

DISCHARGE PULSE PHENOMENOLOGY

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A model is developed which places all of the published radiation induced discharge pulse results into a unified conceptual framework. Only two phenomena are required to interpret all space and laboratory results:

- a) Radiation produces large electrostatic fields inside insulators via the trapping of a net space charge density, and
- b) The electrostatic fields initiate discharge streamer plasmas similar to those investigated in high voltage electrical insulation materials; these streamer plasmas generate the pulsing phenomena which have been seen by many workers.

The apparent variability and diversity of results seen to date in space and laboratory experiments is an inherent feature of the plasma streamer mechanism acting in the electric fields which were created by irradiation of the dielectrics. The implications of the model are extensive and lead to constraints over what can be done about spacecraft pulsing.

INTRODUCTION

At first look one is struck by the diversity of pulsing results reported on spacecraft and ground testing of irradiated dielectrics. A new vocabulary has been developed in this community (blowoff, bulk pulsing, punchthrough, surface discharge, brushfire, bi-layer, charged-surface, floating-conductors, breakdown-potential) which may be responsible for unnecessarily increasing the diversity of results. Until recently, experimenters were hindered by the facts that the field of investigation was still young and that apparently new observables kept appearing. One experimenter would observe flashes of light, another would see a potential drop, another measured pulses of current, still others observed microdamage after the irradiation emission of ions, emission of energetic electrons, area-charge scaling, lack of pulsing under certain spectra, cessation of pulsing under continued irradiation, pulses of opposite sign, etc., etc.

For the past decade I have been correlating the occurrence of pulses with radiation generated electric fields in the bulk of irradiated insulators. Electrical insulation breakdown and prebreakdown events are usually (ref 1,2) related to an applied electric field strength. We find that irradiated polymers begin pulsing when the estimated radiation induced electric field exceeds 100 kV/cm (ref 3). In the process of reviewing (ref 4) the spacecraft charging literature I concluded that whenever pulses were observed, the irradiation had produced internal space charge densities large enough to create fields in excess of 10^5 V/cm within the dielectric.

Researchers in the field of electrical insulation have consistently divided the phenomenon of breakdown into two parts: Prebreakdown and Breakdown (full permanent failure). So far it appears to me that we see only the prebreakdown phenomena in our space radiation situation. If one applies an electric field in excess of 10^5 V/cm to a solid dielectric, then random and very small current pulses are observed which are called prebreakdown events. These pulses are associated with flashes of light and very small discharge streamers which last on the order of nanoseconds or less. The insulator does not fail even after the occurrence of thousands of prebreakdown pulses. Such pulses are sometimes thought to be due to the failure of very small weak spots or the discharge of microvoids within the solid. I am not aware of one complete reference to this phenomenon but there are many papers dealing with various aspects of it in the electrical insulation literature. Reference 2, the IEEE Transactions on Electrical Insulation, and the annual proceedings of the Conference on Electrical Insulation and Dielectric Phenomena (IEEE sponsored) are good starting points. Prebreakdown phenomena is a rapidly growing research field which contains, in my opinion, some exciting solid state physics problems.

In this paper we show how all the spacecraft charging results, both ground and space results, can be explained by the mechanism of electric field generated pre-breakdown streamer channel formation. The electric fields are due to either applied voltages in dielectrics, or to radiation generated space charge electric fields, or to a combination of the two. The streamer formation is a quantum mechanical many-body process which is only recently being attacked with appropriate tools; its existence is observed but not understood. These processes "explain" all spacecraft effects including: area scaling, pulse height, pulse width, pulsing frequency, radiation spectrum dependencies, microwave emission, surface discharging, bulk pulse characteristics, fibrous material discharging, correlations (or lack of) with surface potential, light flashes, edge effects, emission of ions and electrons, etc.

RADIATION GENERATED E FIELDS

Estimates of radiation generated electric fields in dielectrics are available (ref 3,5-8) but only a few good measurements have been made. The measurements are difficult and actually measure charge density (ref 9,10) not electric field. The electric fields are obtained from the charge density by use of Poisson's equation. One excellent review (ref 11) is available which surveys most of the existing charge density work and is a good introduction to the literature. The literature on this topic is extensive but does not answer the critical engineering question "Given a particular dielectric device under various broad radiation spectra what electric fields are generated?" Most of the cases that have been discussed involve monoenergetic electron beams and short total irradiation times ($<10^8$ rads total dose). A few cases address the question of broad spectra but then simplify the modeling to assume no electronic conduction occurs in the electric field.

Photon irradiations simulate the broad energy spectrum situation because photon spectra themselves, as well as the excited electrons generated by each monoenergetic portion of the photon spectrum, are often broadly distributed in energy. Calculations indicate that photons from 10 KeV to 2 MeV produce electric fields of nearly 10^6 V/cm, (ref 7,12) in most practical geometries. Only for the case of slabs surrounded by very thick layers (>1 electron range) of identical atomic number material do we find field strengths below 10^4 V/cm in photon irradiated solid insulators. Photon beams produce a net charge deposition somewhere in irradi-

ated solids by a number of processes depending on photon energy but one process always occurs; the attenuation of the photon beam results in a concentration gradient of highly excited electrons which then diffuse and "pile up" in the more weakly irradiated regions, and this process will generate 10^3 V/cm fields in most good solid insulators. Other processes produce much larger fields in photon irradiated solids.

It is possible to conceive of an irradiated solid which does not develop net spatial charging. A radioactively doped insulator with uniform doping profile would not charge. But such a device would not be practical in electrical application since electrodes or surfaces remove the uniform doping constraint and create large fields near the electrodes or near the surfaces. I have not encountered a practical dielectric device which will not charge with strong E fields. The E fields are usually strongest near electrodes or near surfaces and edges and are produced partly by the divergence of the high energy electron currents (or by their flux gradients) near the surfaces and electrodes.

In practical devices only conduction processes will prevent the accumulation of excess charge to levels where E exceeds 10^5 V/cm. Basically, all highly excited (>10 eV above conduction band) electrons are stopped in solids with more than 10^5 V/cm stopping power and in the absence of conduction, this process of stopping electrons is the field limiting factor: if the electric field exceeds the stopping power of the solid, then the excited electrons would be accelerated out of the solid until the resulting field strength decreased to the stopping power. In reality, for the exposure rates expected in space ($<10^3$ roentgens/second) it is the radiation induced conductivity and the dark conductivities which are the parameters which most strongly control the electric field strengths.

One can make changes in the incident radiation spectrum until one is "blue in the face" and only insignificant changes in peak E field will result. In the highly insulating dielectrics (low conductivity) one cannot prevent fields from exceeding 10^5 V/cm, however some faulty models have been invoked to predict such impossible lower field cases by, for example, the use of so called "penetrating" radiations.

It turns out that for the best dielectrics and for nearly any radiation spectrum and any geometry the field strength will exceed 10^5 V/cm somewhere in the solid and in some special cases can reach 10^7 V/cm. To avoid this high field strength one needs only to increase the conductivity. Based on ten years experience, I find that equation 1 is a good guide to the field strength dependence on conduction processes at low dose rates ($<10^3$ rads/second). Geometry and spectrum changes will not produce more than an order of magnitude correction to equation 1 predictions.

$$(E \text{ Peak}) \approx 10^{-12}/k(1+\sigma/kD) \quad (1)$$

where: 10^{-12} has units of (sec·V)/(cm²·ohm·rad),
 k is the coefficient of radiation induced conductivity in units of (sec/ohm·cm·rad),
 σ is the dark conductivity in units (ohm·cm)⁻¹,
 D is the average dose rate in the volume of interest in units of rads/sec.

For the best dielectrics k is typically 10^{-18} (seconds/ohm·cm·rad) resulting in peak fields of 10^6 V/cm. Of course k is dependent on many things including D, so one must evaluate k at the dose rate of interest, D, using eq 2.

where RIC is empirically determined for the dielectric material in question. References 3-8, 12 and 13 have examples of electric field strength profiles in irradiated dielectrics. Reference 3 compares the occurrence of pulses with the electric field strength in irradiated dielectrics.

ELECTRICAL INSULATION BREAKDOWN PHENOMENA

Background

While surveying the breakdown literature I learned that there are apparently many failure modes for electrical insulation. In most of the modes a very large current flows for long enough times to blow a fuse or kill a power supply. However, in most of the spacecraft tests to date we only see rapid pulses without permanent failure and without continued pulsing.

In the insulator industry this kind of pulsing is known as high voltage DC prebreakdown phenomena. If one applies an electric field of order 10^5 to 5×10^5 V/cm to a good dielectric, small pulses may occur as depicted in figure 1 for a period of an hour or so and may even reoccur for a short time again many days later but usually the short pulses have stopped unless one changes polarity or increases the field strength. These pulses are called prebreakdown events and usually do not lead to full breakdown. However, if one applies sufficient field strength a rapid burst of prebreakdown pulses will be immediately followed by full breakdown of the insulation.

In the case of space radiation it is unlikely that total breakdown occurs because there is no "stiff" power source which can continue to provide significant current to the system. Even though peak currents approaching 10^3 amperes have been seen during short pulses, the dielectric was not destroyed as an insulator by one pulse. With maximum differential potentials of 10^4 volts and incident currents of 10^{-9} A/cm² we find that space radiation cannot produce a d.c. power flux exceeding 10μ Watts/cm². It is unlikely that such low power flux will permanently change an insulator into a conductor. Thin oxide electronic device insulations, however, are hurt by the transient pulses.

The most common dielectric experiment is shown in figure 2. A current is measured between two electrodes while the dielectric is irradiated and/or biased. Any currents or current pulses, including the motion of irradiation driven charged particles (usually electrons), will register on the meter according to the equation in figure 2. If one measures I throughout the irradiation and independently knows the dose-depth and charge-depth distributions for the radiation then one can calculate the E fields internal to the dielectric (ref 3,7). Pulses will also show up on the meter according to the equation. The experiment in figure 2 is the most generally useful arrangement.

A common embodiment of figure 2 is to have most of the space between $X=0$ and $X=A$ in vacuum and thin layer of solid dielectric of thickness d from $X=A-d$ to $X=A$. Again, electric fields build-up in both the vacuum and the dielectric but space-charge accumulates only in the dielectric. Because space-charge cannot accumulate in the vacuum, charge current flowing in the vacuum must be a constant across the vacuum

space (in the quasi-static approximation which is valid for this spacecraft problem) although it can vary in time.

Consider an idealized current pulse of arbitrary magnitude J_p . Let $d \ll \lambda$. Then if J_p occurs in the vacuum region, it must be constant across the vacuum and

$$I = \frac{1}{A} \int_0^{A-d} J_p \cdot dx \approx J_p$$

But if J_p is confined to the dielectric then

$$I = \frac{1}{A} \int_{A-d}^A J_p \cdot dx < \frac{d}{A} J_p \quad (3)$$

To date, most experiments were designed such that $\frac{A}{d} \approx 5000$.

Thus pulses confined to the dielectric will be detected much more weakly on the ammeter I than similarly sized pulses in the vacuum will be detected. Therefore an ammeter set to a scale to detect pulses in the vacuum will not detect similar pulses in the dielectric.

The Basic Phenomenon

All of the observed pulsing phenomena reported by spacecraft charging investigators can be explained as normal derivatives of the streamer phenomenon described in reference 2 and reported extensively in the prebreakdown electrical insulation community. It is found that solid dielectrics subjected to electrical stresses greater than 10^5 V/cm (and in some instances as low as 10^4 V/cm) spontaneously develop streamers of gas/plasma phase matter which start at a point but rapidly expand along a line roughly parallel to the local electric field vector. The streamers tend to form tubes whose diameters are in the range 0.1 to 10 microns (typically 1 micron) but can become much larger where many streamers join together, and appear to have no limit to their maximum length. Streamers continue to propagate as long as sufficient E field exists at the tip of the streamer.

Figure 3 is a pictorial streamer. Stop action photographs indicate that streamers are usually brightest at their tip but emit light throughout their length. The insulation industry reports a wide range of propagation velocities from 10^3 to 10^6 m/sec but for conditions of electron irradiation Balmain et al. report (ref 14) velocities of 10^5 to 10^6 m/sec. In Balmain's case streamers propagate at or just beneath the surface and surface effects may play a role in the propagation velocity so it might be instructive to do similar tests for the deeper penetration case.** Under electron irradiation it appears that streamers originate at a surface (where the field strength is maximum) and propagate to or a little beyond the average

**footnote: deeper penetration will not be obtained by raising the energy because the surface potential rises to slow the incident electrons to roughly 2 keV incident energy. Most of the irradiation in Balmain's experiments was by 2 keV electrons. Instead, we should ground the surface with UV photons or low energy protons (ref 13).

trapped electron depth whence they turn at right angles and spread out at this depth; the right angle turn is made because the plasma filled streamer has almost eliminated the potential difference between the tip of the streamer and the dielectric surface so that the E field vector at the tip is now perpendicular to the original field direction and pointing towards the centroid of the spacecharge electrons (ref 15).

Streamers have been seen to occur in many materials (liquid, crystals, glasses, polymers) used for insulating purposes. In all these materials streamers similar to those reported by Balmain (ref 15), by Gross (ref 16), and by the many people using irradiation to create Lichtenberg trees, are occurring in dielectrics which are under electrical bias stress alone.

It appears that the basic streamer forms as a highly ionized plasma tube. The plasma is extremely dense and under high pressure so that when it approaches a surface it "explodes" from the surface allowing plasma subsequently formed at the streamer tip to escape through the tube. At the cessation of the discharge propagation one finds the remains of the discharge to be a tree or bush shaped network of hollow tunnels. Reference 17 reports on measurements of this highly ionized plasma debris which escapes the solid. In the case of applied electric bias experiments, the plasma may be confined to the dielectric by the electrodes so that hollow tunnels do not occur and the plasma resolidifies in place. However, if the plasma tube propagates between electrodes entirely across the dielectric, it becomes a conductive tunnel effectively shorting out the insulator for as long as the power supply can maintain sufficient plasma arc power to continue the plasma between the electrodes.

Although streamers have been seen to develop at 10^4 V/cm applied bias, they may have actually occurred at localized high field regions due to space charge which was developed by conduction process. I would guess that at least 10^5 V/cm is required to initiate streamers but that once formed they can continue to propagate in lower field regions, perhaps in regions of field strength as low as 10^4 V/cm or less.

The streamer obtains its energy from the electric field, not from the space charge itself. For typical geometries the spacecharge density developed under irradiation is in the range 10^0 to 10^4 coulombs/meter³. Thus a one micron diameter tunnel intersects from 5 to 5×10^4 excess trapped charges (electrons, holes, ions) per centimeter of propagation. Assuming that a reasonable fraction of the atoms within the tube are ionized by the streamer propagation/formation process there are of order 10^{10} ions and free electrons per centimeter of 1 micron diameter tube. Thus the excess spacecharge contributes very little to the plasma density.

I don't know of any physics which can predict the occurrence of these streamers. Electric field strengths of 10^6 V/cm probably cannot accelerate an internal free electron much beyond 10 eV kinetic energy because at higher kinetic energies the stopping power on the free electron in, for example, polyethylene exceeds 10^6 V/cm (ref 18). Thus one free electron cannot avalanche because it takes more than 10 eV on average (probably from 20 to 30 eV) to create a secondary free electron. Perhaps, in a region of high field, occasionally it happens that sufficient local random ionization occurs to significantly alter the band structure and the dielectric constants so that the stopping power is significantly reduced and free electrons can accelerate to avalanche levels. Assume that 50 eV is necessary for free electron avalanching: then at 10^6 V/cm E field we require a thickness of order 0.5 microns

to generate this kinetic energy. A lower limit may exist on the thickness of material required to initiate a streamer and this effect is partly responsible for the increased breakdown strength of very thin film insulators. In addition, the statistics of streamer initiation are such that rare atomic level events may be the initiating mechanism; application 10^6 V/cm does not cause streamers automatically everywhere, they happen rarely and far apart relative to their size.

Empirical knowledge of the streamers allows us to explain the spacecraft charging results even though we don't understand streamer physics. Streamer propagation velocity, total streamer volume, streamer tube diameter, ionization density inside the streamer and the empty tunnel which remains, along with electric field strength, are sufficient parameters to explain the spacecraft charging phenomena. Using this empirical data and applying standard electromagnetic analysis, the rest of the paper explains the observed pulsing results. In addition, the modeling predicts results which have yet to be investigated. However, this modeling has not been tested and it would be wise to do so: for example, one should make measurements of the externally measured pulse current and relate it to the specific streamer tunnel which produced the pulse.

Electric Fields and Streamers in Spacecraft Dielectrics

The most common spacecraft charging laboratory experiment has been irradiation of thin polymer or glass sheets by approximately 20 keV electron beams in vacuum. The irradiated side (front) of the sheet can float to any potential but the other side (rear) of the sheet is attached to a grounded electrode. Experimenters have monitored current to the electrode, discharge current to the electrode, discharge current pulses to the electrode, potential of the front surface, light flashes, discharges associated surface trees, and electron, ion, and neutral particle emission from the front surface. Figure 4 is an estimate of the electric fields in a 1 millimeter thick mylar sample bombarded by 20 keV electrons (ref 13). These electric fields are crucial to an understanding of the results of the experiments.

Referring to figure 4, at 36 seconds the front surface attained a potential of -18 kV and therefore it was being bombarded by 2 keV electrons. Because of secondary electron emission the front surface will remain at this -18 kV potential as long as it continues to be bombarded by 2 keV electrons. However, the internal fields continue to evolve as shown in figure 4. The field profile at 1036 seconds is essentially a final equilibrium value as change will occur only very slowly beyond this time under continued irradiation. Reasonably similar curves would occur for teflon or polystyrene or other highly insulating solid. Notice that the 10^5 V/cm electric field strength is sufficient to initiate streamers with either polarity.

Figure 5 shows the electric field calculation for a 25 micron mylar sheet where the front surface is held at ground potential during the 20 keV electron beam irradiation. In this case even larger electric field strength occurs (exceeding 10^6 V/cm) near the front surface. If one changes the sheet thickness to any value in excess of 10 microns it turns out that only minor changes in the equilibrium electric field would occur at the front surface for either fig. 4 or fig. 5 conditions. However, the equilibrium field strength at the rear surface is roughly proportional to the inverse thickness of the sheet.

The electric field profiles in figures 4 and 5 are crucial to understanding spacecraft charging phenomena to be described below. The field profiles between the front surface and the charge centroid (where $E = 0$) are key to understanding the

phenomena because a discharging or pulsing sample under irradiation is, in the sense, hopping between the two extreme cases shown in figs. 4 and 5.

In the case of an insulator with both surfaces grounded, pulses have been correlated with the theoretical electric field strength (ref 3). The pulses occur only under field strength exceeding 10^5 V/cm. Also, the pulses had the polarity consistent with the polarity of the electric field which had exceeded the minimum field strength required for pulses in the individual sample.

EXPERIMENTAL SCENARIOS

There are several specific experiments reported in the literature. Each experiment can be explained by the streamer hypothesis as follows.

Floating Front Surface Potential

Consider the experiment of figure 6 where a dielectric in vacuum is irradiated and its irradiated surface is allowed to float to any potential. If the dielectric is thicker than the penetration depth of the monoenergetic electrons, then the front surface fields will be approximately as shown in figure 4 for any choice of beam energy above one keV. As the irradiation progresses from its inception, the potential of the surface "rises" and slows the incoming electrons until the quasi-equilibrium occurs where the secondary electron current cancels the incoming primary beam current. The quasi-equilibrium will occur when the primary electrons bombard the surface at the "secondary electron second cross-over energy" (ref.19), typically from 1 to 3 keV. The continued irradiation by 1 to 3 keV electrons produces further field strength enhancement at the front surface. At long times the sample will have lost the field contributed at early times by the deeply penetrating higher-energy electrons because of compensating conduction currents.

Assuming that:

- E_0 is the initial electron kinetic energy in eV,
- ϕ_2 is the second crossover energy in eV
- ϕ_e is the quasi-equilibrium surface potential
- E_d is the electric field magnitude in most of the bulk of the dielectric
- E_v is the electric field magnitude in the vacuum in front of the dielectric
- l is the dielectric thickness
- a is the distance from the front surface to the ground plane on the other side of the vacuum;
- R is the penetration range of initial E_0 electron beam

$$\text{then } E_0 - \phi_e = \phi_2 \quad \text{typically 2 keV,} \quad (4)$$

$$\text{and } E_v = \phi_e/a \approx E_0/a \text{ for } E_0 \gg \phi_2, \quad (5)$$

$$\text{and } E_d \approx \phi_e/l \approx E_0/l \text{ for } l > R, \quad (6)$$

but the E field near the front surface will remain as shown in figure 4 for any choice of E_0 , A, or λ greater than R.

If one monitors the potential of the front surface during an irradiation, the result is often as shown in figure 7. The front surface potential rises roughly to the "second cross over" level. After some irradiation time (which is very variable) a pulse occurs discharging the front surface. The second pulse may occur with a shorter elapsed time and at a lower surface potential than the first pulse. Subsequent pulses may occur at even lower surface potential and sometimes at very close time intervals. Finally all pulsing ceases and the surface reaches the "second cross over" level permanently.

The experimental results such as shown in figure 7 can be explained in the following way. Electric field strengths of 10^5 V/cm or greater (fig 4) cause a discharge streamer to form near the front surface and the resulting plasma erupts from the surface. The negative plasma components then accelerate across the vacuum space to the vacuum chamber walls effectively "grounding out" the surface potential. The positive components return to the surface of the dielectric spread out over most of the surface. The plasma particles actually spread out in the vacuum due to a combination of effects including pressure waves, diffusion and electric forces and then, from everywhere in the vacuum, they flow to the appropriately biased surface. The streamer channels resulting from this process are hollow, having ejected all their mass into the vacuum and producing sufficient charged particle quantities to discharge large areas; as much as 10^{-2} coulombs has been seen and a great deal more charge is probably available judging from the largest lichtenberg trees that I've seen.

The polarity of the current pulse seen in the rear electrode current monitor is such that a net electron flow occurs from the dielectric through the vacuum to the chamber walls. The surface is not discharged by streamers flowing through the dielectric to the rear electrode for a fundamental reason: If a streamer were to cross through the dielectric from the rear electrode to the the front surface, it would make a shorting contact with only a small portion of the front surface but would then burst from the front surface at high pressure spilling plasma into the vacuum. The major discharge would then proceed in the vacuum region as discussed in the preceding paragraph. However, for reasons to be published in the near future, I believe that, due to radiation alone, a streamer will not propagate entirely through a dielectric but will reach only one surface; in otherwords, for the experimental conditions published to date the so called "punchthrough" discharge is an impossibility.

The surface potential discharge measurements are discussed in references 20 through 26. The return current to the rear electrode is discussed in references 15, 20 through 26. The emission of particles into the vacuum is discussed in refs 17 and 22 and elsewhere in this conference proceedings.

So far during the irradiation we have described the first pulse which then discharges the surface. The discharged surface now changes the field profile within the dielectric increasing the field strength immediately below the surface. The incident electrons go back to their initial value of energy, say 10 or 20 keV and begin the surface charging process over again. But the electrons are, at least for a while, penetrating more deeply within the dielectric and attempting to produce field profiles as described in figure 5. Larger E fields are produced to deeper depths than figure 4 shows, but only after the first pulse occurs. It is these larger and

deeper fields which then produce more pulsing in shorter time increments. As the pulsing progresses, field strengths vary between the extremes shown in figures 4 and 5 and the depth dependence varies between these extremes. Finally, in analogy to the well known capacitor prebreakdown phenomena, all the "weak spots" between the surface and full electron penetration depth are "pulsed" and further pulsing ceases until the radiation spectra change significantly. Exact calculation of the field profiles during a series of breakdowns has not been performed so this description is only qualitative. It is well known that the streamers create physical damage but that this damage does not increase the probability for future streamer occurrence and that under d.c. stress, pulsing usually ceases after a time depending usually on the field strength.

An interesting result is predicted by the above phenomena. The field profile in figure 4 is such that a surface pulse is not likely because the field strength at the surface is not exceptional and involves very little depth. The note to figure 4 indicates that the basic concepts used to derive the figure are known to be faulty in such a way that as time under irradiation continues, electrons will drift deeper and deeper into the dielectric so that the field profile will very slowly move towards that shown by figure 5. As this drift occurs, the probability that a "weak spot" near the surface finds itself in a high field region slowly increases. Once this weak spot is found by the drifting field front, a discharge occurs and almost instantly the field strength is significantly increased in the dielectric to deeper depths and perhaps many new weak spots are found resulting in a flurry of pulses. Finally all the weak spots near the surface are discharged and pulsing ceases. This effect has not been reported formally but K. Balmain has indicated to me that the initial pulse takes a long time to occur in electron beam experiments but once it happens the remaining pulsing happens relatively soon.

If one evaluates eq. 6 for most of the published experiments it turns out that the electric field in the bulk of the dielectric beyond the electron penetration range significantly exceeds 10^5 V/cm. For example, many experiments were performed using 20 keV electrons on approximately 100 micron thick samples; this resulted in field strengths of approximately 2×10^6 V/cm. Reference 13 has calculations of electric fields in thin polymers. You are, I hope, wondering why I have neglected this large electric field which occurs in most of the dielectric. I neglect this big bulk field because it produces only very small electrical pulses (though it produces many pulses) which can not be monitored in this arrangement. The bulk pulses are similar to the pulses discussed under the section "Both Surfaces Grounded" below.

Meter Current, I, Floating Front Surface

The discharge pulse current I flowing in the meter (fig 2) depends on several variables such as front surface potential, surface area, and random fluctuations. Not every pulse causes the front surface potential to go nearly to ground potential (ref. 24). In general one finds that, (ref. 15):

- a) discharge pulse time duration \propto (surface area)^{1/2}
- b) discharge pulse current \propto (surface area)^{1/2}
- c) total discharge coulombs \propto surface area

These rules are for the conceptually simple cases where all other variables (other than surface area) such as dielectric constant, insulator thickness, and surface voltage, are held constant.

What happens if we change the other parameters? What is the physical process which causes these effects? Again the answers can be found in the streamer propagation process and its resulting plasma. Reference 15 argues that the scaling with the $\sqrt{\text{area}}$ result is due to a streamer propagation process because the streamers which propagate at a reasonably constant velocity (ref. 14) have lengths scaling as the linear dimension of the insulator which necessarily scales as the $\sqrt{\text{area}}$. In the addition, I argue that the total charge available is limited by the total volume of the streamer tunnels; and if every atom initially in the tunnel is singly ionized when it arrives in the vacuum space, there is a great deal of charge available to "ground" the front surface. Injecting an excess of charge of both signs into the vacuum space does not by itself fully ground the front surface because a great deal of the plasma charge is shielded from the electric fields by the plasma itself. Instead, the injected plasma will spread out in the vacuum in a way which depends on its initial temperature, pressure, velocity, density and vacuum E fields and then scatter off the walls of the vacuum chamber, and the scattered components may also contribute to the "grounding" of the front surface. Injecting an excess of charge however does cause the surface potential to drop with a similar statistical distribution for any surface area and this will often happen because the tunnel volume varies nearly linearly with the surface area (tunnels tend to spread out in a fan shape under the entire surface which has been irradiated).

If one were to vary the sample thickness the concepts proposed here might predict the following relationships:

- d) pulse time duration $\propto (\text{sample thickness})^{-1/2}$
- e) pulse current $\propto (\text{sample thickness})^{-1/2}$
- f) total discharge coulombs $\propto (\text{sample thickness})^{-1}$.

Varying the surface voltage might cause these scaling laws:

- g) pulse time duration $\propto (\text{surface voltage})^{1/2} f(v)$
- h) pulse current $\propto (\text{surface voltage})^{1/2}/f(v)$
- i) total discharge coulombs \propto surface voltage.

And varying the dielectric constant might give us scaling laws like:

- j) pulse time duration $\propto \epsilon^{1/2}$
- k) pulse current $\propto \epsilon^{1/2}$
- l) total pulse charge $\propto \epsilon$

The function $f(V)$ is inserted to indicate that the separation of the positive and negative components of the plasma in the vacuum is strongly dependent on the electric field strength in the vacuum such that the rapidity of grounding of the surface is sensitive to this effect.

The actual meter current, $I(t)$, during the pulse depends directly on the collapse of the vacuum electric fields caused by the separation of the plasma particles. In these experiments no external voltage source is applied, it is only the electrostatic fields due to trapped space charge which force currents to flow; therefore the current flow is purely a displacement current since no real charge flows through a complete circuit. The plasma only responds to and collapses the electric field where the plasma resides; this occurs within the streamer tubes and in the vacuum space. Figure 8 describes the geometry.

Consider the one dimensional case where plasma in the form of uniform sheets of unipolar charge is injected between two grounded electrodes placed "a" meters apart. Let there be one positive sheet and one negative sheet each of the equal charge density, ρ coulombs/m², and spaced dx meters apart.

Then the image charge density induced in either electrode by the charge sheets is given by

$$\Delta \sigma = (\rho / a) dx. \quad (7)$$

Between the sheets the electric field created by the two sheets is given by

$$\Delta E = \rho / \epsilon \quad (8)$$

and is zero elsewhere.

Eq. 7 then becomes

$$\Delta \sigma = \frac{\epsilon \Delta E}{a} dx \quad (9)$$

and the current density required to generate the image charge is

$$\Delta I = \frac{d}{dt} \Delta \sigma = \epsilon \frac{d}{dt} (\Delta E dx/a) \quad (10)$$

Returning to the problem of excess plasma generated in a vacuum between biased electrodes we can apply eq. 10 by assuming that many sheets are injected throughout the vacuum which changes E everywhere in the vacuum. Linear superposition of electric fields holds in a vacuum so we can generalize eq. 10 to

$$\Sigma \Delta I = I(t) = \frac{\epsilon}{a} \int_0^a \frac{\partial E}{\partial t} dx \quad (11)$$

where $E = E(x,t)$ is a continuous function over space and time.

Let me postulate that the dominant effect in a discharging dielectric with one surface floating is the injection of a net neutral plasma into the vacuum. The plasma spreads out in the vacuum to neutralize the existing vacuum electric fields and the meter current I is given by eq. 11. Because we do not know the dynamics of this plasma injection and spreading we can't a-priori calculate $I(t)$, but we can predict the integral over the pulse duration:

$$Q = A \int I(t) dt \quad (12)$$

where A is the surface area of the dielectric. It turns out that in most experiments Q was nearly equal in magnitude and opposite in polarity to the "so called" surface charge residing on the irradiated insulator surface (actually residing in the bulk typically within 5 microns of the surface). This is equivalent to the statement that the plasma fully collapsed the electric field in the vacuum.

The amount of charge injected by streamers will be discussed later; this should be a variable number depending on the total irradiation fluence as well as on geometrical factors.

Pulses in Dielectrics with Both Sides Grounded

An extensive set of experiments (ref 3) have been performed in the geometry of figure 2 where dielectric fills the entire space between the electrodes. In this case only small pulses were seen and negligible charge was removed from the dielectric during the pulsing process. Tunnels are seen in such dielectrics after irradiation and are probably similar to those described above. In this set of experiments thick samples were used (circa 5 mm) under high energy (circa 500 keV) electron bombardment. However, the experimental results can all be explained by the same streamer phenomena as in the floating surface case.

The tree which results from the streamer connects to an electrode at one point and branches out into the bulk of the dielectric. Again the basic principle is that the streamer is a dense plasma which can collapse the electric field in the volume occupied by the plasma. However, the streamer follows tortuous paths and the calculation of meter currents is complicated beyond the simple concepts engendered in eqs 7-12. There can be regions in the dielectric which initially have zero electrostatic field strength but once a streamer has propagated some distance it can introduce significant space charge density into these originally zero field strength regions. In other words, a streamer must initiate in a high field region but once it has traveled some distance it can create a high local field strength near its tip in a region which initially had zero electric field. In fact, the bulk of the "tree branches" in radiation induced trees occur in initially low field regions of the dielectric. In the process of forming trees, streamers can produce large current flows in relation to the current which would be required to eliminate the electrostatic fields initially present in the volume of material penetrated by the streamer. Equation 11 cannot be applied alone to this problem.

For the region of the streamer which runs parallel to the electrostatic fields eq. 11 is valid but one must remember that the cross sectional area, A, in eq. 12 is typically a square micron so that the total charge Q is very small.

In the experiments, typical fields were 10^5 V/cm so that eq. 12 provides the following estimate of charge pulse magnitude due to the portion of the square micron streamer parallel to E.

$$Q = A \int I(t) dt = (A \epsilon/a) \int_0^a \int_0^t \frac{dE}{dt} dx' dt \quad (12a)$$

Assuming that the field E is fully collapsed in some short time T, assuming that E is roughly constant and assuming the streamer passes nearly all the way through the sample, we get:

$$\begin{aligned} Q &= A \epsilon E \\ A &= 10^{-12} \text{ meter }^2 \\ \epsilon &= 10^{-11} \text{ farads/meter} \\ E &= 10^8 \text{ volts/meter} \\ Q &= 10^{-15} \text{ coulombs} \end{aligned}$$

For the region of streamer perpendicular to the initial E field the streamer propagates most commonly because of high charge density and effectively conducts this charge to the electrode. The argument is essentially that the streamer forms the path of a line integral over which every element has nearly zero E field, i.e.:

$$E(\ell) = 0 \quad \text{everywhere along path } \ell,$$

$$\frac{dE}{d\ell} = 0 = \rho$$

in analogy with Gauss' law. This condition is met when there is no net charge in the streamer tube (tunnel) which implies that the streamer removed the net charge originally along the streamer length.-----

The net charge injected by irradiation is in the range 10^0 to 10^4 coulombs/ m^3 (refs 13,27) so that per cm of tunnel length the following charge is removed:

$$\begin{aligned} \text{for } 10^0 \text{ Coul}/m^3, \quad Q/cm &= 10^{-12} m^2 * 10^{-2} m/cm * 10^0 \text{ Coul}/m^3 \\ &= 10^{-14} \text{ coul}/cm \end{aligned}$$

$$\text{for } 10^4 \text{ coul}/m^3, \quad Q/cm = 10^{-10} \text{ coul}/cm$$

Of course these estimates again assume a tunnel cross section of a square micron.

One more component of meter current flows in the streamers which are antiparallel to the original static E field. This component is the collapse of the static E field across the streamer. Eqs 11 and 12 provide an estimate of this current contribution. Assume a 0.1 mm thick sample with an E field strength of 10^5 V/cm in the streamer region with 1 square micron streamer 1 cm long. In this case eq. 12 reduces to

$$Q = A \frac{\epsilon}{a} E \Delta x = 10^{-16} \text{ coulombs}/cm \text{ tunnel}$$

where $A = 10^{-6} \times 10^{-2} m^2$, $a = .0001 m$, $\Delta x = 10^{-6} m$.

The net result of this modeling is that for the kinds of tunnels seen in low dose rate tests (micron diameter, less than a meter total tunnel length) one would expect integrated current pulses to be measured less than a nanocoulomb when shorted electrodes are on both sides of the dielectric. This is in contrast to the floating front surface where the vacuum currents produce measured charge transfers exceeding a microcoulomb. The numbers which result from both the model and the assumptions are in agreement with the range of pulsing results seen in experiments.

The pulsing rates (pulses per unit time or per unit fluence) seen in the open front surface experiments are in rough agreement with the rates seen in fully grounded experiments (ref. 3, 28,29). This is further evidence that in both geometries the pulses have a common origin.

Pulse Energy for Floating Surface Case

Previous calculations have only estimated charge flow. For the radiated EM wave problem one needs an estimate of maximum pulse energy because the collapse of the E field radiates waves directly as well as causing image charge motions. Because the dynamics of the field collapse are not known to me, I cannot address the directly radiated EM wave intensity problem; it is certainly complex containing plasma oscillation components as well as resonant cavity ringing phenomena. But we can estimate the initial electrostatic energy available to be radiated.

Referring to figure 8 and assuming as usual that most of the trapped charge resides near the floating surface we find that most of the electrostatic energy resides in two fields. If V_0 is the surface potential, then the energy stored per unit surface area in the dielectric is given by

$$\mathcal{E}_d = \epsilon V_0^2 / 2a \quad (13)$$

where a is the dielectric thickness, and the energy stored in the vacuum (per unit area) is

$$\mathcal{E}_v = \epsilon V_0^2 / 2b \quad (14)$$

where b is the distance through the vacuum to ground (or one debye length in the space plasma). Assuming that the sample dielectric constant is similar to vacuum, that the vacuum spacing b is 0.5 m—and that the sample thickness is 10^{-4} m we find that

$$\frac{\mathcal{E}_d}{\mathcal{E}_v} = \frac{b}{a} = \frac{.5}{10^{-4}} = 5 \times 10^3 \gg 1. \quad (15)$$

However, the electrostatic energy within the dielectric is not discharged by a propagating streamer. Only the volume occupied by the streamer is discharged. If we let \mathcal{E}' be the discharged electrostatic energy, then in the vacuum the total discharge energy is

$$\mathcal{E}'_v = \epsilon (\text{Vacuum volume}) V_0^2 / 2b^2 \quad (16)$$

and for the streamer the total discharge energy is

$$\mathcal{E}'_d = \epsilon (\text{Streamer volume}) V_0^2 / 2a^2 \quad (17)$$

Assuming a sample surface area of 10^{-2} m², a dielectric constant similar to vacuum, a streamer length of 1 meter with one square micron cross section we find

$$\frac{\mathcal{E}'_d}{\mathcal{E}'_v} = 4 \times 10^{-3} \ll 1. \quad (18)$$

Thus the discharge pulse energy is significantly smaller in the dielectric than in the vacuum for the typical irradiation geometries reported to date. Yet it is the plasma created in the dielectric which causes the relatively large energy dumps in the vacuum region of space.

Real Spectra Effects, Surface Potential, and Enhanced Pulsing

It has been reported that the space shuttle tiles show no discharge pulses under monoenergetic irradiation but do pulse when irradiated with a broad spectrum (ref 30). This effect will also occur in space and, contrary to popular opinion of the moment, the effect proves that testing with monoenergetic beams is not necessarily a worst case test.

The cause for the effect has not been proven but I postulate the following cause. Early in the irradiation, before pulses begin, the surface comes to its equilibrium potential say 2 keV below the incident monoenergetic electron energy. Figure 4 describes a typical result where surface potential equilibrium occurred in 36 seconds (ref 13). The electric field at the front surface which can produce streamers that eject plasma into the vacuum will not penetrate beyond 0.1 micron. The rest of the dielectric beyond 0.1 micron will produce streamers which connect to the rear electrode, not to the vacuum. Balmain finds that he must wait long times for discharging to begin (ref. 29) even at his much higher dose rates. Such long times probably invalidate fig 4 conclusions because of trapped charged diffusion effects which would bring the high fields near the surface to deeper depths. It may be that 0.1 microns of material is unlikely to produce a streamer, it may require 1.0 microns or more of depth to allow a streamer to propagate. Thus in Balmain's experiments he waits until diffusion has moved the charge centroid (where $E = 0$) to some depth perhaps 1 micron or more. At this point in time a streamer initiates and pulsing begins. But with a broad spectrum one doesn't have to wait, the high energy tail rapidly produces the deeper surface field penetration.

Figure 9 describes the quantitative approach for estimating the importance of the tail. The dielectric surface comes to a potential ϕ_e in space typically between 0 and -10 kV. The surface has a backscattered plus secondary electron yield curve (ref. 31) which, when folded with the space electron energy spectrum, produces a specific energy \mathcal{E}_ℓ determined by

$$I = \int_{\phi_e}^{\mathcal{E}_\ell} N(\mathcal{E}) \left[1 - \delta(\mathcal{E} - \phi_e) \right] d\mathcal{E} = 0 \quad (19)$$

where $N(\mathcal{E})$ is the space electron energy distribution. This is equivalent to saying that the net current to the sample by all electrons below \mathcal{E}_ℓ is zero. \mathcal{E}_ℓ will generally be > 1 kV above the second crossover energy for most polymers and at energies above \mathcal{E}_ℓ the backemitted yield (figure 9) is roughly a constant. Typically in space the electron energy spectrum above \mathcal{E}_ℓ can be characterized by a function like

$$N(\mathcal{E} > \mathcal{E}_\ell) = N_0 \mathcal{E}^{-n}, \quad n > 1 \quad (20)$$

and we can solve directly for I

$$I = \int_0^{\infty} N(\mathcal{E}) \left[1 - \delta(\mathcal{E} - \phi_e) \right] d\mathcal{E} = \int_{\mathcal{E}_\ell}^{\infty} N(\mathcal{E}) \left[1 - \delta(\mathcal{E} - \phi_e) \right] d\mathcal{E}$$

$$I \approx \left[1 - \delta(\mathcal{E}_\ell) \right] N_0 / (n-1) \mathcal{E}_\ell^{n-1} \quad (21)$$

If we know the spectrum (such as eq. 20) we can determine \mathcal{E}_g from eq 19 and by measuring I we can then determine the total incident current above \mathcal{E}_g because all this current must go to the electrode. Now if $I > 10^{-12}$ A/cm² it is in principle capable of creating sufficient field strength over sufficient depth to produce streamers at the surface because the tail beyond \mathcal{E}_g is depositing charge beyond 0.1 micron depth in sufficient quantities. The above mechanism is postulated to explain the shuttle tile results where monoenergetic electrons do not cause discharge but broad spectra do. The extensive polymer results where monoenergetic electrons cause pulsing but only after inordinate time delays is postulated to be due to slow carrier drift (typically up to 5 microns as reported in the literature) before deep trapping. The basic reason for the difference is, again, postulated to be due to a streamer phenomena i.e: there is some minimum dielectric thickness, probably field dependent, required for the generation of these (non thermal type) streamers.

EXPERIMENTAL PREDICTIONS

Several new experimental results can be predicted from this modeling. These experiments could be a check on the model.

Containment of Streamer

The streamers reported by Balmain et. al. are almost surface streamers. At first look they appear similar to the bulk streamers which occur at deeper depths when irradiated by higher energy (100 keV - 10 MeV) electrons in air. However, I think both streamers are produced by electric fields as the driving force. If one were to perform Balmain's irradiations with a very thin (say 500 Å Al) front grounded electrode then the streamers would occur mostly at 5 micron depth and be similar to the trees generated by higher energy irradiations. The resulting tree would burst through the 500 Å electrode leaving a hole.

However, if one were to use a 2 mm thick electrode tightly clamped to the surface and irradiate with say MeV electrons, I predict that streamers still form but do not leave the sample. The streamer will re-solidify in its track. It might be visible as a trace of less crystallinity after the event. One could look at the edge of the sample for the flash of light to be sure that a streamer occurred. In my experiments with heavy electrodes, trees were never seen leaving the dielectric at the electrode, they were only seen at a gap or at the edge of the electrode.

It is often presumed that trees only originate at gaps, edges, or flaws. I feel they can originate elsewhere but of course prefer "high field" or "weak spot" regions associated with gaps, edges, or flaws. The experiment above using 500 Å Al electrodes should demonstrate that streamers also propagate to (or start at) an electrode interface and in this case will blow away the electrode at this point. I have seen this effect with carbon paint electrodes which are admittedly not very smooth and may have had a microcrack at the discharge site.

Experimental Proof of Vacuum Field Collapse Thesis

I propose irradiating a sample in the geometry of figure 8 while holding the irradiated surface at ground potential (either using VUV light to photoemit electrons from the surface or using a thin grounded metalization). This will make all pulses seen by meter I very small. Then one can simulate the floating surface field in the vacuum by biasing the lower electrode in fig. 8 to +10 kV through a very high

impedance. This will cause the pulses to become the large type just as if the front surface had been charged to -10 kV.

In addition I propose biasing the lower electrode with a very low impedance. This will allow one to collect much more of the plasma charge which the streamer injects into the vacuum. Or, at least, it allows more of the charge to be separated and to register as a current on the meter. Thus, in this low impedance case charge collected will not scale with surface area but will scale with streamer volume. In such experiment one must be sure to expose the upper electrode to the vacuum plasma in order to collect the positive plasma charge, otherwise the plasma will just clamp the surface potential to the lower electrode and the charge collected will, again, scale with surface area.

Streamer Volume/Plasma Charge Thesis

One can irradiate a sample in a chamber which also has two extra electrodes near the front of the dielectric. These electrodes can be biased at high voltage and with low impedance so that a fraction of the plasma charge will be collected on the electrodes and appear as a current in a meter connecting the two electrodes (one electrode is biased positive and one negative). The integrated current is then proportional to the amount of plasma injected into the vacuum.

One irradiates until the first pulse occurs and immediately turns off the beam. The total streamer volume is then measured (I'll let you figure out how) and compared to the pulse charge measured. This is repeated using differing dose rates, beam energies and sample sizes until a large distribution in pulse sizes is generated. The streamer volume as measured by the remaining tree volume should scale with the pulse charge. (Of course this presumes that the plasma charge collection efficiency is a monotonic function of the streamer size.)

This experiment is also a measure of the limit to pulse size. The ultimate pulse current magnitude is limited by the total free charge in the streamer plasma. In the scaling experiments reported to date I think it is true that the streamer injected free charge far exceeding the charge required to drop the insulator surface to ground. In addition, experiments with radiation induced lichtenberg trees indicate that they usually spread out to encompass most of the solid so that the total streamer volume will scale roughly as the total irradiated surface area. It will also scale with the static field strength just prior to streamer formation because the trees are known to put on more branches when the discharge occurs at higher field strength.

Coupling to Biased Spacecraft Elements

It is well known that electromagnetic coupling will occur to other elements on a spacecraft when a discharge occurs. The plasma injected into the vacuum creates another coupling mechanism. Other elements with bias and near the discharge site will interact directly with the plasma. This mechanism could be more important than direct EM coupling. Experiments on this phenomenon are obviously specific to the spacecraft application but they can be a-priori modeled since experiments B and C above provide the basic information for modeling this phenomenon.



Pulse Rate versus Dose Rate

It is often thought that the pulse rate relates to the dose rate. In experimental tests this is roughly true as long as the sample continues pulsing. However, the thought is contradicted by the fact that all pulsing stops after some time (for pure polymers only, fiber filled materials can pulse virtually forever, refs 3, 28, 30).

A better interpretation would be similar to the common high voltage capacitor pre-breakdown pulse explanation. In this case, if one first applies 10^5 V/cm to a dielectric small pulses are seen which eventually stop. Presumably the weakest spots have been relieved. Raising the field to 2×10^5 V/cm introduced more pulsing which also stops, presumably relieving more weak spots. In the case of radiation, a higher dose rate simply causes the high field strengths to evolve more rapidly but once equilibrium fields are attained pulsing will soon stop.

Pulses Caused by Changing Spectra

After an irradiation has progressed to electric field equilibrium and pulsing appears to have stopped, further pulsing is only occasional. However, a change in radiation energy spectrum will cause a relatively rapid redistribution of electric field strength. This redistribution can cause new weak spots to find themselves in a high field region and pulsing can begin again. Such an effect has been seen (ref. 28).

Do Punchthrough Breakdowns Occur?

Whenever insulators are irradiated in air (the air ions hold the surface at ground potential) the resulting tree exits from only one surface; no punchthrough occurs. This happens for good reason; the electric field distribution will not propagate a streamer all the way through the insulator. The streamer stops propagating when the field at its tip goes to zero (figs. 4 and 5). Given a constant spectrum it is unlikely that conditions can be created to get a streamer all the way through the insulator by normal streamer propagation mechanisms.

However, if one streamer has been formed and the spectrum changes then a new streamer may occur and intersect the earlier streamer's hollow tunnels. The force of high pressure then may drive the new streamer through the old tunnels and seemingly penetrate through the sample. This occurrence appears to me to be very infrequent.

On the other hand, if one looks at figure 4 it is possible for streamers to occur at the rear electrode and propagate to within 0.1 micron of the front surface. In this event it may be that the pressure in the confined streamer is enough to blow off the 0.1 micron layer at some point and effectively propagate the streamer through the entire insulator. Since I don't know the pressure developed in the streamer nor do I know the dynamics of crater blowoff, I can't discuss the constraints on this process.

REFERENCES

1. J. J. O'Dwyer, The Theory of Electrical Conduction and Breakdown in Solid Dielectrics, Clarendon Press, Oxford, 1973.

2. P. Budenstein, IEEE Trans. Elec. Ins. EI-15, 225 (1980).
3. A. R. Frederickson, IEEE Trans. Elec. Ins. EI-18, 337 (June 1983).
4. A. R. Fredrickson, Proceedings Xth International Symposium on Discharge and Electrical Insulation in Vacuum, 395 (1982), IEEE Catalog #82CH1826-7.
5. B. L. Beers et. al. IEEE Trans. Nuc. Sci. NS-28 (6), 4529 (Dec 81).
6. D. A. Berkley, J. Appl. Phy. 50, 3447 (1979).
7. A. R. Frederickson, IEEE Trans. Nuc. Sci. NS-22, No. 6, 2556 (Dec 1975).
Also see: "Radiation Induced Electrical Current and Voltage in Dielectric Structures." AFCRL-TR-74-0582, Nov. 1974. Available from National Technical Information Service.
8. K. Labonte, IEEE Trans. Nuc. Sci. NS-29, 1650 (1982).
9. G. H. Sessler et. al., IEEE Trans. Nuc. Sci. NS-29, 1644 (Dec 82).
10. Bernhard Gross and Kenneth A. Wright, Phys. Rev. 114, No. 3, 725 (May 1, 1959)
11. B. Gross, Topics in Appl. Phys. 33, "Electrets", 217-84.
12. J. Pigneret and H. Stroback, IEEE Trans. Nuc. Sci. NS23, No. 6, 1886 (Dec 76).
13. A. R. Frederickson and S. Woolf, IEEE Trans. Nuc. Sci. NS 29, 2004 (Dec 82).
14. K. G. Balmain, et. al., IEEE Trans. Nuc. Sci. NS 29 1615 (Dec 82).
15. Balmain, K. G. and Dubois, G. R., IEEE Trans. Nuc. Sci. NS26 (No. 6), 5146 (Dec 79).
16. Gross, Bernhard, Phys. Rev. 107 (No. 2), 368 (July 15, 1957).
17. Hazelton R. C., Churchill, R. J., and Yadlowski, E. J., IEEE Trans. Nuc. Sci. NS 26, 5141 (Dec 79).
18. Ashley, J. C., Radiation Research 90, 433 (1982).
19. Whipple, E. C., Reports on Progress in Physics 44, 1197-1250 (1981).
20. Verdin, Derek, "Electrostatic Discharging Behavior of Kapton Irradiated with Electrons", NASA CP-2182, AFGL-TR-81-0270, pg 96 Spacecraft Charging Technology 1980 (NTIS AD/A114426).
21. Passenheim, B. C. et. al., IEEE Trans. Nuc. Sci. NS-29, No. 6, 1594 (Dec 82)
22. Yadlowski, E. J., Hazelton, R. C., and Churchill, R. J., IEEE Trans. Nuc. Sci. NS 27, No. 6, 1765 (Dec 80)
23. Flanagan T. M. et. al., IEEE Trans. Nuc. Sci. NS 26, No. 6, 5134 (Dec. 79)

24. Stevens, N. J. et. al., "Testing of Typical Spacecraft Materials in a Simulated Substorm Environment" AFGL-TR-77-0051, NASA TMX-73537, page 431 in Proceedings of the Spacecraft Charging Technology Conference Feb 77. NTIS AD/A045 459
25. Staskus, J. V., and Berkopec, F. D., "Test Results for Electron Beam Charging of Flexible Insulators and Composites" NASA CP-2071, AFGL-TR-79-0082 Spacecraft Charging Technology - 1978, page 457 (1979) NTIS AD/A084626
26. Yadlowsky, E. J., Hazelton, R.C. and Churchill, R. J., *ibid*, p. 632.
27. Frederickson, A.R., AIAA Progress in Astronautics and Aeronautics 71, 386 (1980).
28. Frederickson, A. R., "Bulk Charging and Breakdown in Electron-Irradiated Polymers", Spacecraft Charging Technology 1980, NASA-CP-2182, AFGL - TR-810270, P. 33 (1981) (NTIS AD/A114426)
29. Balmain, K. G. and Hirt, W., *Ibid* p. 115.
30. Frederickson, A. R., and Chesley, A. L., IEEE Trans. Nuc. Sci. NS-30, (Dec. 1983)
31. Burke, E. A., IEEE Trans. Nuc. Sci. NS 27, 1760 (Dec. 1980)

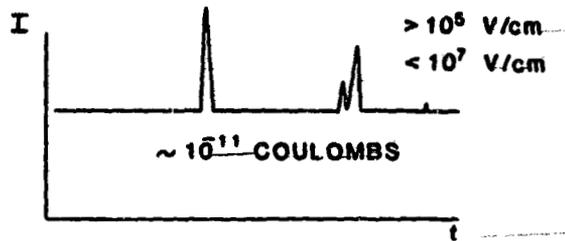


Figure 1. Pictorial of current to the electrodes of a dielectric filled capacitor under constant dc bias. The non-zero background current is due to dark conductivity in the dielectric. The pulses are called prebreakdown events and usually occur at fields of 10^5 V/cm or higher. Pulse sizes vary but are small, commonly of order picocoulombs.

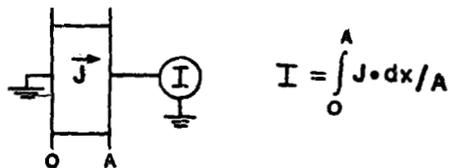


Figure 2. The measured current in a wire connecting two electrodes is the spatial integral of the currents in the space between the two electrodes. The distance between the electrodes is "A" in this figure.

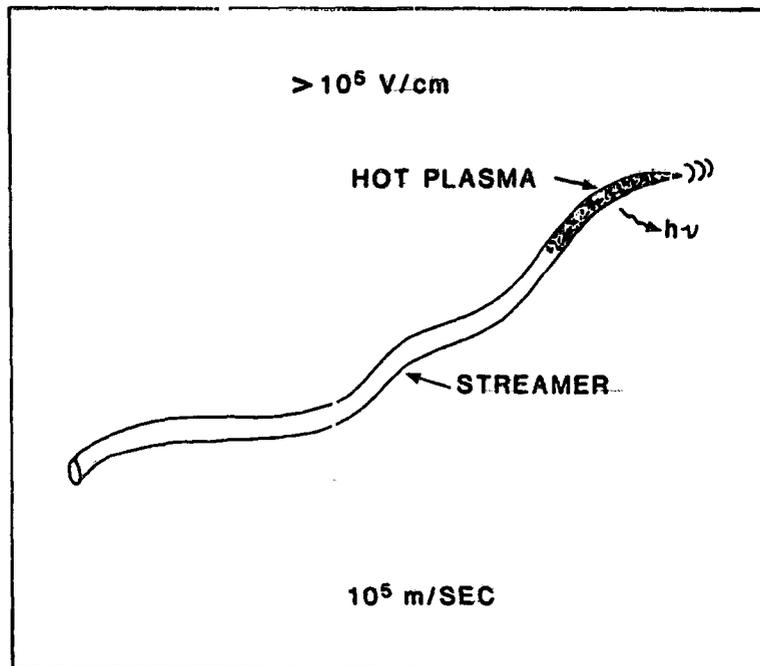


Figure 3. Once a streamer forms in the dielectric the streamer tip propagates parallel to the E field at 10^5 m/sec . The streamer probably starts at or near the surface.

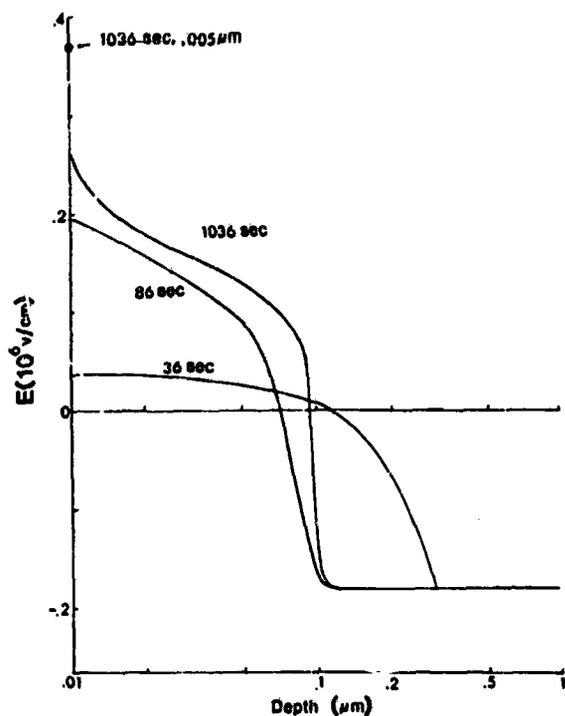


Figure 4. Calculated electric field strengths versus depth from the surface of mylar irradiated by 10 keV electrons at 10^{-9} A/cm². The irradiated front surface of the 1 mm thick mylar is floating while the rear surface is grounded. The irradiation begins at 0 seconds. It is important to note that these results are obtained under the assumption that radiation generated charge carries do not drift beyond 100 angstroms which is known to be incorrect. However, the drift rate and the distance travelled before deep trapping is not well known but 5 micron drifts have been seen in ten minute experiments. Such effects would cause these E fields to become larger while the depth at which E=0 slowly drifts to deeper depths, perhaps a few microns.

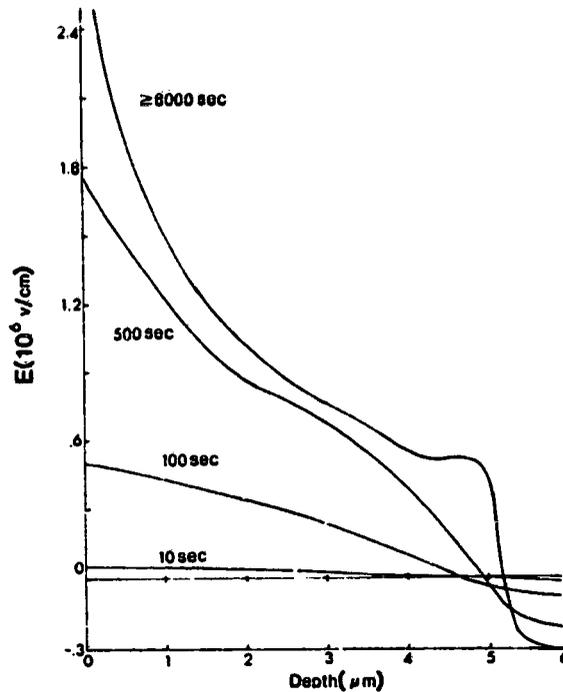


Figure 5. Calculated electric field profile in 25 micron thick mylar with both surfaces grounded. The front surface (zero depth) is irradiated by 20 keV electrons beginning at zero seconds. Increasing the thickness of the mylar would not change the results at depths between 0 and 5 microns.

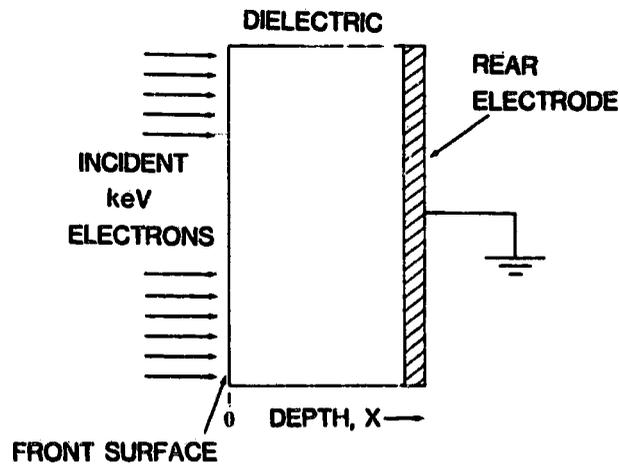


Figure 6. Typical irradiation geometry. This simple structure is inside a metallic vacuum chamber. The front surface can be left floating or it can be grounded by application of a very thin conductive coating.

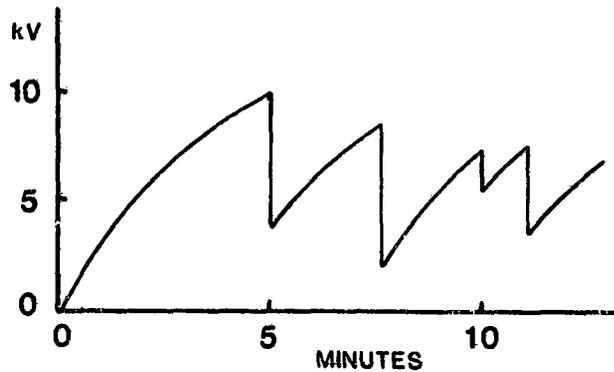


Figure 7. Floating front surface potential as a function of time during irradiation as described in figure 6. The precipitous drops in potential are due to discharges. This is a typical (but not a particular experiment) result but other results have been observed also, including for example no discharges.

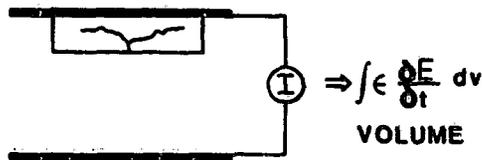


Figure 8. Meter currents resulting from a discharge in which actual charged particles do not reach the electrode. The electric field change is responsible for the metered current. Since we can't know the charged particle trajectories, we must determine I from this displacement current alone. Here, V is volume. We can make an estimate of the total change in E and the volume in which it occurs even though $\partial E/\partial t$ is indeterminate.

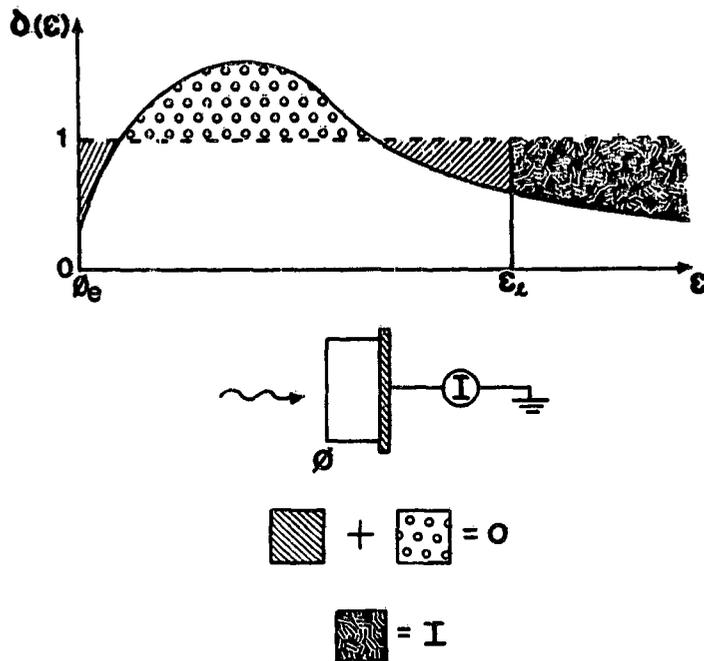


Figure 9. Measured rear electrode current at late times in a long irradiation by a broad energy spectrum. ϕ_e is the equilibrium front surface potential. ϵ_l is the electron energy below which all incoming electrons produce no net meter current due to back emitted electron effects. $\delta(\epsilon)$ is the back emitted current for a current of incident electrons at initial energy ϵ . ϵ_l is usually a few keV above ϕ_e . This figure depicts why the simplified solution in eq. 21 is a good approximation since δ is nearly constant above ϵ_l .