet radiation, the author thought, might produce a large swarm of photoelectrons around the test insulator which would cause breakdown at a much lower voltage. As the results in Chapter III show, ultraviolet radiation definitely does tend to lower the breakdown voltage. An ultraviolet-initiated discharge could then be used to switch energy for a slowly charged system into a load within a few nanoseconds. The advantages of such a switch would be: 1) its triggerability; 2) its ability to carry large, repeated pulses of current and 3) its fast closure time without need of parallel switching.

B. Summary of Past Work

The discovery of Shannon et al. (4) that stepped, truncated cones gave very good protection against flashover for d-c voltages on vacuum-dielectric interfaces led naturally into their use for pulsed voltage applications. Extensive work by Smith (3) with smooth, truncated cones confirmed that this shape, given the proper configuration (Figure 2), could give excellent breakdown strength, for pulsed voltages. Smith tested such materials as polyethylene, epoxy, lucite, glass, sulfur, pyrophylite and rubber in various cylindrically symmetrical configurations. "Group I" materials such as polyethylene, epoxy, lucite, and glass showed the most promise, combining good mechanical properties with a high resistance to flashover for proper configurations. Smith found that the breakdown strength was quite strongly affected by the slope angle of the truncated cone (Figure 2). Moderate "positive angles", that is the truncated cone positioned so that its larger base is adjacent to the cathode, of about 50° for "Group I" materials gave generally the best breakdown voltages while "negative angles" of about 10° gave generally the worst results. Although the cone angle of the test insulator quite markedly affects the breakdown strength, Smith found that the breakdown voltage is quite independent of the following:

1) The thickness of the sample, i.e. no "total voltage" effect or transmit time phenomena is involved.
2) The diameter of the sample if it is greater than or equal to the sample thickness.
3) The electrode material.
4) The identity of the residual gas.
5) The gas pressure providing it is less than 10^{-2} torr (Figure 3).

From his experiments, Smith concluded that the breakdown may start at any point on the insulator surface, the initiatory electrons supposedly coming from emission by "dielectric whiskers". The initiatory electrons, given a suitable energy range (Figure 4), could give rise to more electrons by secondary emission as the primaries collided with the insulator surface. These secondaries, gaining energy from the in situ electric field, could give rise to even more electrons by secondary emission which could easily form a multiplying electron swarm down the side of the insulator.

Several investigators (5, 6) of vacuum-dielectric flashovers using d-c voltages have also proposed electron multiplication by secondary emission as an important mechanism in the breakdown process.

These investigators, however, seem to conclude unanimously that the initiating electrons must come from near the triple intersection of insulator, vacuum and cathode. Furthermore, pulse work by Srivastava (5) strongly suggests that the initiatory electrons are born near the cathode-insulator junction.

Bugeav and Mesyats (7, 8, 9) have postulated a sheath of desorbed gases close to the insulator surface which, upon being ionized by the action of the multiplying electron swarm down the insulator side, provides a low impedance path for the breakdown current. Their work also includes high-speed framing camera photography of discharges across thin (i.e. two mm.) sections of insulator material.

The following is a composite summary of the breakdown process derived from previous experimenter's work. The results of this study will be shown to modify and expand this description of the breakdown process:

1) Initiatory electrons are emitted either by dielectric "whiskers" along the surface of the insulator in which case, the discharge can start anywhere along the surface <u>or</u> electrons are emitted at the triple intersection of insulator, vacuum, and cathode.

2) Electron multiplication through secondary emission causes an electron swarm down the side of the insulator.

3) The electron swarm ionizes a sheath of desorbed gas along the insulator surface.

4) The ionized sheath forms a conducting current path for the breakdown current.

5) The insulator flashes over.

The work of this study, to be discussed in detail in later chapters, points strongly to a surface charging mechanism which has a substantial effect on the breakdown voltage. The point of origin of the initiatory electrons is discussed and emission from dielectric "whiskers" is shown to be unimportant. Streak photography of the breakdown streamer shows a roughly constant streamer velocity going from cathode to anode. The effect of strong magnetic fields and ultraviolet irradiation on breakdown is thoroughly discussed and the overall breakdown mechanism is analyzed in detail.

DESCRIPTION OF EXPERIMENTAL APPARATUS

A. General

The facilities of the High Voltage Laboratory in conjunction with the Laboratory of Plasma Studies at Cornell University were employed for the experimental work of this thesis. In particular, the Cornell relativistic electron beam accelerator system (10, 11) was modified to the extent that it was useful for conducting flashover tests. This system,(Figures 5, 6, 7, 8, and 9),consists of a conventional Marx generator that pulse charges one of two available Blumlein-diode combinations. The Blumleins are folded strip transmission lines that use overvolted, stabbed polyethylene switches to produce a pulse with a duration of about 60 nsec. and a risetime of about 6 nsec. The diode assembly, which normally served to manufacture a pulsed relativistic electron beam, was modified for this study (Figure 10) so that dielectric samples could be conveniently inserted and tested.

The Marx generator consists of sixteen -0.5 μfd. I.C.S.E. capacitors rated at 100 KV each which are charged in parallel through copper sulphate charging resistors. The capacitors are discharged in series via an arrangement of spark gaps located in a plexiglas column whose pressure can be adjusted externally. Once the bank of capacitors is charged, the erection of the Marx output pulse can be initiated by triggering the #2 gap with a 100 KV pulse. The trigger pulse is produced by a thyratron-switched capacitor which in turn drives a pulse transformer. The Marx is charged plus and minus from a transformer rectifier circuit.

The Marx pulse charges either of two folded strip transmission lines (Figure 7), hereafter known as Line I and Line II, through quick disconnect flexible stainless steel tubing. Line I is rated at 800 KV with two, 2 ohm sides while Line II has a slightly lower impedance at 1.75 ohms per side and is rated at a maximum of 600 KV. Both lines are folded planar Blumleins using sheets of .010" Mylar for insulation. Both lines sit in water-tight wooden tanks which contain copper sulfate solution to grade high field concentrations and prevent breakdown of the insulation at field enhanced points. Line I has a diode assembly made of .303" stainless steel plates separated by four, 1" lucite rings which are capacitively graded. Line II's diode assembly employs 5/8" thick aluminum plates which are separated by three 1" lucite rings. A more detailed picture of the diode construction can be gained from figures 9 and 10. The diode is evacuated by a 2" silicone oil diffusion pump operated in series with a forepump. New pieces of lucite inserted into the vacuum system, for example a new cover plate, usually take at least 24 hours to outgas so that the limiting vacuum can be obtained. The limiting vacuum is close to 5×10^{-5} torr.

The diode assembly was modified for dielectric testing (Figure 10) by replacing the anode foil by #100 stainless steel mesh, replacing the plasma cathode with a 6 7/8" diameter 1/4" thick brass plate, and adjusting the length of the cathode stalk so that a press fit could be obtained for the dielectric test specimen between the brass cathode and the mesh anode. The length of the cathode stalk can be adjusted by using differing lengths of 4" O.D., 1/16" - wall brass tubing along with spacer rings and disks of brass and aluminum. The anode-cathode spacing can easily be changed to within .010" of the desired gap by using this arrangement. The stainless steel mesh used for the anode is able to withstand considerable mechanical stress. Hence the anode-cathode gap is usually made slightly shorter than the thickness of the test specimen, thus causing a slight bowing of the anode mesh and ensuring an excellent press fit of the insulator between the test electrodes. Additional qualities of the anode mesh are (1) great resistance to damage, and (2) optical transparency. The former has allowed tens of shots with currents in excess of 100 KA while the latter has made it possible to photograph the flashover event across the test insulator directly through the anode. The modified diode assembly for insulator flashover studies as described above will be henceforth referred to as the "test cell".

Since Smith (3) has gone into some detail concerning types of insulator materials, this study was restricted to only one material, namely polymethyl methacrylate, better known as plexiglas or lucite. Lucite is a good example of Smith's "Group I" type of materials along with epoxy, polyethylene and glass. This material has successfully held off gradients of greater than 100 KV/in for thousands of shots in the Cornell accelerators as well as being used extensively for insulation purposes in pulse power applications at A.W.R.E., Ion Physics, Physics International, E.G.& G. and Sandia. Not only does lucite have good insulation properties, but it is also easily drilled, machined, hot formed, or otherwise shaped. This is quite an advantage when compared with ceramic or alumina insulators which are not so easily shaped.

Insulators tested were in the form of right cylinders or truncated cones with base diameters of three and four inches. The cone angle (Figure 1), γ, is measured between a perpendicular to the cathode surface and the slope of the cone. When using the truncated cones or frustra, the largest base always was adjacent to the cathode, i.e. only positive cone angles were investigated. Positively angled cones have shown attractive voltage hold-off capabilities in both the d-c (4) and pulse cases (3). Since one hoped to work in the highest breakdown regime possible, only positive angles were investigated.

To mount the insulator in the test cell the following procedure was used:

(1) Clean electrodes and insulator surfaces thoroughly with alcohol.

(2) Attach insulator to cathode plate with a small spot of contact cement.

(3) Screw cathode plate with insulator attached onto cathode stalk.

(4) Affix anode mesh and cover plate, then pump down letting atmospheric pressure provide a tight press fit for the insulator between the anode and cathode.

The presence of a dielectric in a parallel plate geometry distorts the otherwise uniform field due to polarization effects. In other words, some field gets excluded from the body of the dielectric due to polarization which is then made up in the vacuum gap. The behavior of the electric field near the insulator surface can be ascertained by noting the usual boundary conditions: (1) the tangential component of $\vec{E}$ is continuous and (2) the normal component of $\vec{D}$ is continuous across a surface. In the case of a truncated cone (Figure 11), the electric field tends to be concentrated at the nose of the cone and correspondingly decreases at the base. Thus an asymmetry in the field distribution is introduced by the dielectric.

Due to voltage limitations on the test equipment, the maximum insulator thickness used was 0.70". Test insulators with thickness greater than this could have possibly required voltage pulses greater than 600 KV to break them down. Since Line II, on which the majority of tests were made, is only rated at 600 KV it was deemed prudent not to exceed 0.70" for insulator thickness. When the Blumlein insulation fails, it necessitates several man days worth of effort to repair; a task that was avoided as much as possible.

B. Diagnostics

Methods used to investigate the behavior of the flashover were: (1) time synchronized voltage and current waveforms (of the flashover event), (2) integrated and streak photography, (3) photodiode pulses (for the triggered spark gap in the ultraviolet-irradiation studies) and (4) charging voltage for the magnetic field capacitor bank and the discharge current through the field coils.

The voltage stress across the test cell for Line I was monitored by a resistive voltage divider encased in epoxy and inserted in the line near the test cell. Test cell voltage on Line II was measured by both a resistive and a capacitive voltage divider. The resistive dividers consisted of a chain of ten ohm, 2 watt carbon resistors with a low-voltage tap-off, arranged so that mutual inductances cancel as much as possible, and encased in epoxy for insulation purposes. The capactive voltage divider (Figure 12) is identical to the one described by Leavitt, Shipman, and Vitkovtsky (12). A much more detailed account of the construction and calibration of these monitors may be found in Figure 13.

Currents were measured on Line I via a torodial copper sulphate monitor whereas a torodial resistive monitor using carbon resistors was used on Line II. A detailed account of these monitors including construction and methods of calibration may be also found in Figure 13. The placement of those monitors can be found by referring to Figure 9.

A long PVC tube filled with copper sulphate solution with a low voltage pick-off section served to monitor the output of the Marx generator. From the Marx output (Figure 14), one can easily tell the switching voltage of the Blumlein to within 10%.

Typical time synchronized waveshapes of voltage and current for a flashover event are shown in Figure 13. Here the capacitive voltage divider and torodial resistive current monitor of Line II have been used. Note the rapid fall-off of voltage on the test cell once the peak value has been obtained. The time at which the flashover occurs can be accurately determined by noting when the current pulse starts, i.e. just before the peak voltage is achieved. The voltage peak is somewhat rounded due to the response times of the capacitive divider and the oscilliscope (Textronic 556) used. The resistive dividers appear to be somewhat faster but exhibit a disturbing amount of inductive pickup for the first ten nsec. after the Blumlein switch fires. A resistive divider was used to time correlate the advent of breakdown with the beginning of the streak camera shutter pulse (Figure 18) since it was important to determine the time of occurence of the flashover rather than the magnitude of the voltage pulse. The capacitive monitor, which could measure absolute voltage within 1% with a risetime of 3 nsec., was used in all but the magnetic field experiments to give an accurate measure of the breakdown voltage. In the magnetic field tests on Line I, a resistive divider with capacitive tuning to reduce the initial inductive spike gave relative flashover pulse heights.

Integrated photographs of the test cell with insulator in place could be taken directly through the anode mesh and lucite cover plate. A standard Speed Graphic camera with Poloroid film was used. It was usually necessary to fit neutral density filters over the camera lens to limit the exposure since the flashovers across the insulator generated intense light. Type 47 Poloroid film gave excellent spacially resolved, time-integrated photographs of the discharge (Figure 15).

To obtain the resolution of the discharge process, a TRW STL image converter camera with a fast streak unit was employed (Figure 16). This camera uses an image converter tube with an electronic shutter to "streak" an image on a piece of film. The rate of streaking is made as linear as possible by positive and negative ramp voltages fed to deflection plates in the image converter tube. Distance along the streak is thus proportional to time. One can then study the time evolution of a discharge by noting changes in luminosity across the width of the streak as a function of distance along the streak. The electronic shutter of the image converter tube, normally closed, is opened by a fast voltage pulse of at least plus 300 volts. This trigger pulse also initiated the ramp deflection pulses which cause the image to streak. In these experiments, the trigger pulse was provided by an oblate loop of styroflex cable near the solid dielectric switch of the Blumlein. The sudden breakdown of the switch within 5 nsec. causes a large local change in magnetic flux which can excite voltage spikes over 400 KV in the styroflex loop. A voltage pulse is induced also by the erection of the Marx generator although it was smaller than the pulse produced by the overvolting stabbed polyethylene switch. The relative magnitudes of the two pulse can be altered by the position of the loop adjacent to the switch area. The most favorable ratio of Blumlein pulse to Marx pulse was about 3:1. Attenuators are introduced between the styroflex loop and the streak camera so that the Marx pulse is never sufficient to trigger the image converter tube and deflection pulses. A typical oscilliscope trace of the trigger pulse is shown in Figure 17.

Unfortunately, the behavior of the streak camera is somewhat nonlinerar near the very start of the streak even with near ideal, square trigger pulses. This nonlinearity is caused by (1) the delay time between the trigger pulse and the "shutter open" condition, (2) delays between the trigger pulse and the onset of the ramp deflection voltages, and (3) "kneeing" of the ramp voltages as they are getting away. Figure 19 shows the relative positions of the shutter pulse to the positive and negative going ramps in an oscilliscope trace. The shutter is said to be "open" when 90% of the maximum pulse height is reached.

In order to get a meaningful record of the flashover across the test specimen, the camera must be in its linear region by the time the light of this event reaches the camera. To insure this, the shutter pulse must have switched the camera "open" long enough for the nonlinearities in the ramp voltages to disappear. To make sure of this experimentally, the diode voltage pulse and shutter pulse were displayed simultaneously on a time synchronized oscilliscope trace (Figure 18). One can find why the two pulses are displaced in time by considering the following times from the initial firing of the Blumlein:

I. Delays to flashover:

(1) 20 nsec. for the travel time of the discharge wave down the length of the Blumlein to the test cell.

(2) about 8 nsec. from the very start of the voltage pulse at the test cell to when the insulator flashes.

II. Delays to start of shutter pulse:

(1) travel time of about 10 nsec. in the trigger loop and cable to streak camera.

(2) get away time of camera electronics of 25 nsec. ± 5 nsec. with 25 mil stabbed switches.

For large switches, i.e. those with a 40-mil stab, a negligible getaway time for the camera electronics was observed but for the 25-mil stabbed switches used in the flashover tests there appeared to be a getaway time of 25 nsec. ± 5 nsec.

Fortunately, all these delays need not be considered in order to judge whether or not the camera is operating in a linear manner. One merely looks at the time synchronized trace of flashover voltage and shutter pulse. Advancing the shutter pulse 13 nsec. in time relative to the flashover pulse, due to the delay in light coming from the test cell to the camera optics, one arrives at the true time coincidence between the shutter pulse and the flashover event. If the shutter pulse has reached its 90% point with about 8 nsec. to spare by the time flashover occurs, the camera is in a linear region. An alternate criteria is to demand that a point 22 nsec. after the start of the shutter pulse occur before flashover takes place, the flashover bring evidenced by the sharp drop of the test cell voltage.

Considerable attention had to be paid to electrical shielding as the Marx spark-gap column, dielectric switch in the Blumlein, and the open sides of the Blumlein were all considerable sources of RF noise. All cables were either doubly-shielded or solid outer conductor (styroflex) and run directly over ground planes to (1) eliminate electrostatic pickup, and (2) make ground loops as small as possible. All signal cables entered a double copper mesh screen room where the oscilliscopes were housed. Furthermore, all power lines were inductively decoupled from ground. The streak camera and its power supply were kept in shielded boxes and the umbillical cord between them was double shielded.

C. Ultraviolet-Irradiation Test Set-Up

An overall schematic for the ultraviolet-irradiation test set-up is shown in Figure 20. A trigatron spark gap, discharging an energy storage capacitor, provided copious amounts of ultraviolet radiation.

The capacitor with 14 μfd. at 20 KV was charged to 10 KV for each test, thus providing an energy discharge of 700 joules. The spark-gap assembly was mounted on a lucite cover plate in which a 3/16" quartz window had been torr-sealed into place. Quartz has an excellent band pass characteristic for wavelengths between 1,800 and 40,000 Angstroms. The ultraviolet shone through the quartz window and the anode mesh where it then illuminated the test insulator. An E.G.&G. TM-11 unit activated by the system firing button provided a 30 KV trigger pulse which triggered the trigatron. An Electronic Aids Model 208 Variable Time Delay Generator was used to hold up the normal firing sequence of the Marx and Blumlein so that the trigatron would be producing a near peak light output when the test voltage pulse arrived at the test cell. In order to be sure that the spark gap was going when the Blumlein fired, a photodiode, whose output signal was time synchronized with the firing of the Marx (Figure 21) was employed to produce a signal proportional to the intensity of the trigatron light.

D. Magnetic Field Test Set-Up

The magnetic field for examining the breakdown process was provided by discharging a 480 μfd. capacitor bank rated at 14 KV through a set of field coils. The field coils consisted of thirteen individual epoxy encased loops connected in series and separated by 1"-thick formica rings. The whole assembly is about 28" long with an I.D. of 6" (Figures 22, 23). The capacitor discharge through the field coils is lengthened by crowbarring the current pulse at its maximum. The crowbar switch, which shorts out the capacitor bank, consists of an ignitron triggered as the bank voltage goes through its first zero. Otherwise, the capacitor bank would continue ringing with the inductance of the field coils. By crowbarring at the peak of the current pulse (the voltage zero) the current pulse is stretched by the L/R time of the field coils; a considerably longer time than the quarter ringing period. The guide field current was monitored (Figure 24) by measuring the voltage across a short length of bus wire through which the current passed. The bank was charged up and its voltage monitored by a Kilovolt Corporation high-voltage power supply.

The current pulse, with a rise time of about 8 msec., a fall time of 35 msec. and a half width of 25 msec. is much slower than the events during the insulator flashover. Therefore the magnetic field at the instant of flashover may be treated as a d-c field. With a pulsed field, however, one needs to be concerned about the time penetration of that field through enclosing metal structures. To maximize the penetration of these fields through the metal support plates of the test cell, the magnetic field experiments were run on Line I which has .303" thick stainless steel plates as opposed to Line II which has 5/8" thick aluminum support plates for the test cell. Since the e-folding penetration distance, δ, of a pulsed field is:

$$\delta = \sqrt{\frac{T}{\pi \mu \sigma}}$$

where: T = period of the applied pulse
μ = magnetic permeability
σ = electrical conductivity

The stainless steel plates are preferred due to their higher resistivity. For stainless steel:

$$\mu = 4\pi \times 10^{-7} \text{ henry/meter}$$
$$\sigma = 1.4 \times 10^{2} \text{ mho/meter}$$

Taking the pulse half-width as 25 msec. we have:

$$\delta = \sqrt{\frac{2.5 \times 10^{2}}{4\pi^{2} \times 1.4 \times 10^{-5}}}$$

$$\delta = 6.7 \text{ meter}$$

Since the stainless steel plates are only .303" thick, we may discount any effect of the metal after a fraction of a millisecond.

Therefore, the field strength in the region near the test insulator depends only on the geometry of the coils, the position of the insulator relative to the coils, and the current through the coils. J.J. Bzura (14) at the Laboratory of Plasma Studies, Cornell University, has successfully run a computer program supplied by Princeton University for determining the on-axis magnetic field of this particular coil configuration. Results of this program show that the on-axis axially directed component of the field in the region near the test sample is about 50% of the maximum central field. From geometrical considerations the radial component of the field appears to be 30 - 40% of the maximum central field at the vacuum-dielectric interface of the test insulator.

Note that:

$$B_{max} = 1.33\ V_B$$

$$\text{and}\quad V_B = 41.4\ I_{max}$$

where: B_{max} = maximum central field - kilogauss

V_B = capacitor bank voltage - kilovolts

I_{max} = peak coil current - amps

Since later tests results showed that the magnetic field had little effect on the breakdown process, no further effort was made to define more precisely the radial and axial components of the magnetic field.

EXPERIMENTAL RESULTS

A. General

One of the most striking features of the flashover across the lucite test insulators was the lack of physical damage. Even after tens of shots with peak current near 100 KA there was little evidence of damage. The only changes to the insulator surface were faint, barely discernable snake-like discolorations a few mm. across that wound down from cathode to anode. On one occasion a slightly melted spot along the rim of the insulator at the cathode end was found. This, however, was only 1/2 a mm. high and a few mm. wide. In his experiments, Smith (3) has also noticed a similar lack of damage to lucite insulators at high pulsed currents.

There was also very little damage done to both the brass cathode plate and the stainless steel anode mesh. Sometimes fan-like black discolorations of the cathode plate with a radius of about 1/2 cm., each occuring along the rim of the cathode end of the insulator, could be observed. These discolorations were probably due to some slight blow-off of the plastic due to the energy deposited during flashover. A quick wipe with alcohol, however, restored the cathode surface to its former smooth finish. Discoloration of the anode mesh at the spot where the plastic made a press-fit against mesh was also observed but no major roughening or burning of the mesh could be detected.

From observations, of the integrated photographs, it appears that the breakdown usually occurs at two or more sites with four or five channels being not uncommon. However, judging from the intensity of the light emission, most of the current is usually carried by one main streamlet. These breakdown sites are not entirely random but instead seem to posses a kind of memory dependent on where previous breakdowns have occured. In a given series of shots (Figure 14), for example, the breakdowns tend to occur at the same positions on the insulator. When the cathode plate along with the insulator is rotated, the breakdown sites are rotated in the same manner. Close observation of the test specimens at these breakdown sites shows evidence of the fan-like discolorations of the cathode plate previously mentioned although the surface of the plastic shows no sign of damage. Since these active breakdown sites are rotated along with the cathode plate and insulator and since,furthermore, the position of these sites coincides with the fan-like discolorations of the cathode plate, evidence strongly points to an initiating process at the cathode-dielectric-vacuum intersection. Trump (6) among others, has also pointed out the imporatance of this triple intersection point.

Kofoid (15) has proposed a simple mechanism to explain the activity of the breakdown sites observed in the author's experiments. Assuming the butt end of the insulator does not press flat against the cathode plate at every point around its circumference there could exist certain voids at points between the plastic and the brass cathode plate. In these voids the local electric field may be intensified by as much as a factor of κ , the dielectric constant, due to the polarization of the dielectric. Since lucite has a dielectric constant of three, one could expect the local electric field in the spaces caused by bad contact between cathode and insulator to be intensified by roughly the same factor. Hence one could find field enhanced points around the perimeter of the test insulator which would preferentially break down. The fan-like discolorations on the cathode plate might then be the result of intense currents arcing across these bad contact areas and consequently spraying some plastic material on the cathode plate.

The breakdown voltage did not change markedly in the first ten to fifteen shots. Since a great number of consecutive shots with the same insulator were not taken, nothing is known about long term conditioning effects. It is interesting to compare the seeming lack of "conditioning" for pulsed voltages with the very real conditioning effects observed for d-c voltages. Srivastava (5) and Shannon (4) have reported breakdown voltage strengths to increase by factors of two to four after several hours of continuous voltage stress. This improvement in breakdown voltage after several hours of voltage stress is probably due to the burning away of microprotrusions on the cathode which cause field enhanced points which may initiate the flashover.

The scatter in the breakdown voltage was typically ± 10%. Hence any influence exerting an effect less than 10% on the breakdown voltage is lost in the "noise" unless a great number of shots with the same set of parameters is taken. Since each shot is quite time consuming, e.g. on the order of half an hour not counting set-up time which may run into days, the maximum number of shots with a given set of parameters was usually limited to five so that a wider range of interesting phenomena could be investigated. It was the general philosophy of this study to discount any effect causing less than a 10% change in the breakdown voltage as being irrelevant.

A series of shots was conducted to see what effect, if any, a coating of silicone oil would have on the breakdown process. As suggested by Mr. J.C. Martin of A.W.R.E., the Cornell accelerator-diodes have their lucite insulators coated with a light film of silicone diffusion pump oil. His experience has shown that such a coating of oil aides in the cleaning of the insulator if it is contaminated by either a flashover of the insulator or blow-off from the anode. Shots were tried in which one half of a specimen was coated with DC 704 silicone diffusion pump oil and the other half kept clean. This type of diffusion pump oil has an extremely low vapor pressure so as not to interfere with the vacuum system which had an ultimate capability of about 5×10^{-5} torr. If the oil coating hindered or helped the breakdown process appreciably, the breakdown would tend to occur on one side or the other, i.e. the coated or the uncoated side.

After five shots with the insulator half coated with oil, a total of nine spark channels were observed on the coated side while eight were seen on the uncoated side. Not only did the total number of breakdown channels seem to be distributed evenly between the coated and the uncoated sides, but the main current carrying channels also showed no preference for one side or the other. Furthermore, the average breakdown voltage for the five previous shots with an unoiled insulator was within 10% of the average breakdown voltage wihh the half-oiled insulator. Thus it seems the oil coating makes little or no difference in the breakdown process. Care should be taken, however, to insure the oil is wiped on only in a thin layer. If a oil droplet forms on the insulator due to excess oil, the flashover strength can be somewhat reduced. For example in one case where excess oil was used in wiping down the insulator, a droplet formed near the cathode 3 or 4 mm. in diameter. The insulator flashed over at this point with a breakdown voltage about 20% less than normal.

The silicone pump oil used had a dielectric constant quite similar to that of lucite, i.e. about 2.5 for the oil and 3.0 for the plastic. The close match in dielectric constants might well be one explanation for the silicone oil's minute effect on the breakdown voltage.

Breakdown voltage was measured with 3" base diameter truncated cones .495" thick with positive cone angles of 0°, 30°, and 45°. These insulators had never been fired before and were kept clean by wiping them down with alcohol after each shot. Results of this series of shots with breakdown voltage being plotted against cone angle are shown along with some of Smith's data (Figure 25). Each point of the author's data was the average of at least four shots with the shot-to-shot scatter being about 10%.

B. Streak Photography

Streak photographs (Figures 26, 27) of the breakdown event were taken through the anode mesh as described in **Experimental** Apparatus. All photographs were taken with 45° truncated cones so that as one looked through the mesh, the discharge could be seen completing from one electrode to another. An integrated photograph was taken with each streak photograph so that the streak could be easily identified with the corresponding discharge site on the insulator. In all the observed events the discharge starts at the cathode and completes to the anode in a time of about 3 nsec. The discharge is seen on the streak photograph as a triangular front-ended streak with the apex at the cathode and widening out until the light of the discharge fills in the anode-cathode gap. Since the image formed by the TRW streak camera is being swept upwards on the plane of the film, good spatial resolution of the flashover event is obtained only for discharges occuring to the left and right of the image. When a discharge occurs at the top or bottom of the image and the flashover path is parallel to the streaking motion of the camera, no spatial resolution is obtained. The number of "good" streaks in which useful information about the crossover time of the discharge can be obtained is further limited by difficulties in triggering and the non-linearity of the deflection pulses as outlined in the Experimental Apparatus. "Good" streaks are clearly identified by their triangular front ends (Figure 26) while "bad" streaks start out with a diffuse blob of light (Figure 27). The crossover time of the discharge (3 nsec.) was obtained by measuring the length of the triangular front section in four "good" streaks.

C. Magnetic Field

In a series of shots with and without the pulsed magnetic field described in the Experimental Apparatus, breakdown voltage across a 45° truncated cone, .495" thick was measured. As described in the Experimental Apparatus, this field behaves essentially like a d-c field for the times relevant to the flashover event. In four shots with the axial component of the field as high as 9 kilogauss and the radial component near 6 kilogauss, no effect on the breakdown voltage was discernable.

The magnetic field shots had breakdown voltages within 10% of the previous five shots taken without any magnetic field. Since the average scatter is about 10%, it appears the magnetic field does not have a relevant effect on the breakdown process. The effect, if any, is of second order which would require many shots and a statistical treatment of the data. Integrated photographs of the breakdown event (Figure 28), however, showed a slightly more diffuse discharge with the magnetic field. This is due, perhaps, to the many more collisions an electron would make with the residual gas molecules in the vacuum system as the electron gyrates in its cyclotron orbit.

The breakdown voltages in this series of tests were derived from a resistive divider that had considerable inductive overshoot. This overshoot, however, was quite constant from shot to shot so that the author is quite confident that relative voltage levels from shot to shot could be accurately compared. The voltages for this series were only relative measures, but as the magnetic field showed a negligible effect on the breakdown voltage, no effort was made to gain an absolute measure of the voltage. Due to the negative results, this experiment was not pursued further. Note that the other breakdown voltages in the rest of this study were measured absolutely on a capacitive voltage divider calibrated to 1%.

D. Ultraviolet Irradiation

The test insulator was bathed with ultraviolet light from a triggered air gap during the flashover event to see what effect, if any, the radiation would have. Truncated lucite cones with 3" base diameters and .495" thick were used whose cone angles were 0° and 45°, respectively. The results of these tests can be summarized in the following table:

0° (Cylinder)		45° Cone Angle	
With Spark	Without Spark	With Spark	Without Spark
V_B = 138 KV	V_B = 164 KV	V_B = 356 KV	V_B = 380 KV
4 shots	5 shots	5 shots	5 shots

Where: V_B = Breakdown voltage

DISCUSSION

A. General

Previous experimenter's work (refer to Introduction) has suggested to this author the following synopsis of the breakdown mechanism which will be subsequently discussed and modified according to the author's work;

1) initiatory electrons are emitted either by dielectric "whiskers" along the insulator surface in which case the discharge can start anywhere along the surface <u>or</u> these electrons are emitted only at the triple intersection of insulator, vacuum, and cathode plate.

2) electron multiplication by secondary emission causes an electron swarm down the side of the insulator.

3) the electron swarm ionizes a sheath of desorbed gases along the insulator surface.

4) the ionized sheath forms a conducting path for the flashover current.

5) the insulator flashes over.

The first issue to consider is where the initiatory electrons are born. Smith (3) concluded that the initiatory electrons arise from dielectric "whisker" emission on the insulator surface thus leading to a discharge able to start anywhere along the insulator surface. Streak photographs by the author (Figures 26, 27) as well as framing camera photographs by Bugaev and Mesyats (7, 8) clearly show, however, that the discharge always starts at the cathode end of the insulator and completes to the anode. Furthermore, the importance of "active sites" along the cathode-insulator junction in controlling the "memory" of where the breakdowns occur strongly suggest that flashover begins at the cathode.

One can easily postulate local electric fields strong enough to cause field emission at the cathode by (1) field enhancement of metalic microprotrusions on the cathode surface (16, 17, 18, 19) and (2) field intensification in voids where the insulator makes poor contact with the cathode (15). Since field-enhancement factors, γ, of several hundred are commonly reported in the literature (18) and since the field enhancement factor for a lucite-cathode void can be as great as three, one can easily envisage local fields large enough for field emission. More precisely, for the author's experiment:

Gross Electric Field = 250 KV/cm

Field Enhancement Factor ≈ 200

Field Intensification Factor ≈ 3

This combination implied local fields of the order of 1.5×10^8 V/cm. Since 7×10^7 V/cm. is usually considered sufficient for field emission (Figure 29), it seems likely that field emission occurs.

Furthermore, the oil coating experiments of the author casts grave doubt on the validity of the dielectric "whisker" emission mechanism proposed by Smith. Dow Corning DC 704 silicone diffusion pump oil was wiped on half of the insulator surface with the other half kept clean. Assuming the oil film would cover up these dielectric "whiskers", one should predominately get discharges forming on the uncoated side of the insulator where the whiskers would be free to emit. This is not the case, however. As was reported in the Experimental Results, the current carrying streamlets show no preference at all for either the coated or the uncoated side. Thus it appears that emission from the cathode-dielectric junction offers the best explanation as to where the initiatory electrons are born.

Several authors (3, 5, 6) have advanced electron multiplication by secondary emission as being an important intermediate step in the breakdown process. In the electron multiplication process energetic electrons impinge on the surface of the plastic causing one or more electrons to be knocked free. These secondaries are then free to set loose secondaries of their own after gaining energy for the _in situ_ electric field. If the gain factor, δ, is greater than one, it is possible to start an avalanche of electrons down the insulator surface. A typical secondary yield curve and gain factor curve vs. electron energy is shown in Figure 4.

The electronic multipication process helps explain two of the outstanding features of the flashover, namely (1) its extreme rapidity and (2) its path along the dielectric-vacuum interface. In the few nanoseconds in which the flashover takes place, only electrons are mobile enough to move centimeter distances. Ions are effectively immobilized by their inerta. The electron multiplication process, being a surface phenomena, explains why the discharge takes place at the vacuum-dielectric interface. Furthermore the electron multiplication process explains qualitatively the results Smith (3) and the author have obtained for breakdown voltage as a function of the cone angle of the insulator (Figures 2, 25). The lowest breakdown voltages occur for small negative angles. The insulator breakdown strengths improve dramatically as the cone angle goes moderately positive (+50°) and improve somewhat for moderately negative angles (-50°). The dramatic improvement of positively angled cones would arise from the very difficult time electrons would have to re-encounter the insulator surface and keep an avalanche process going. The moderate improvement of breakdown voltages with cone angles near -50° can be explained by the lessened electric field component tangential to the insulator surface, the field component that serves to drive the avalanche. The lowest breakdown voltages would come about at low negative angles where electrons can re-encounter the insulator surface conveniently and yet have quite a strong electric field component along the insulator surface to drive the avalanche.

By itself, however, the secondary emission multiplication process fails to answer the embarassing question of why electrons re-encounter the insulator surface at all for positive cone angles. Electric fields of the order of 250 KV/cm. exist across the anode-cathode gap; hence some considerable force must exist to encourage electrons to travel at right angles to the main field and strike the insulator surface. Otherwise, the electron multiplication avalanche would never get started. Two possible forces the author considered were 1) magnetic and 2) electrostatic.

The magnetic force considered was the pinch force exerted by the displacement current. Conduction currents would be non-important in producing pinch forces since the electron multiplication process is precursive to the actual breakdown when large conduction currents flow. The test cell with insulator in place is essentially a capacitor and if very rapid rise voltage pulses are considered, considerable capacitive current can arise. For this experiment, typical voltage rises of 100 KV/nsec. were obtained with a test cell capacitance of near 120 pf. For this combination capacitive currents of the order of 10^4 amp/m^2 were observed. Clark (13) in his work with the Cornell accelerator-diodes has found magnetic self-pinching for a conduction current across the diode anode-cathode gap to become apparant for current densities of the order of 2×10^5 amp/m^2. Since the pinch force for a displacement current should be equivalent to the pinch force exerted by a conduction current, one may conclude that for 100 KV/nsec.-rise pulses in the Cornell test apparatus the capacitive-current pinch effect should be of second order. This condition is borne out by the general similarity of the voltage breakdown curves for various cone angles and pulse rise times shown in Figure 25.

The 300 nsec.-rise pulse produced a breakdown curve shaped much like the one for the 6 nsec.-rise pulse only smaller in absolute magnitude. Since the capacitive current is two orders of magnitude less for the 300 nsec-rise pulse as opposed to the 6 nsec.-rise pulse, it seems clear that neither of the two cases is strongly influenced by the capacitive current. The 300 nsec. pulse produces current densities of the order of 10^2 amp/m^2, three orders of magnitude down from the current densities needed for self pinching in the Cornell accelerator-diodes. Further experiments should, however, not discount the capacitive-pinch mechanism entirely as voltage rises of 10^6 V/nsec. or increased capacitances of the insulator-electrode structure, could permit in capacitive-current pinching.

The other mechanism to consider is electrostatic attraction by the presence of a large positive surface charge on the insulator. Watson (20) has proposed such a surface charge arising from the thermionic emission by hot electrons from shallow trap levels in an imperfect dielectric. Whitehead (21) observed that imperfections in a solid often lead to intermediate energy levels between the normal valence and conduction bands where electrons can be "trapped" (Figure 30). Electrons in these shallow trap levels may require only a small fraction of an electron volt to escape into the conduction band where they can then be loosed by thermionic emission occasioned by the strong local fields. Srivastava (5) and others have noticed charging of the insulator in vacuum for d-c voltages and Watson (20) has some experimental support for charging in the pulse case.

Assuming for the moment that a positive surface charge does indeed draw electrons to the insulator surface, what is the nature of the surface charging current, J (E)? One has:

$$J\ (E) = \frac{d\sigma}{d\tau}$$

where: σ = the surface charge on the insulator

assume: $J\ (E) \sim E^n$, E is the electric field

$\frac{d\sigma}{d\tau} = K$, K is some constant for simplicity.

Therefore: $\sigma \sim E^n t$, t is time

For example, with thermionic emission $J\ (E) \sim T^2$, where T is the electron temperature, and $T \sim E^2$ (22) implying $\sigma \sim E^4 t$.

For breakdown to occur, the surface charge must be greater than or equal to some σ_{CRIT}, a critical surface charge at which electrons are drawn sufficiently strongly to a positively angled surface so that multiplication can occur. This implies:

$$\sigma_{CRIT} \sim E^n_{CRIT}\, t$$

t = pulse risetime
E_{CRIT} = critical electric field needed for breakdown

Therefore we should need steadily increasing field strengths, E_{CRIT}, for breakdown as the voltage-pulse risetime gets faster. This is indeed what is observed (Figure 25). As the pulse rise time quickens, the breakdown voltage for each cone angle increases monotonically. Now assuming 3.3 for the value of the exponent, n, one finds $E^n_{CRIT} t$ is constant within a factor of two for the same cone angle. Cone angles of 0°, 30°, and 45° were used in comparison with pulse risetimes of 6 nsec, 30 nsec, and 300 nsec, (Figure 31). Note that the value of $E^n_{CRIT} t$ increases with cone angle. This is to be expected as the σ_{CRIT} needed for electron multiplication should increase for larger positive angles. In other words, larger angles need a greater positive surface charge for electrons to be drawn back to the insulator surface. The exponent of 3.3 was chosen to give a good fit to the data. Note that this is not far different from n = 4 as would be the case for true thermionic emission as proposed by Watson (20). To explain the differences between the two values of the exponents, the author suggests that some of the surface charge produced by the thermionic emission leaks off prematurely onto the neighboring electrodes. This leak rate would be a function of the electrode material and the interelectrode distance. Thus the actual surface charging current, J (E), might go as $E^{3.3}$ instead of $E^{4.0}$ due to the leakage current.

The presence of a positive surface charge on the insulator would also tend to heighten the electric field near the cathode thus presenting another reason for the discharge to initiate at the negative electrode.

Bugaev and Mesyats (8) have suggested the formation of a plasma sheath along the insulator surface as a precursor to the actual breakdown. In their work with high-melting-point dielectrics such as steatite and forsterite, they proposed that the sheath is formed form desorbed gas from the insulator surface such as N_2, O_2, CO_2, and H_2 which is ionized by the multiplying electron swarm. For lucite, which has a low melting point, this sheath could also be formed of plastic vapor heated by the passage of the electrons. The sheath, once ionized, would form a low-impedance path capable of carrying the large flashover current.

B. Discussion of Streak Photography

Streak photographs taken by the author indicate that the discharge propagates at an average rate of approximately 8 x 10^8 cm/sec across a 1.78 cm. thick insulator at a 45° positive angle and 10^{-4} torr. This is much faster than the rate of 3×10^{7} cm/sec reported by Bugaev and Mesyats (8) as measured with a high speed framing camera for 2 mm. thick samples. However, the Russian work was done with cylindrical specimens as opposed to the 45° positive cone in this study. Since for a cylinder the normal field to the insulator surface produced by the positive surface charge is not bucked by the external field (as for a positive cone) much higher normal fields can result. These stronger fields would pull the multiplying electrons much more strongly to the surface resulting in a shorter mean-free path between impacts and a slower streamer. The streamer velocity appears to be quite constant as it travels from cathode to anode across the insulator surface. The triangular front end of the streak shows this quite clearly (Figure 26). The constancy of the streamer velocity suggests some sort of viscous drag, perhaps the "drag" of the secondary electrons striking the plastic as they multiply down the insulator surface. A qualitative discusssion of electron motion along the insulator surface is given in the appendix.

C. Magnetic Field Results

The results of the magnetic field tests with radial and axial components of the magnetic field of the order of several kilogauss indicate no major change in the breakdown voltage. Any effect on the breakdown process due to the magnetic field is probably 10% or less. In addition, the Cornell accelerator-diodes have been operated for many tens of shots without internal flashovers while various experiments using a magnetic field were conducted for the relativistic electron beam program.

D. Ultraviolet Irradiation Results.

The ultraviolet irradiation tests conducted with the radiation from a triggered air gap show that such radiation definitely lowers the breakdown voltage. This effect is most pronounced for a 0° cone angle, i.e. a cylinder, and least pronounced for a 45° positive cone. A 19% reduction in breakdown voltage is observed for the cylinder while a reduction of slightly less than 10% was seen for the 45° cone. Since the average scatter is 10%, the beakdown voltage of the cone is seen to be insignificant. The reduction of 19% for the cylinder cannot be explained by shot-to-shot scatter, however, and represents a true lowering of the breakdown voltage. This radiation lowering of the breakdown voltage could probably be enhanced by enclosing the radiation producing gap in the same vacuum as the test insulator. Thus bandpass filtering effects of the quartz window and air would be eliminated. In particular, the quartz window transmits very poorly below 1,800 Angstroms, thus cutting out some of the shorter wavelengths which could be the most efficient producers of photoelectrons, the photoelectrons that would serve to initiate a breakdown. Thus there are encouraging signs that a high-current, ultraviolet-triggered switch could be developed from a vacuum-dielectric cell that would have a switching time of a few nanoseconds and could be used for hundreds of shots without replacement.

E. Conclusions

The following statements and conclusions summarize the findings of this study:

1) The initiatory electrons for the discharge are produced at the triple intersection of cathode, vacuum, and insulator via field emission.

2) Emission from dielectric whiskers on the insulator surface either does not occur or at least does not have a significant effect on the breakdown process.

3) Evidence is given to support Watson's claim that a positive surface charge forms on the insulator which controls, to a large extent, the insulator breakdown voltage. Data suggests the surface charge arises from a type of modified thermionic emission from the plastic.

4) Streak photography shows a roughly constant streamer velocity across the face of the insulator of approximately 8×10^{8} cm/sec for a 1.78 cm. thick lucite insulator at 10^{-4} torr.

5) No appreciable effect of kilogauss magnetic fields on the breakdown voltage has been found.

6) Ultraviolet irradiation of the insulator shows a definite lowering of the breakdown voltage and suggests the possibility of a fast, high-current, triggered ultraviolet switch.

F. Suggestions for Further Study

The topic of surface charging by thermionic emission or other means is still quite new and should be investigated further. If one could devise a generator producing a continuously variable risetime ranging from 5 nsec. to 1 μsec. and a peak output of 500 KV, the constancy of σ_{CRIT} for a particular cone angle could be probed in more detail. The relationship between pulse risetime and breakdown voltage could also be investigated in more detail.

A spectroscopic analysis of the breakdown flash would be quite informative.

Experiments with resistive coatings on the insulator surface which would (1) resistively grade the potential across the insulator surface and (2) serve to drain positive surface charge from the insulator surface would be quite interesting.

Placing of the ultraviolet source in the same vacuum as the test specimen would result in a greater percentage of energetic photons striking the insulator. A more drastic lowering of the breakdown voltage might then be observed, sufficient for the development of a practical ultraviolet-triggered switch.

APPENDIX

QUALITATIVE DESCRIPTION OF ELECTRON MOTION ALONG THE INSULATOR SURFACE

The following discussion includes a justification of the electron multiplication process, a brief summary of the secondary emission process, and a few rough calculations of the mean free path between electron impacts along the insulator surface.

Streak photographs show that the discharge completes from cathode to anode in about 3 nsec. across a 1.78 cm - thick cone with a positive 45° angle. The streamer velocity, quite constant at 8×10^8 cm/sec., corresponds to an average electron energy of 180 ev. Now the transverse electric field tangential to the insulator surface is of the order or 2×10^5 Volt/cm. Therefore the electrons in the discharge must lose energy in a regular manner over short distances or (1) electrons would reach average energies of many kilovolts and (2) the observed streamer velocity would not be constant. Since the mean free path in air at 10^{-4} torr, the typical vacuum employed in this study, is much greater than the dimensions of the test cell, the only possible way for electrons to lose energy by collision is to impact against the insulator surface. This deduction is borne out by experimental observation as the luminescence of the discharge is always to be found at the vacuum-dielectric interface. The mechanism of electron multiplication thus explains (1) the very high streamer speed, i.e. the movement of the streamer must be electronic in origin, (2) the location of streamer at the vacuum-dielectric interface,(3) the relatively low average electron energy when compared to the high-field gradients the electrons fall through, and (4) the constancy of the streamer speed.

A monoenergetic beam of electrons with energy, E_3, perpendicularly incident upon a surface often results in secondary electrons being emitted from that surface. Figure 4 details the energy distribution function of these secondaries. The first sharp peak near E_3 is due to electrons elastically reflected from the surface while the small bump directly to the left of it is due to inelastic reflections. The broad hump at low energies, typically from about 10-50 ev, arises from true secondary emission. This low-energy emission is derived from atoms that have been pumped into highly excited states via collision with the primary electrons. These excited atoms emit electrons, which, if they are not absorbed by the material, find their way to the surface as secondaries.

The other curve plotted in Figure 4 is a typical electron gain factor graph versus energy of the primary electrons, the gain factor, δ, being the total number of emitted and reflected electrons per incident electron. The shape of the gain-factor curve is quite similar for metals, semiconductors, and insulators with the maximum occuring between 500 and 1,000 ev. The maximum amplitude of δ is near unity for metals and semiconductors but is typically 3-10 for insulators.

Experiments with secondary emission processes are usually carried out with crystaline materials at specific crystal planes and at ultra-vacuum conditions that preclude the formation of monolayers of gas on the specimen surface. Unfortunately, lucite is an amorphous substance that contains large amounts of adsorbed gas. Furthermore, the typical vacuum pressures used in this study, i.e. 10^{-4} torr, certainly do not preclude the formation of a layer of desorbed gas near the insulator surface. Therefore it is virtually impossible to do a "clean" study of the secondary emission properties of lucite at 10^{-4} torr and, to the author's knowledge, no such study has been undertaken. It will be assumed, however, that the shape of the gain-factor curve does not change appreciably for lucite at 10^{-4} torr as compared to other crystaline insulators under ultra-vacuum. A maximum gain factor of at least 2 is also assumed. The behavior of lucite is probably quite similar to pyrex glass which has $\delta > 1$ for electron energies between 50 ev and 2 Kev. (20).

The true secondaries, emitted at low energies, are by far the most important in the electron multiplication process. First, there are many more of them. The area under the low-energy hump of the secondary electron energy distribution is much greater than the area under the spike due to the reflected primaries. Secondly, the low-energy electrons, after picking up some energy from the transverse electric field, are in a high-δ regime whereas the high-energy primaries that gain even more energy from the transverse field enter into a low-δ regime. In other words, primaries with energies greater than several Kev do not produce secondaries nearly as efficiently as primaries with energies of a few hundred ev.

A few interesting rough calculations can now be made. The basic assumption in these calculations is that a normal component of electric field exists via the surface-charging mechanism discussed in Chapter IV which is the same order as the tangential field, i.e. $\approx 10^5$ Volt/cm. Therefore a strong electric field of 10^5 Volt/cm exists to draw electrons emitted from the surface back to the insulator surface. It has been shown previously that the important electrons in the electron multiplication process are the low-energy ones emitted by true secondary emission. The average energy of these is probably near 25 ev. Since the electron is free to be emitted at any angle from the surface, it will be assumed that the average tangential energy and normal energy are equivalent and equal to about 12 ev. An electron with 12 ev can travel 1.2 micron in a field of 10^5 Volt/cm.; therefore, the average height of an electron "hop" on the insulator surface would be of the order of a few microns. The time to stop the normal motion of the electron with respect to the insulator may be derived from:

$$t = \frac{\left(\frac{2\varepsilon}{m_e}\right)^{1/2}}{q^E/m_e}$$

where: ε = electron energy
m_e = electron mass
E = normal electric field
q = electronic charge
t = time

$$t = 1.2 \times 10^{-12} \text{ sec.}$$

The average up and down time of an emitted electron is then about 2 1/2 picoseconds. Since the discharge completes across the insulator in 3×10^{-9} sec., one expects approximately 1.3×10^3 impacts across the 2.5 cm of insulator surface or about 500 impacts/cm. This implies a mean free path of 20 microns between impacts.

If one considers the average gain of energy per "hop" for an electron, the mean free path can be calculated another way. The average electron transverse energy is 180 ev as measured by the streamer velocity. Assuming the electrons are born with about 12 ev of transverse energy on the average, the electrons must gain approximately 330 ev of energy on each hop in the transverse direction so that the average energy is 180 ev. Since the transverse electric field is about 2×10^5 Volt/cm one obtains about 600 hops/cm or a mean free path of about 17 microns. Thus the two calculations are in agreement to within 50% which is about the accuracy assumed for the numbers used in the calculation. A mean free path of 20 microns indicates the streamer would reach a saturation density within a fraction of a millimeter, as verified by the results of the streak photographs.

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(21) Whitehead, S. "Dielectric Breakdown in Solids". Chapter 2. Oxford University Press. 1953.

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Test Cell with Insulator in Place

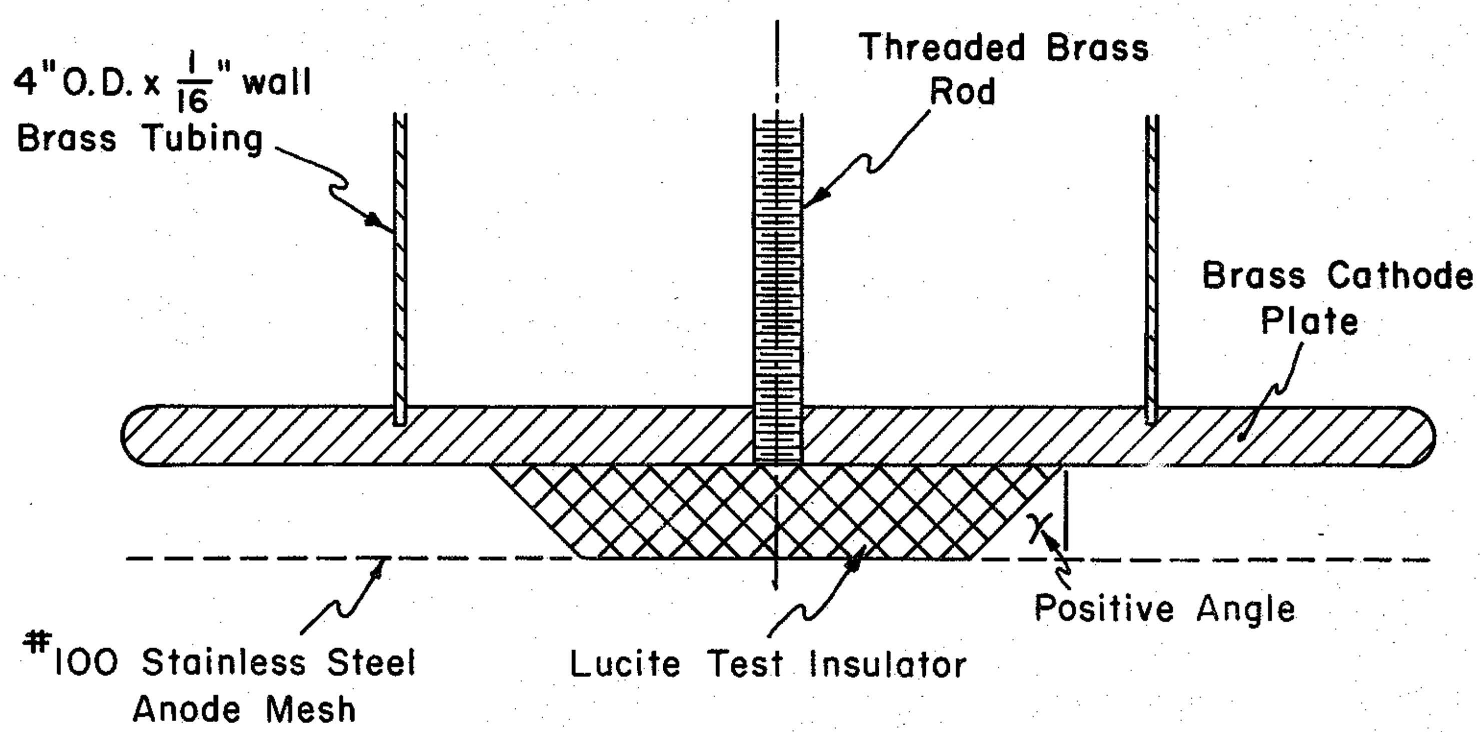


Fig. 1

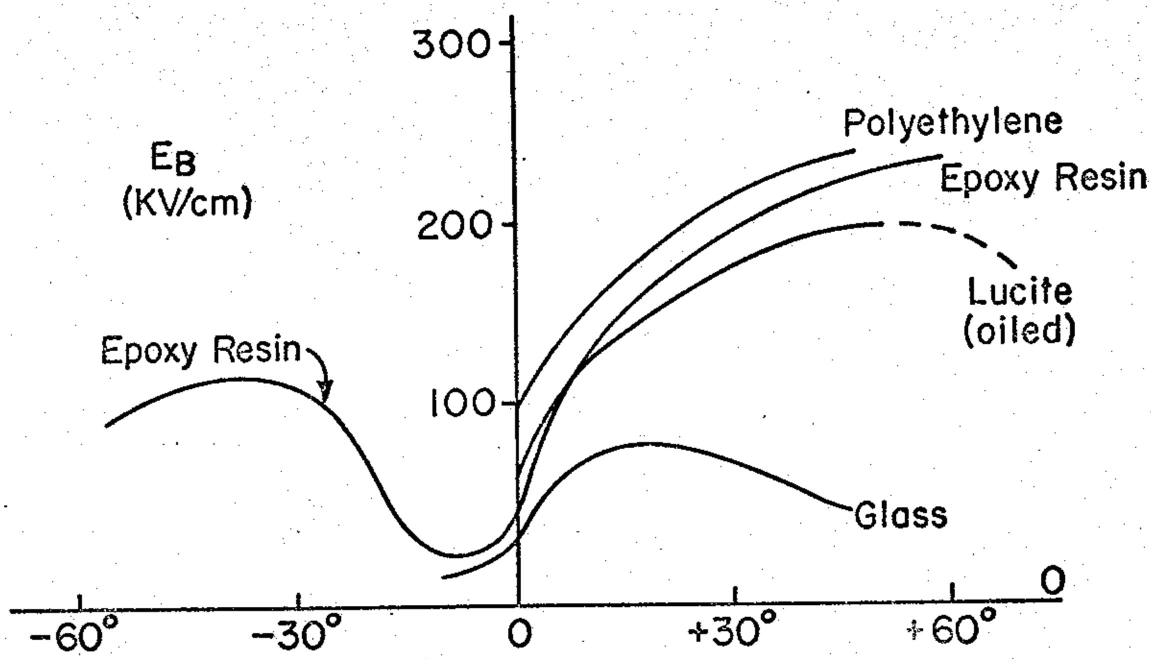


Fig. 2 Cone Angle versus Breakdown Electric Field for a 30 nsec. Duration Pulse (After Reference (3))

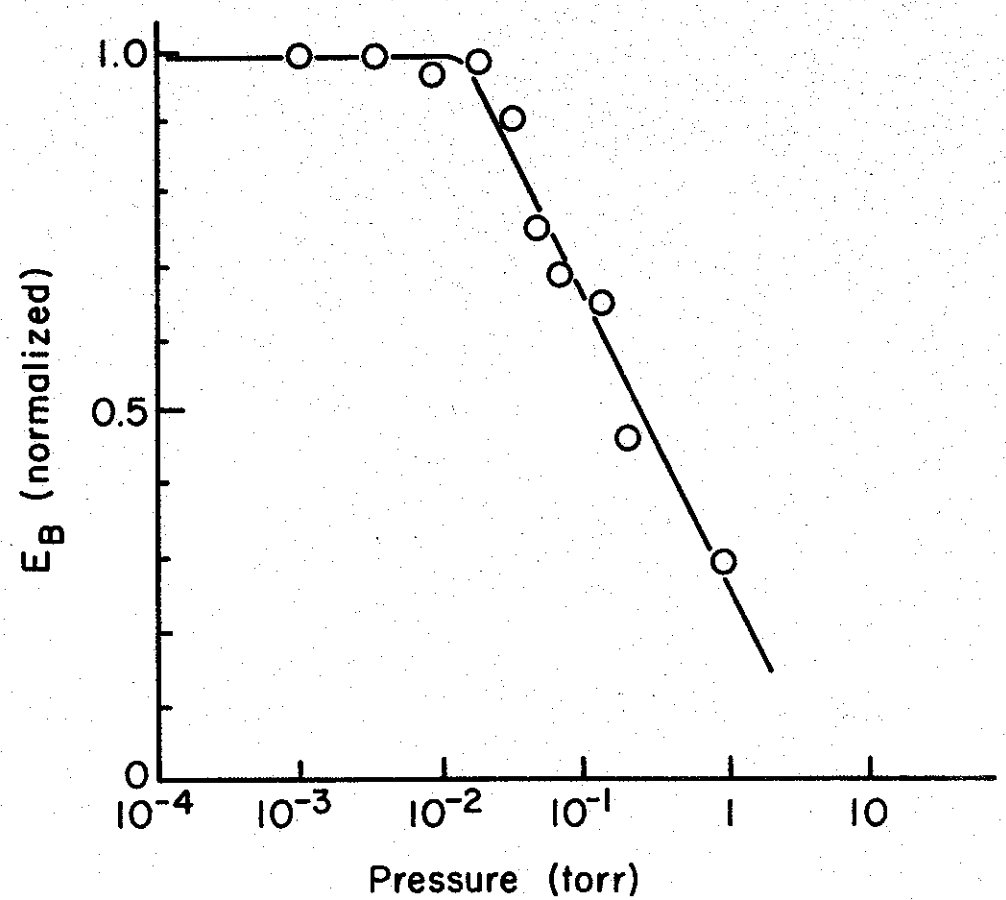


Fig. 3 Pressure Dependence of the Breakdown Electric Field for a 1" Thick, Oiled Lucite Envelope of 25° (After Reference (3))

Secondary Yield Curve and Relative Energy Distribution of Secondary Electrons

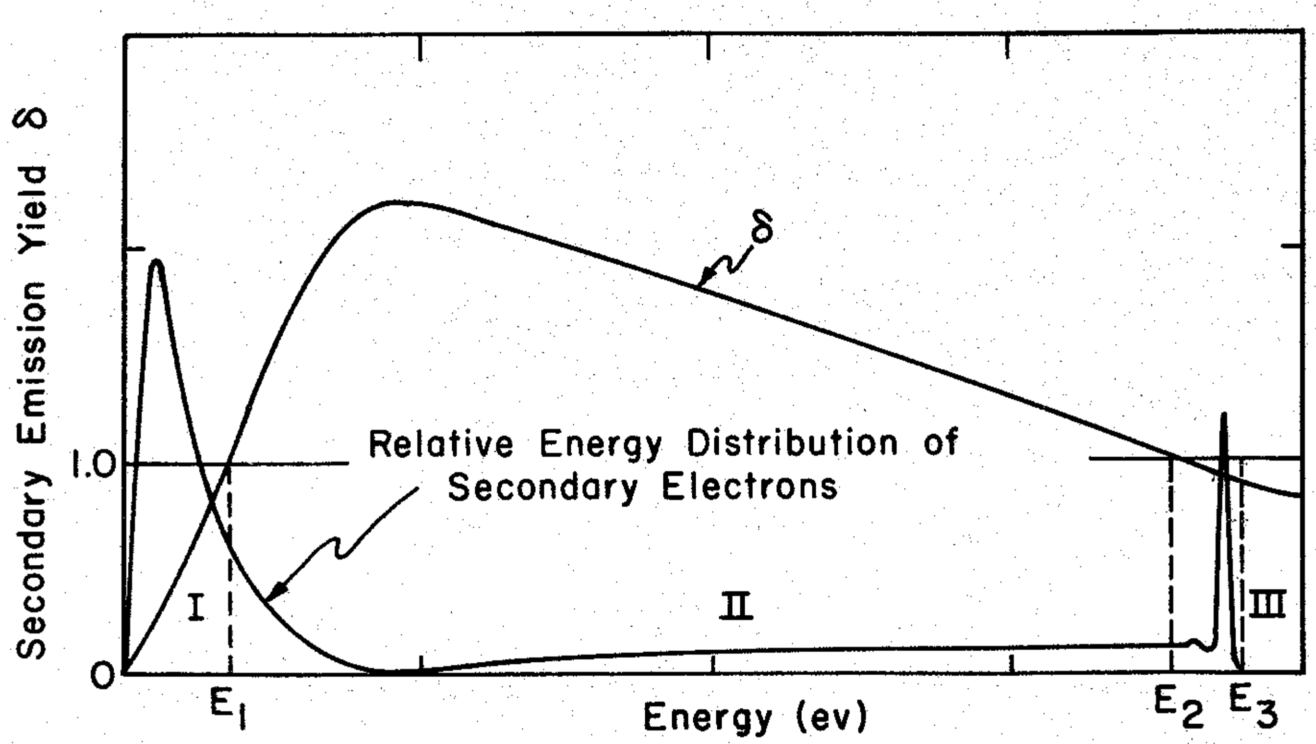


Fig. 4 These Are Typical Curves that Apply to a Wide Range of Metals, Semiconductors, and Insulators. Note that the Secondary Electron Energy Distribution is for a Monoenergetic Electron Beam Impinging on the Material Surface with Energy E_3. The Secondary Emission Yield is Greater than One between E_1 and E_2.

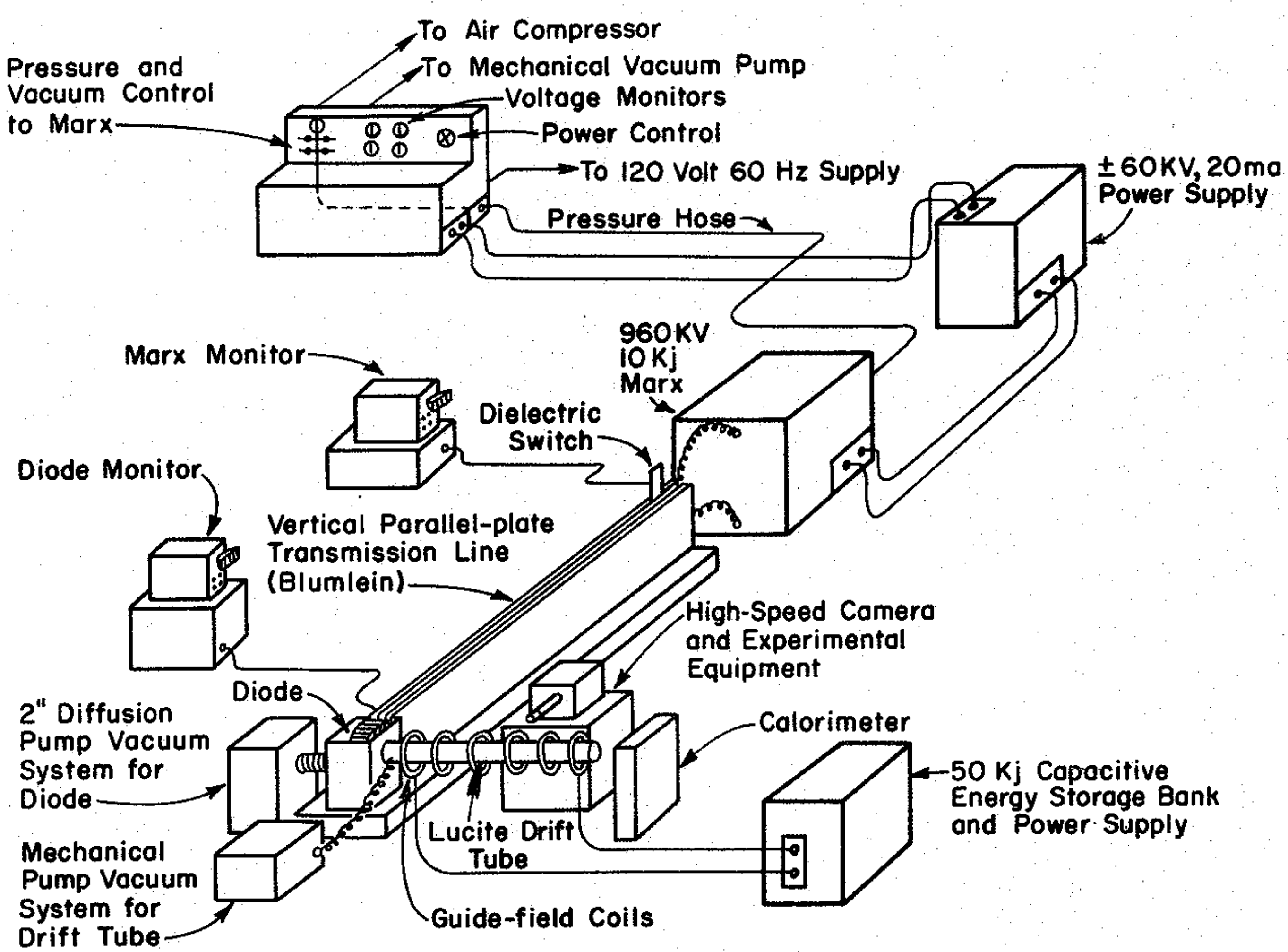


Fig. 5 Projection of the Cornell Relativistic Electron Beam Accelerator System

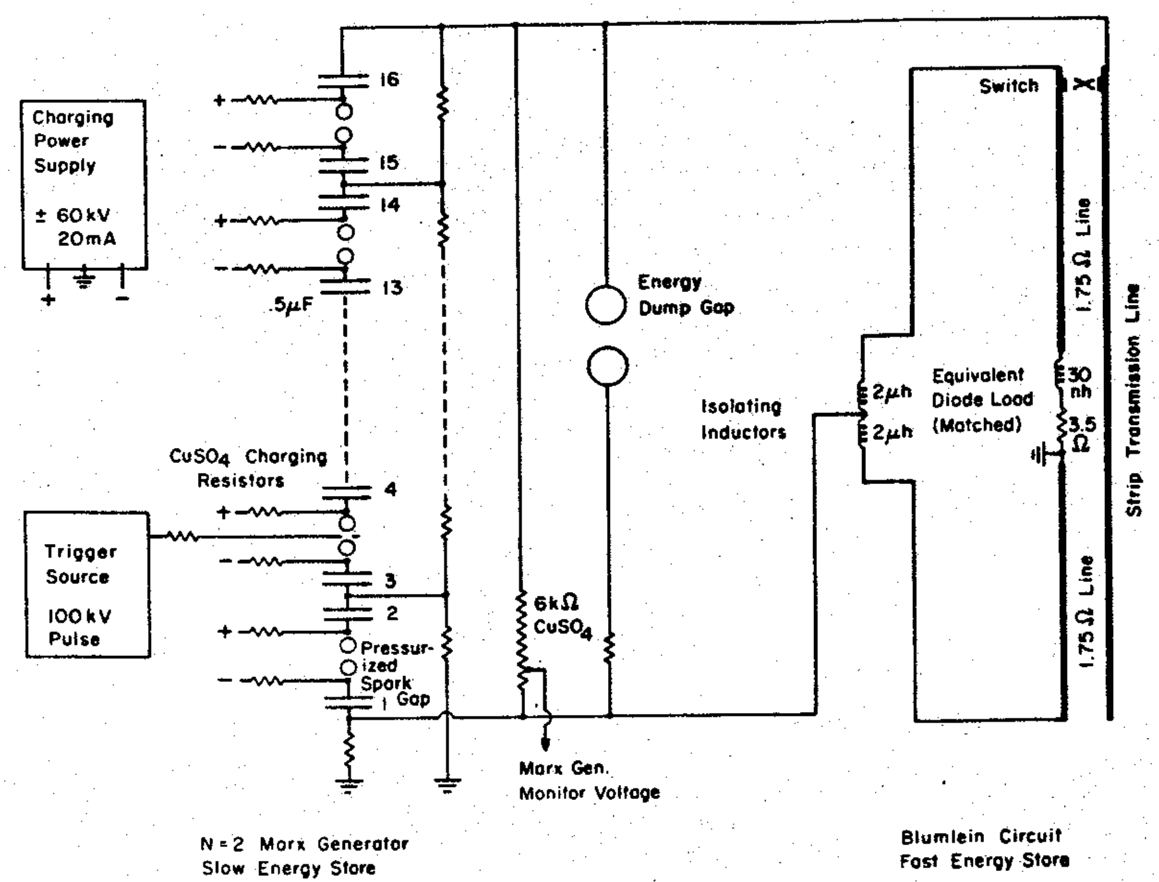


Fig. 6 Simplified System Schematic

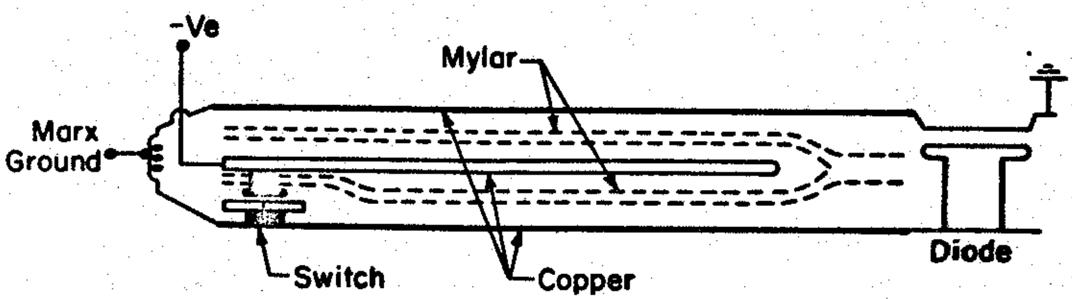


Fig. 7a Folded Blumlein Assembly

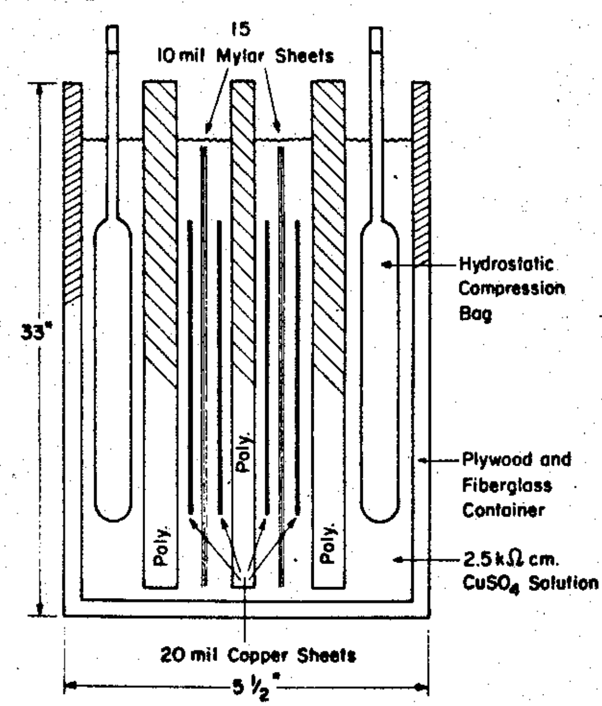


Fig. 7b Transmission Line Construction Details

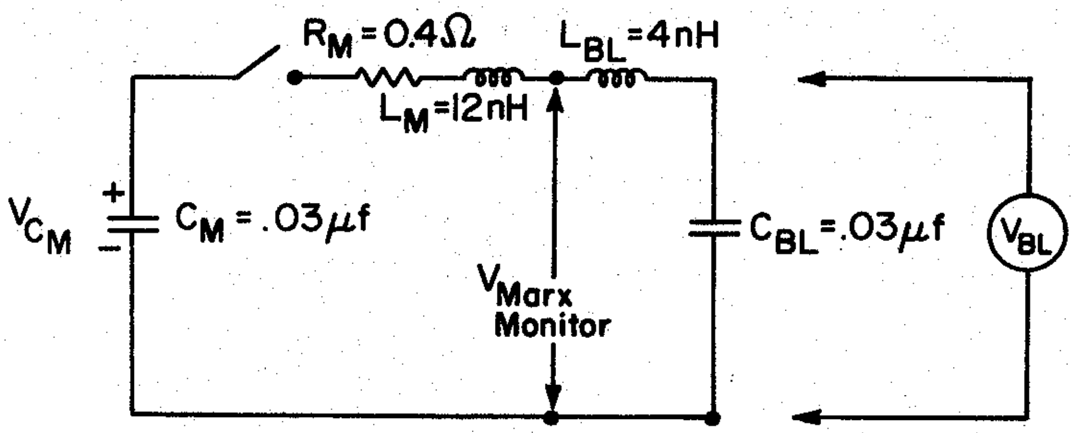


Fig. 8a Simplified Marx-Blumlein Electrical Circuit

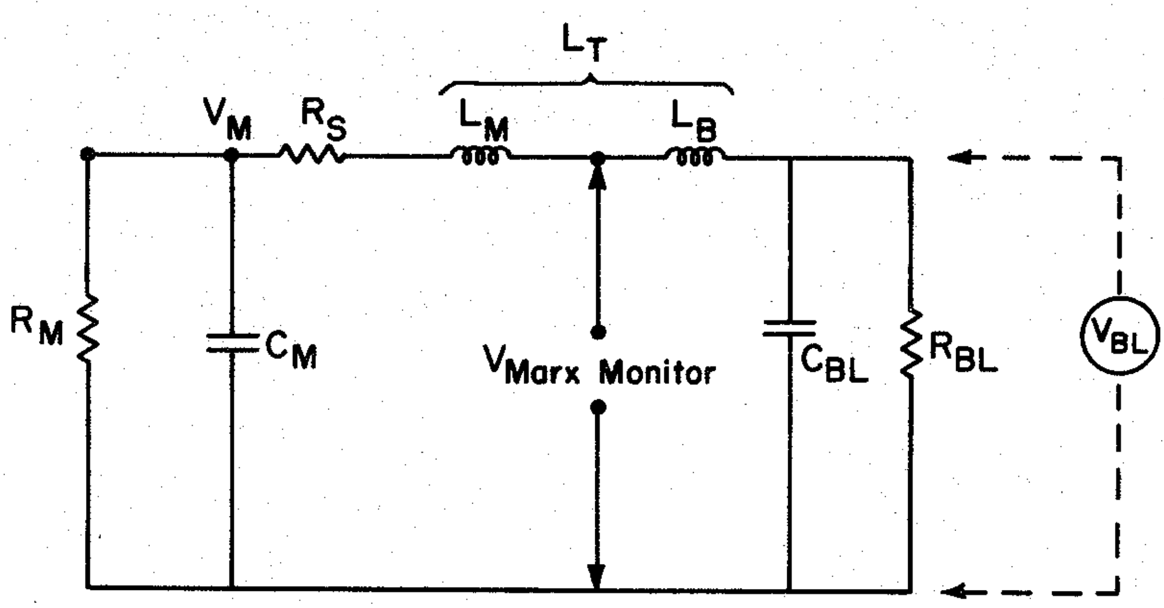
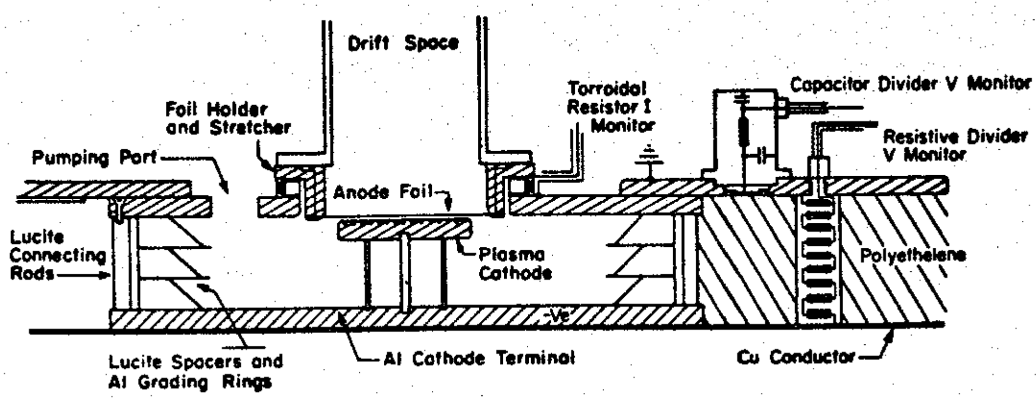


Fig. 8b "Actual" Marx-Blumlein Electrical Circuit



Diode Assembly (Approx. 1/10 full size)

Fig. 9

Test Cell

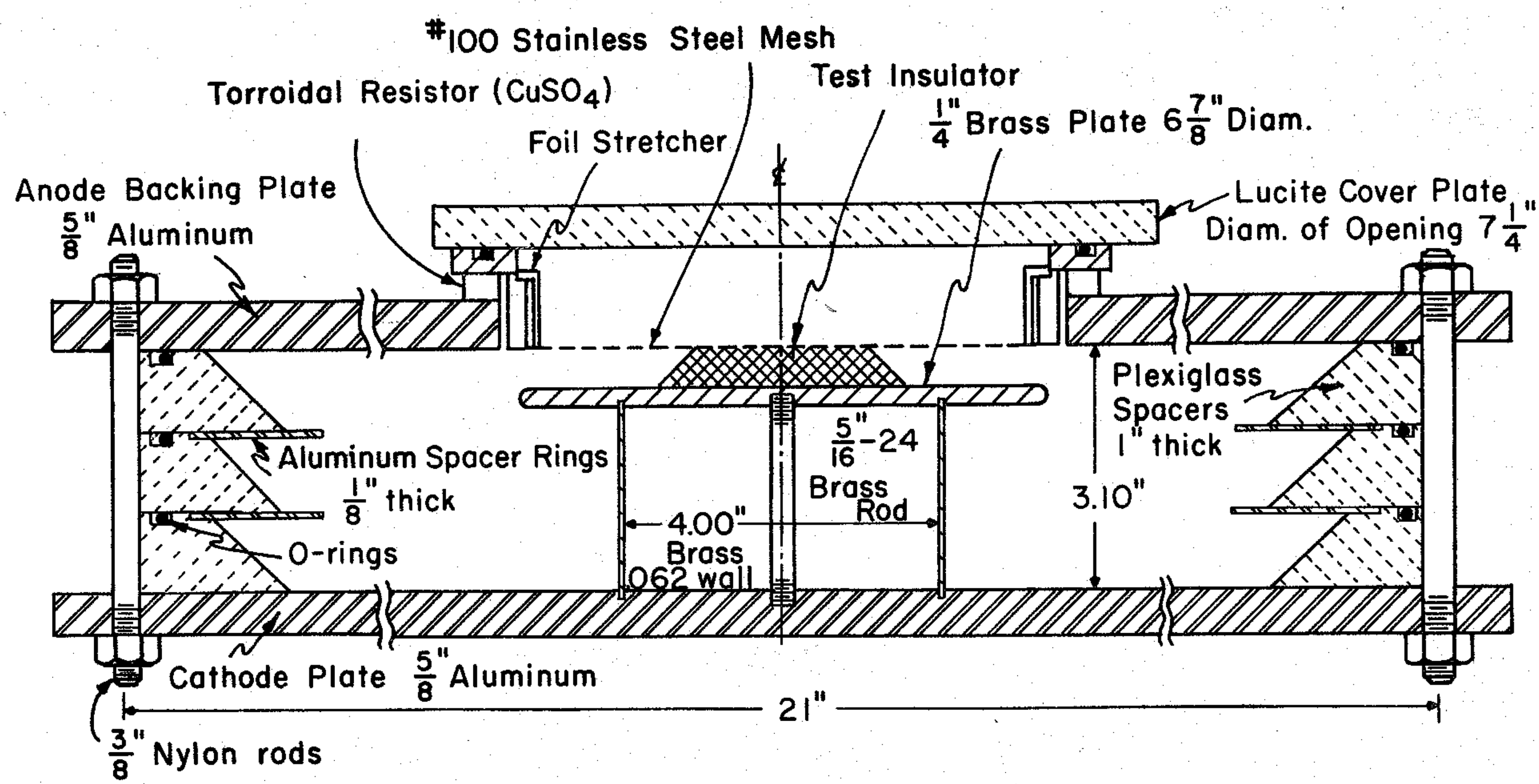


Fig. 10

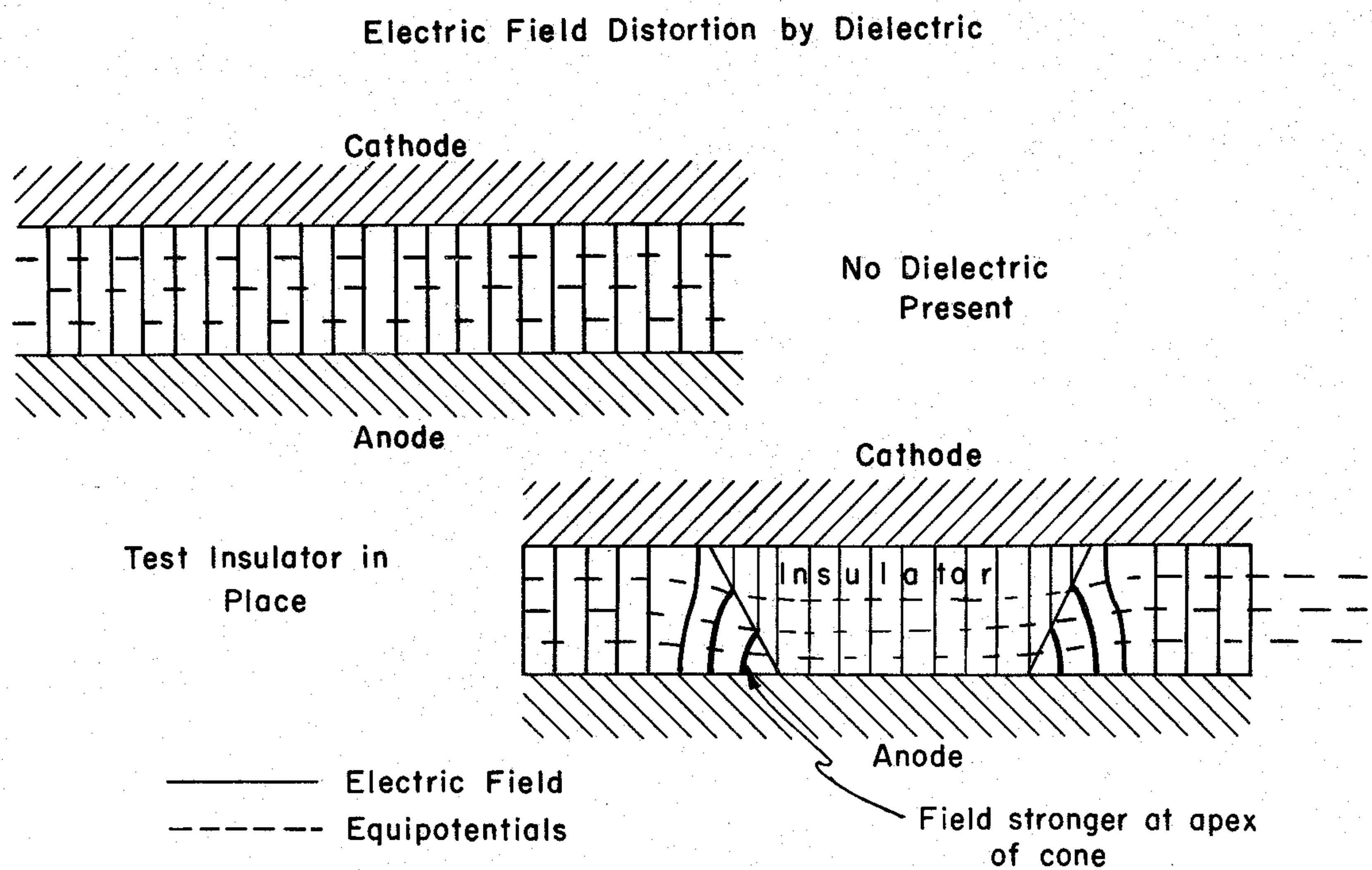

Electric Field Distortion by Dielectric
Cathode
Anode
No Dielectric Present
Cathode
Insulator
Anode
Test Insulator in Place
Electric Field
Equipotentials
Field stronger at apex of cone

Fig. 11

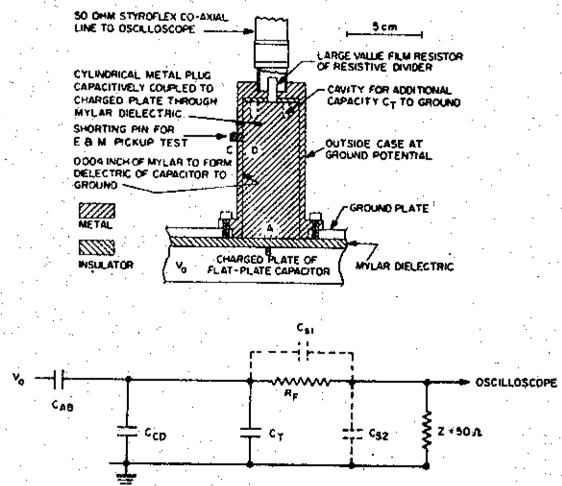


Fig. 12 Schematic Diagram of the NRL Capacitive Voltage Divider (After G.E. Leavitt, J.S. Shipman, Jr. and I.M. Vitkovitsky "Ultrafast High Voltage Probe" Review of Scientific Instruments Vol. 36, No. 9, 1371-2, September 1965)

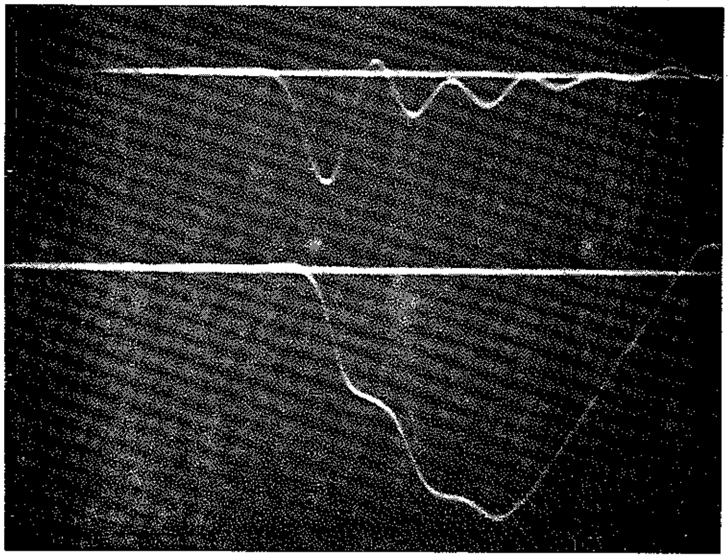
$$V_{OUTPUT} = V_o \frac{C_{AB}}{C_{CD} + C_T + C_{AB}} \left(\frac{50}{R_F + 50}\right)$$

$$T = (C_{CD} + C_T + C_{AB})\,(R_F + 50)$$

For Cornell Case $C_T = 0$, $C_S \approx 10$ pf, $R_F = 1K\Omega$

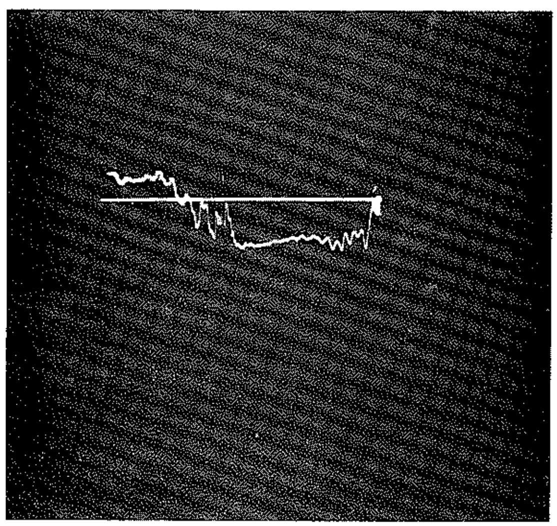
Test Cell
Voltage
286 KV/cm

Test Cell
Current
34 KA/cm



Time - 20 nsec/cm

Fig. 13 Typical Time Synchronized Test Cell Voltage and Current



Time - .96 usec/cm

Fig. 14 Typical Marx Trace

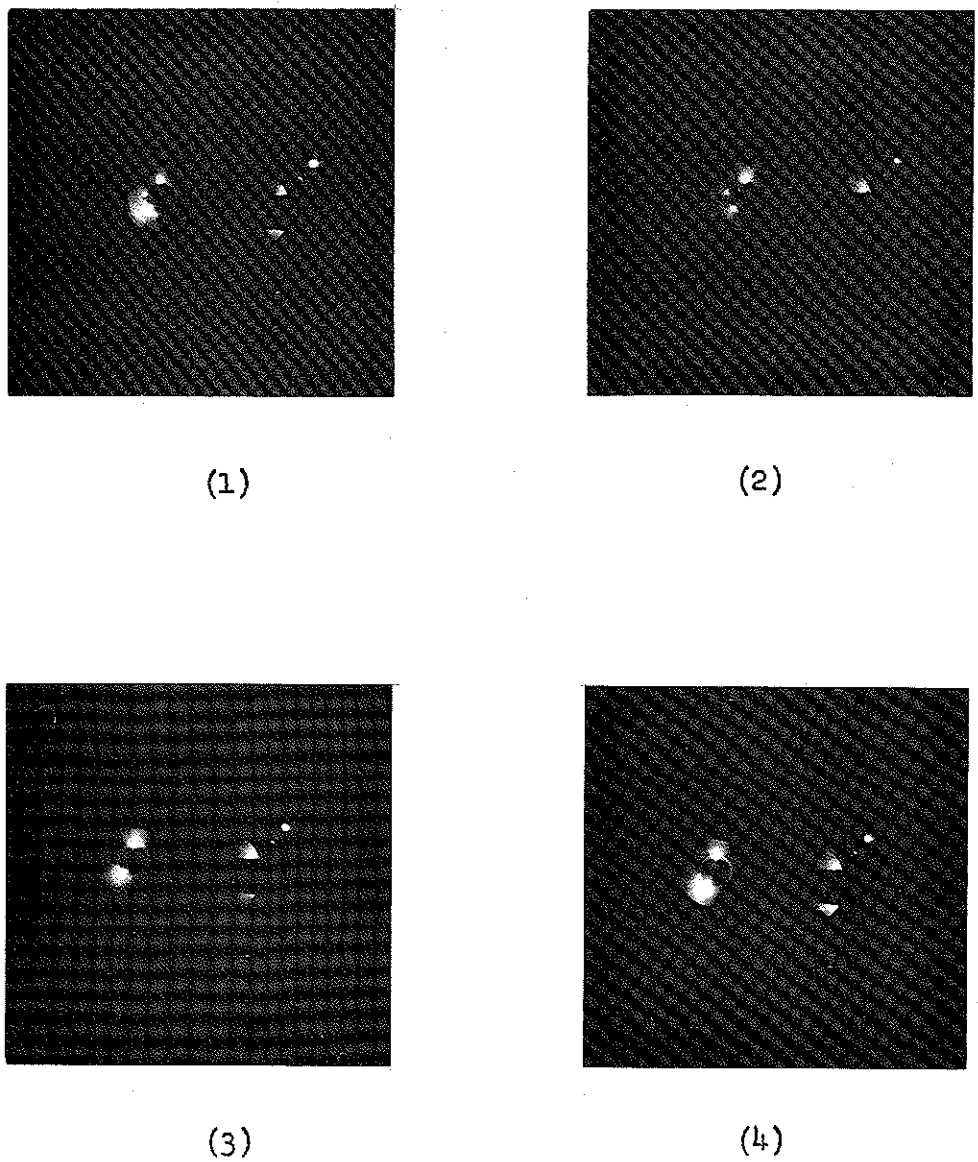


Fig. 15 Sequence of Integrated Photographs showing "Memory Effect" of the Discharge

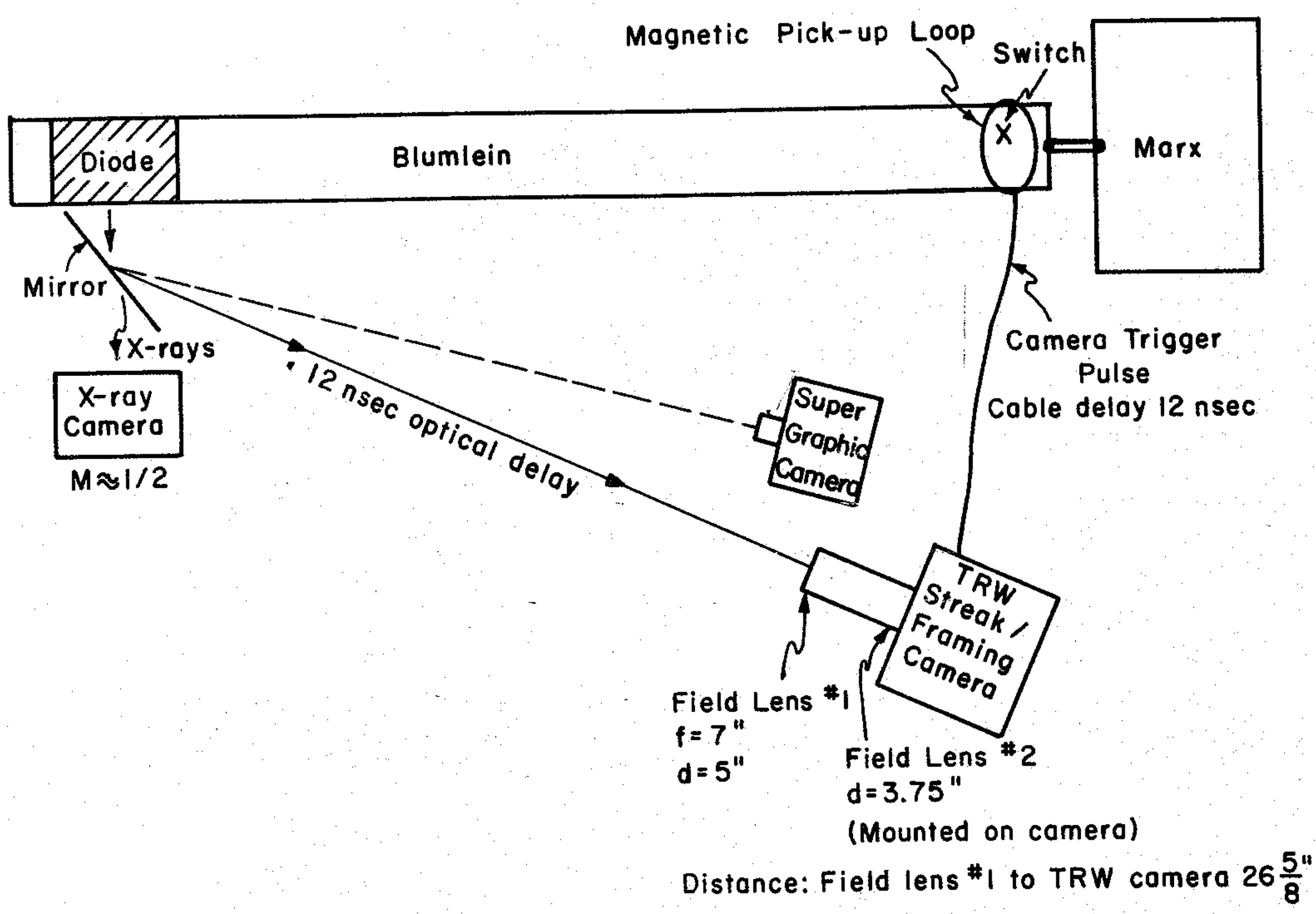
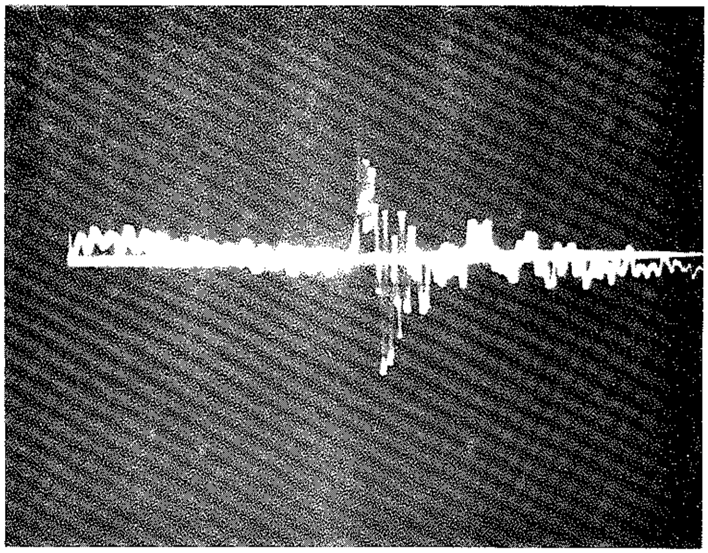


Fig. 16 Expermental Set-up for Streak Camera

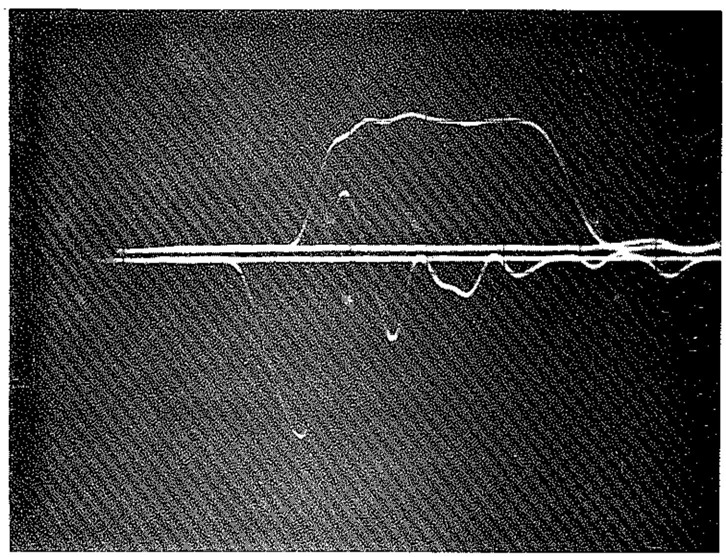


Time - .5usec/cm 157 volt/cm

Fig. 17 Typical Streak Camera Trigger Pulse

Upper Trace - Shutter Pulse

Lower Trace - Test Cell Voltage

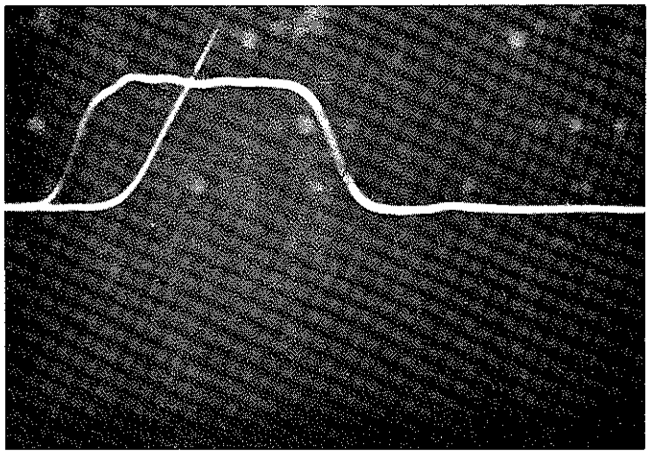


Time - 50 nsec/cm

Fig. 18 Typical Shutter Pulse Time Synchronized with Test Cell Voltage

Ramp Pulse

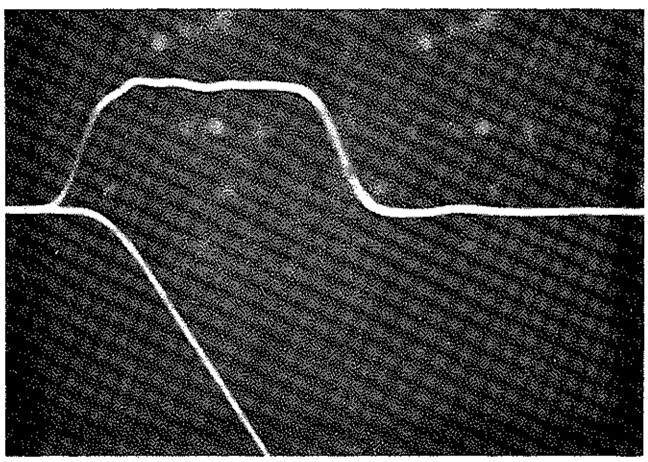
Shutter Pulse



Trigger Pulse - +300 volts
Time - 20 nsec/cm

Shutter Pulse

Ramp Pulse



Trigger Pulse - +300 volts
Time - 20 nsec/cm

Fig. 19 Positive and Negative Ramp Deflection Pulses for Streak Camera with Time Synchronized Shutter Pulse

Schematic Diagram of Ultraviolet-Irradiation Test Set-up

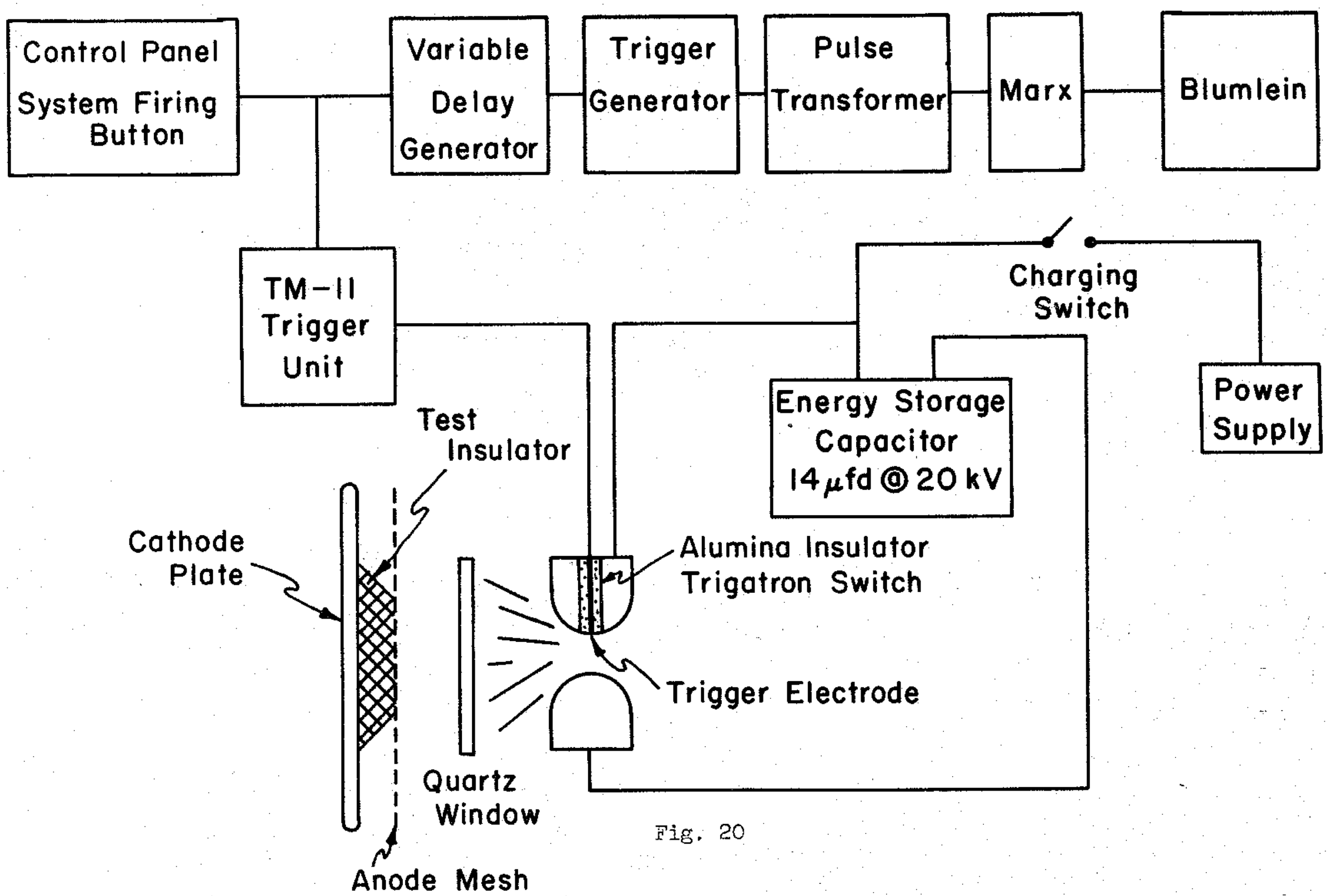
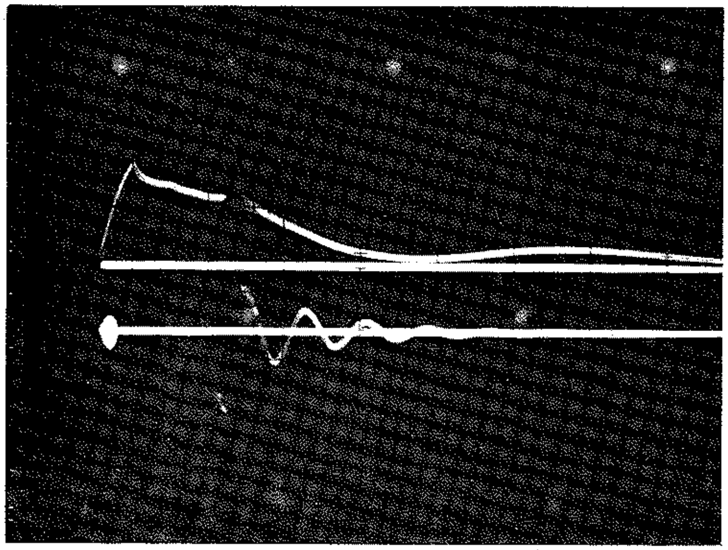


Fig. 20

Upper Trace -
Photodiode
Pulse

Lower Trace -
Marx Pulse



Time - 5 usec/cm

Fig. 21 Typical Photodiode Output Pulse Time Synchronized with the Firing of the Marx

Magnetic Field Test Set-up

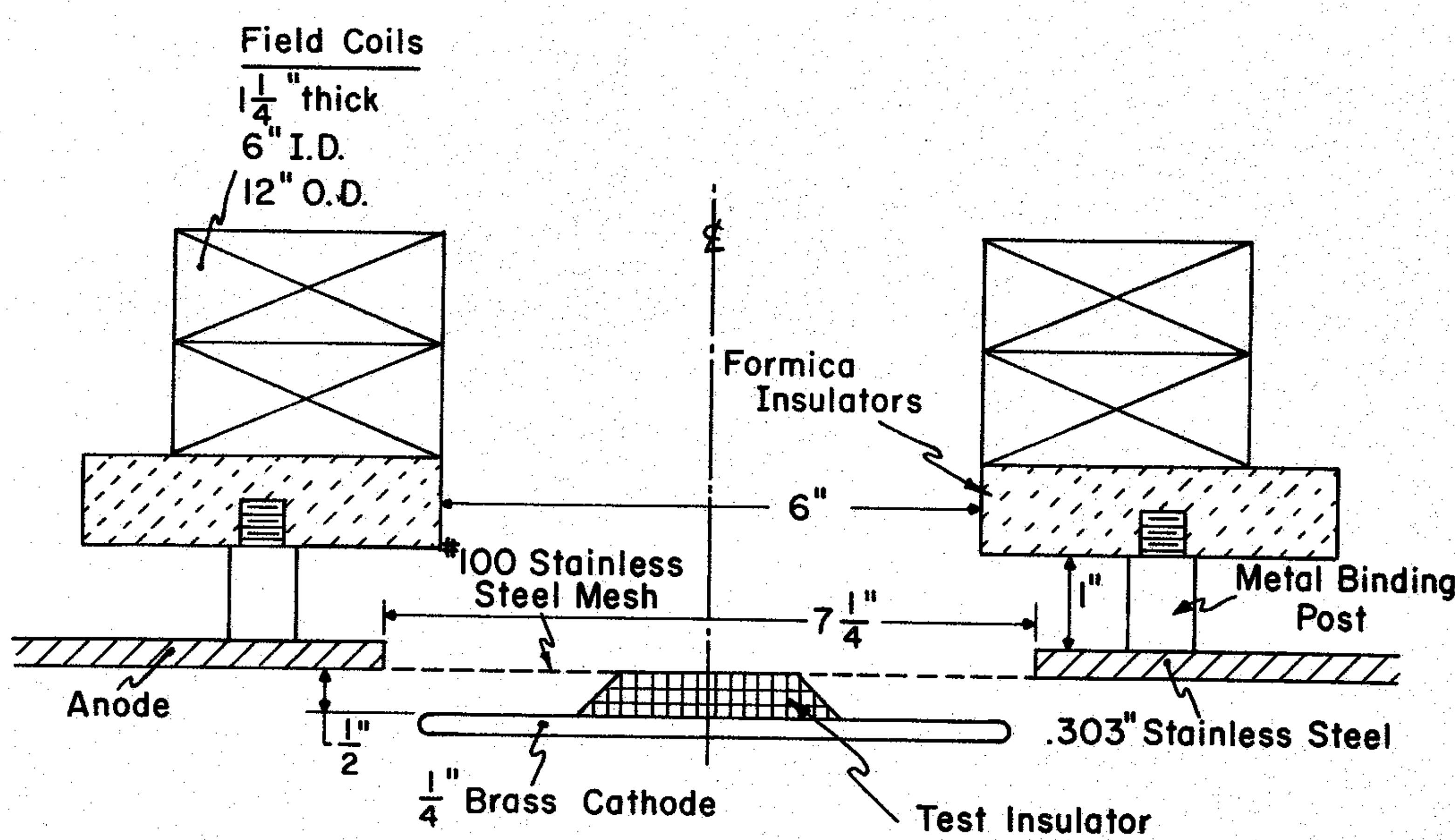


Fig. 22

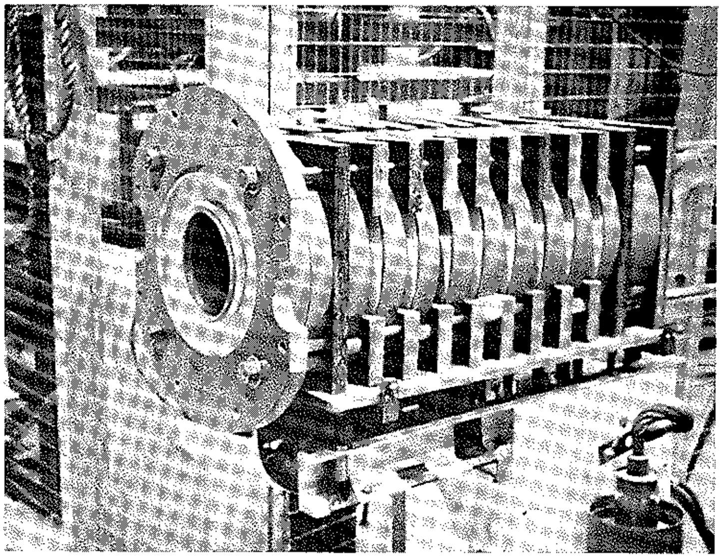
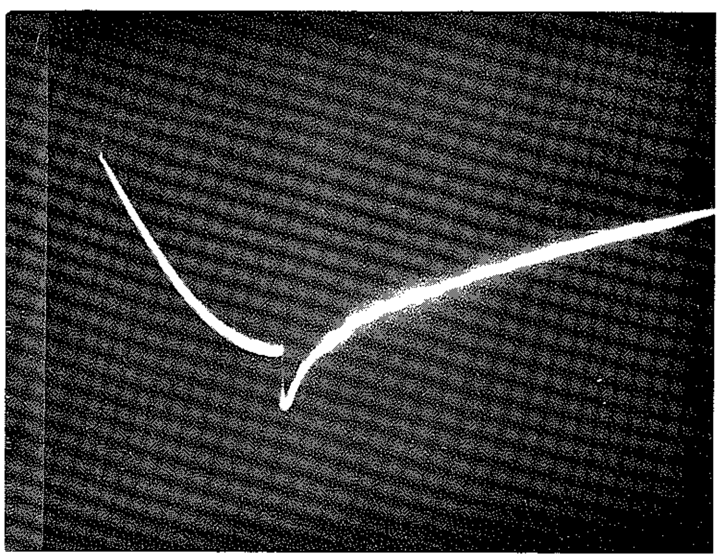


Fig. 23 Magnetic Field Coils



Time - 5 msec/cm

Fig. 24 Typical Field Coil Discharge Current

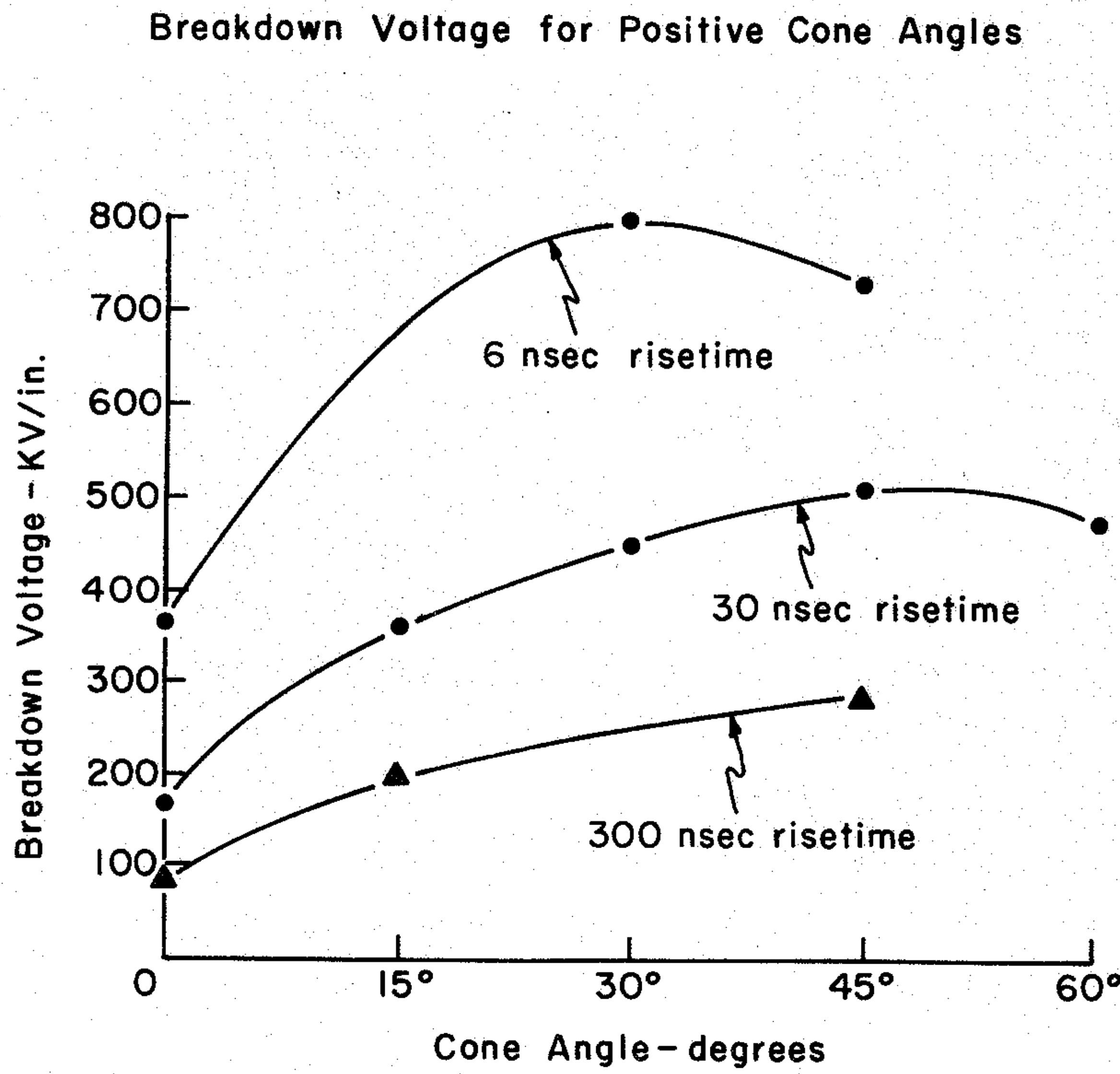
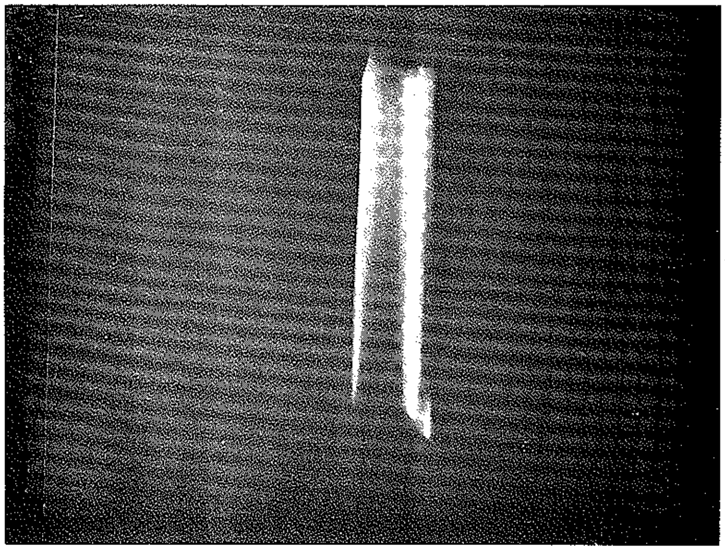
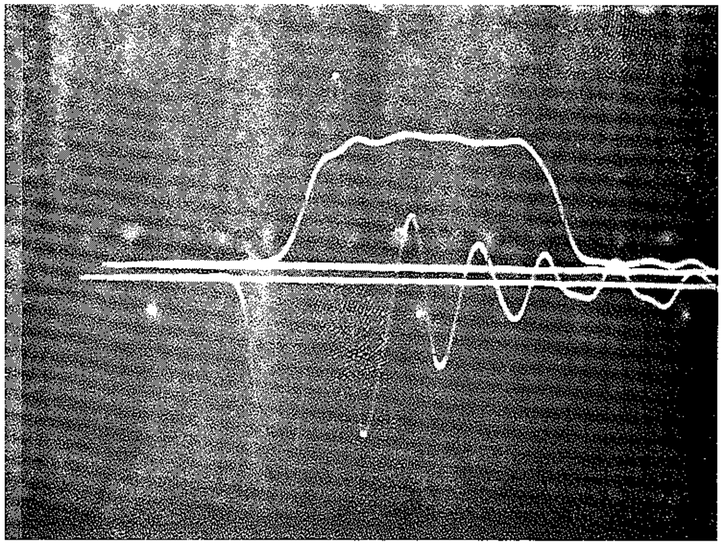

Breakdown Voltage for Positive Cone Angles
800
700
600
500
400
300
200
100
0
15°
30°
45°
60°
Breakdown Voltage - KV/in.
Cone Angle - degrees
6 nsec risetime
30 nsec risetime
300 nsec risetime

Fig. 25



Streak Photograph
Time - 10 nsec/cm (image swept upwards)

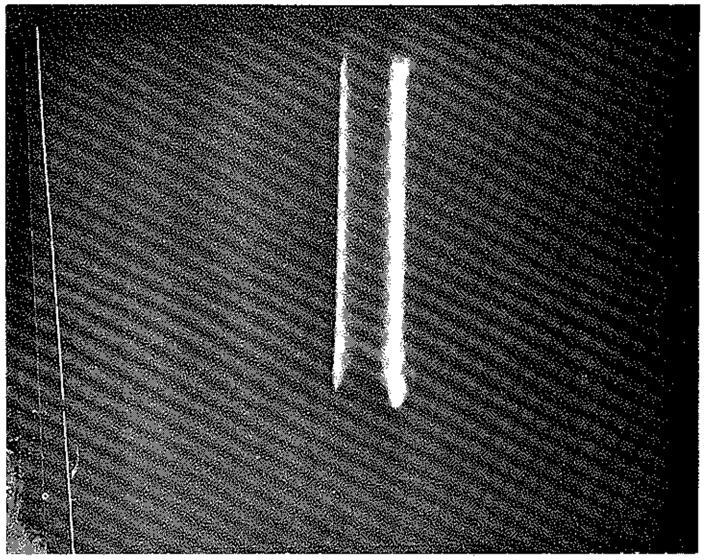
Upper Pulse - Shutter Pulse



Lower Pulse - Test Cell Voltage

Time - 20 nsec/cm

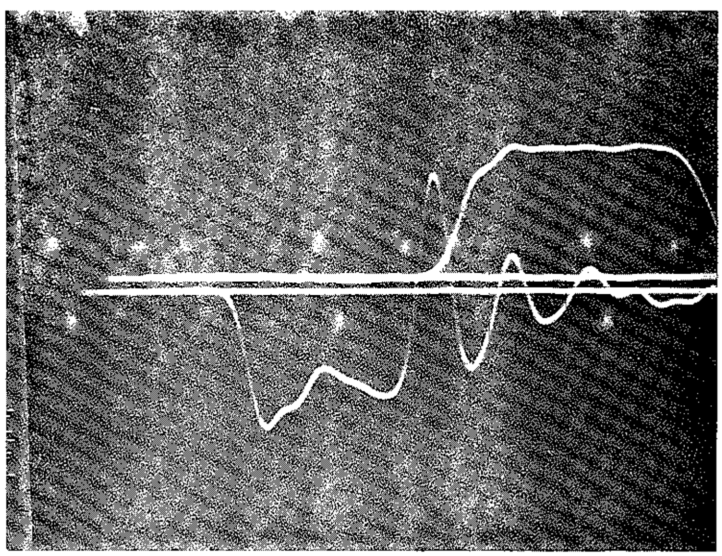
Fig. 26 "Good" Streak Photograph with Time Synchronized Shutter Pulse and Test Cell Voltage



Streak Photograph
Time - 10 nsec/cm (image swept upwards)

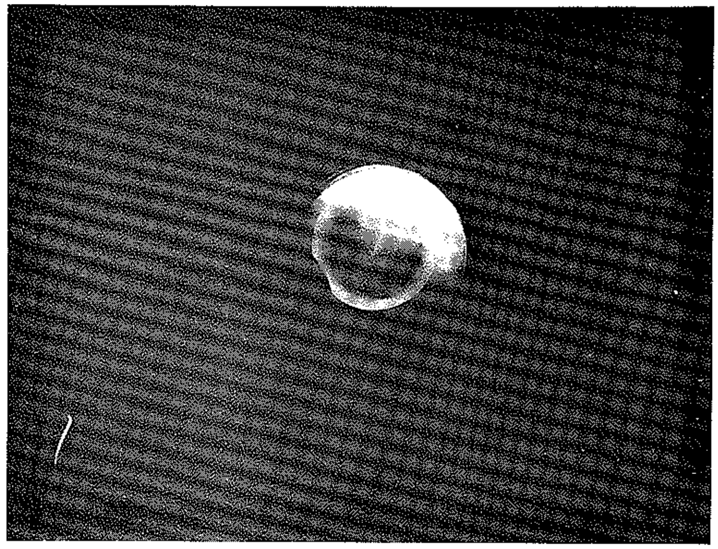
Upper Pulse - Shutter Pulse

Lower Pulse - Test Cell Voltage

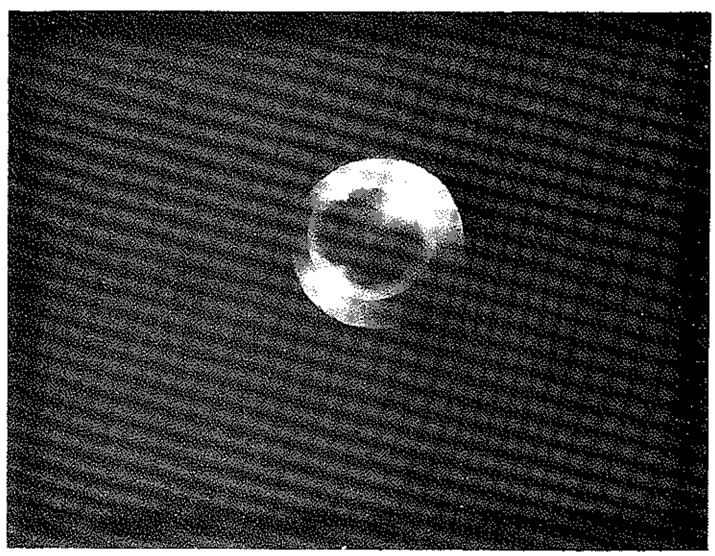


Time - 20 nsec/cm

Fig. 27 "Bad" Streak Photograph with Time Synchronized Shutter Pulse and Test Cell Voltage Pulse



5 KV on Field Capacitor Bank



No Field

Fig. 28 Integrated Photographs of Discharge with and without Magnetic Field

Field Emission Current
as a Function of Field
Strength and Temperature

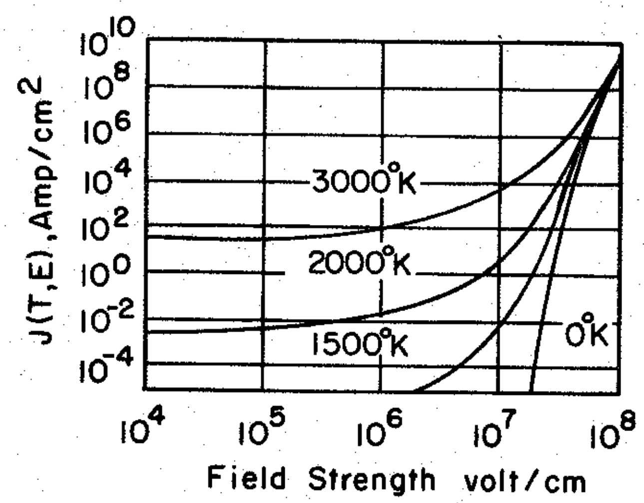


Fig. 29

Energy Band Structure
for an
Imperfect Insulator

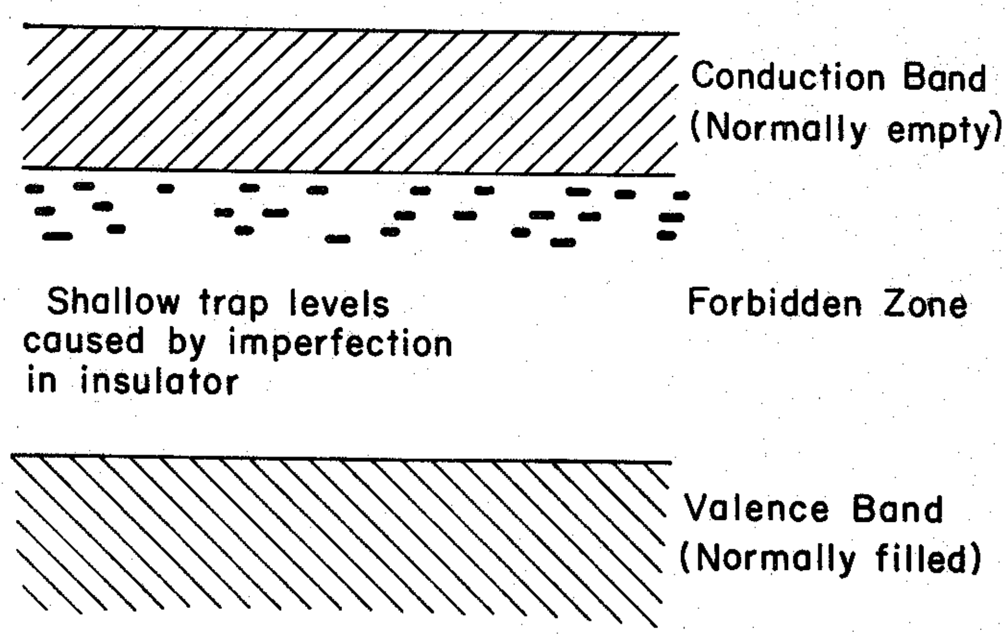


Fig. 30

σ_{CRIT} for Various Cone Angles and Pulse Risetimes

Cone Angle	Risetime – nsec. 6	Risetime – nsec. 30	Risetime – nsec. 300	Average for each cone angle
0°	2.0×10^{10}	0.8×10^{10}	0.7×10^{10}	1.2×10^{10}
30°	2.8×10^{11}	2.1×10^{11}	2.9×10^{11}	2.6×10^{11}
45°	2.1×10^{11}	3.2×10^{11}	4.2×10^{11}	3.2×10^{11}

$$\sigma_{CRIT} \sim E_{CRIT}^{3.3}\, t \;(\mathrm{Volt}^{3.3}\text{-sec})$$

Fig. 31