BULK CHARGING AND BREAKDOWN IN ELECTRON-IRRADIATED POLYMERS

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High energy electron irradiations were performed in an experimental and theoretical study of ten common polymers. Breakdowns were monitored by measuring currents between the electrodes on each side of the planar samples. Sample currents as a function of time during irradiation are compared with theory. Breakdowns are correlated with space charge electric field strength and polarity. Major findings include:

a. All polymers tested broke down.
b. Breakdowns remove negligible bulk charge.
c. No breakdowns are seen below 2 x 10^7 V/m.

A model of surface plasma blowoff is proposed to explain how these results are compatible with other published findings.

I. INTRODUCTION

We have performed an experimental study of radiation induced dielectric breakdowns on several common polymers under electron irradiation. The statistics of the breakdown probabilities can be directly related to the radiation induced electric field strengths and indirectly related to material parameters such as conductivity and radiation damage. More than 100 samples have been investigated and several consistent patterns have emerged. The patterns will be discussed in reference to typical sample responses. At this point in time it looks like each material may have its own breakdown signature and that virtually any good insulating polymer dielectric ($\rho > 10^{15}$ ohm cm) can be made to break down under synchronous orbit irradiation intensities.

Many breakdown processes are conceivable but in this study we constrain ourselves to look for breakdowns occurring in the bulk of the polymer due to electric fields originating only from radiation induced bulk space charge. Other types of breakdowns such as those caused by micrometeorite impact, externally applied voltage, internal thermal effects, or electromagnetic pulses from adjacent space are not addressed.

Over the past several years, a model (refs 1, 2) has been developed to predict electric fields, currents and space charge densities internal to

irradiated dielectrics. The major points in the model will be only briefly described here since they are fully described elsewhere (ref. 2, 3, 4, 5). The radiation driven currents in the polymer are based on data in the literature. The space charge resulting from these currents and from conduction currents is obtained from the equation of continuity. The conduction currents produced by the spacecharge fields include all conduction effects available but to date we find that it is sufficient to include only dark conductivity and radiation induced conductivity. The equations are solved numerically with a computer. Space charge densities, electric field strength and total current are each calculated as a function of depth and time. I feel that this conceptual framework is the best presently available to describe the dielectric response in the above parameters to electron and x-ray irradiation at intensities below the thermal effects threshold and where the electrostatic approximation to Maxwell's equations is valid. Space radiation intensities are at least five orders of magnitude below this threshold. We use the model to describe the time evolution of the radiation induced electric fields and currents resulting from the laboratory or space irradiation of polymer samples.

While the sample is being irradiated we continuously monitor the current flowing between the electrodes which are on each side of the planar samples. The model is very successful at predicting the experimentally observed currents and by implication is probably predicting the internal fields as well. Using a transient pulse monitor during the irradation we find that breakdowns do not occur unless the model predicts that internal fields exceed 2×10^7 V/m. The polarity of the breakdowns is in agreement with model predictions. Since the parameters of the model are well substantiated data based on "fundamental concepts" we can use the model to predict the probable onset of breakdowns (i.e.fields exceeding 2×10^7 V/m) for any* irradiation by x-rays or electrons with any known energy distribution above 1 keV.

It might be argued by some that the use of such high energy irradiations does not correspond to space spectra and therefore does not model results in space. I believe such an argument is very weak. "All" of the important physical processes occurring at 10 or 50 keV also occur at 500 keV and vice versa**. These results are not in disagreement with those of Gross, et. al. at 10 to 50 keV (ref. 1, 15). The only change due to the high energy electrons involves the depth of penetration of the irradiation and thus the extent of material involved. The electric field strengths produced in each case will be similar and have similar time dependences. The concepts presented here are immediately applicable to any electron or x-ray irradiation from 1 keV to 10 MeV.

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* Below 1 keV I have unsubstantiated doubts concerning the models validity since the relation between radiation induced conductivity and dose becomes more complex.

** Except for atomic displacements which occur at 500 keV but are rare.

II. THE EXPERIMENT

A. The Apparatus and Samples

The samples are circular discs approximately ten centimeters in diameter. A carbon electrode is painted over the entire face of the sample through which the electron beam penetrates into the dielectric. A carbon coated aluminum electrode (with guard ring) is spring loaded against the back of the sample; this rear electrode is approximately 7.7 centimeters in diameter. Figure 1 sketches the electrode arrangement.

The sample is housed in a gold coated aluminum vacuum chamber at typically 3×10^{-6} Torr and at room temperature, nominally 20°C. The electron beam exits the accelerator in a 1 cm diameter spot and passes through a titanium foil of .01 cm thickness. The beam loses an average of 70 keV in penetrating the foil and is scattered into a broad beam. The sample lies approximately 40 cm beyond the scattering foil where the beam intensity is uniform to within 20% over the surface of the sample. A metal ring surrounding the sample monitors the beam current intensity. Sample current as measured by meter A in figure 1, and the beam current are monitored by Kiethley model 410 electrometers and chart recorders.

The guard ring arrangement eliminates edge effects and defines the region of current collection in the sample. The experiment closely approximates the one dimensional analysis of the model. The samples are reasonably thick so that surface effects at the electrode-polymer interfaces contribute negligibly to the current monitored by the meter, A.

B. Interpretation of the Results

At the beginning of an irradiation the sample has little or no internal space charge. It appears that the electrostatic fields often associated with nonelectroded polymers are due primarily to surface charge and such charge is bled-off upon application of the electrodes. The beam is turned on and rises within a fraction of a second to a preset level and then its intensity remains constant during the irradiation. Information in the radiation (ref. 2) transport literature is used to assess the distribution in depth to which the primary electrons penetrate and become trapped space charge. We also include space charge introduced by the conduction currents.

Figure 2 shows typical computer predicted electric fields for samples thin compared to the incident electron range. As time progresses, the trapped space charge builds-up and large electric fields develop. Thicker samples result in larger electric fields (ref. 2). It is important to note that the field is bipolar: positive in the left region of the sample and negative in the right region.

Currents caused by the electric fields such as dielectric breakdown currents occurring in the left region of the sample in figure 2 would be positive as measured by the meter A. Similarly caused currents occurring in the right region would be negative. Notice that the peak negative electric field reaches

any given absolute magnitude sooner than the peak positive electric field.

Suppose that discharges will occur when the electric field exceeds 2 x 10^7 V/m. In the case of Fig. 2, we would expect to see negative discharge pulses in meter A first (beginning at about 400 seconds) and positive discharges later (at about 900 seconds). This effect is dramatically seen in our results below.

Meter A also measures the integral over space of the total current flowing in the dielectric. Using the model we predict the measured current at all times and obtain good agreement with experiment. This good agreement lends support to our predicted space charge densities and electric field distributions.

III. RESULTS

It is impossible to completely list all results for the over 100 samples tested. However very obvious trends have developed and indicative results will be used to describe the basic trends. We will begin with the simplest examples and progress to the most interesting cases at the end.

A) .338 cm Polystyrene, 3.64 $\mu A/m^2$, 1 meV

Figure 3 shows the experimental and theoretical measured currents, A, as a function of time. The excellent agreement after 2000 seconds is very gratifying. The discrepancy at early time is not understood but appears unimportant for our purposes; it may be due to a small amount of initial space charge or polarization.

At first look the result in fig. 3 appears uninteresting. However the theory indicates that large electric fields occurred reaching magnitudes of +2.7 x 10^7 V/m and -3.5 x 10^7 V/m at the front and rear surfaces respectively. From the time constant of the curve we can predict the coefficient of radiation induced conductivity to be k = 7 x 10^{-16} sec/ohm-m-rad (ref. 6). The time constants* of the theoretical and experimental curves are similar and in agreement with other irradiations. Based on the theory very large conduction currents were occurring inside the dielectric at late times of magnitude similar to the incident beam current. In terms of their effect on the measured currents the conduction currents cancelled each other to a large extent producing little change in the measured current. The theory quite accurately predicts the cancellation; this is a pleasant confirmation of the theory.

Note that on this particular sample and run no breakdown pulses were seen. Other polystyrene samples exhibited breakdowns similar to results discussed later.

B) .345 cm Polypropylene, 3.77 $\mu A/m^2$, 0.43 MeV

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* The actual data contained sufficient accuracy to measure a time constant even though it appears in only the second and third significant figure.

The irradiation shown in figure 4 differs from the prior polystyrene irradiation primarily by the fact that in this case incident electrons are not energetic enough to penetrate into the rear quarter of the dielectric. Thus the conductivity in the rear quarter of the dielectric is not significantly enhanced by radiation induced conduction and extremely large electric fields may be created after long times (ref. 7).

The 10% discrepancy between theory and experiment is not important and is probably due to an error in calibration. The decay time provides an estimate of the coefficient of radiation induced conductivity, $k = 2.2 \times 10^{-16}$ sec/ohm-m-rad.

The theoretical model provides an estimate for the electric field strength during the irradiation. It is felt that the reasonably good agreement between measured and theoretical currents supports the theory's predictions. The front surface field reached 2×10^8 V/m while the rear surface attained 0.8×10^8 V/m at 2850 seconds. It is surprising that no breakdown was seen.

Approximately a dozen polypropylene samples did not breakdown while another dozen showed multiple breakdowns. One sample, during its third irradiation in a week showed clock-like regular breakdowns spaced a minute apart. Some samples showed breakdowns during one irradiation and no breakdowns during prior but similar irradiations. We will see that breakdowns cannot be predicted on the basis of high field strength alone.

C) .168 cm Polypropylene, 0.6 MeV, 3.18 $\mu A/m^2$

Figure 5 describes the results of this irradiation where the sample is about 1/2 of an electron range thick. The rise and fall of the current at the beginning of the run has been observed in about 25% of the polypropylene samples, has been seen to occur at later times on a few other samples (ref. 2) and is akin to some results under ^{60}Co gamma irradiation (ref. 6). Its cause is unknown.

More importantly, this sample exhibits typical breakdown pulses. The first pulse occurred when the field attained 4×10^7 V/m, and based on the polarity of the pulse, it occurred near the front surface. Notice that even though the fields continued to increase with time to 6×10^7 V/m the discharge pulse rate decreased! The fields at the front and rear surfaces are always approximately equal in this irradiation yet only one pulse is seen to occur in the rear region.

D) .166 cm Polypropylene, 0.43 MeV, 3.46 $\mu A/m^2$

Figure 6 describes the results for this sample, similar to the previous sample irradiated at lower energy. Notice again the unexplained early rise and fall in the measured current. The "large" discrepancy between experiment and theory is probably caused by our inability to accurately calculate dose at depths near the end of the electron range. In this case a factor of three error in dose at the rear surface or 10% error in energy or sample thickness could explain the discrepancy; and such errors are probable. Because

the sample is very close to an electron range thick, it is very sensitive to some of these complex effects; thicker and thinner samples are not at all so sensitive when the theory predicts rear surface fields of 1.6×10^8 V/m and front surface fields of 1.0×10^8 V/m. The front surface reached 1.1×10^8 V/m at 4000 seconds after which breakdowns there became more probable. The magnitudes of these fields is only indicative, not absolutely correct. But it is encouraging to see that the theory predicts correctly which polarity breakdown occurs first.

E) .612 cm Polycarbonate 4.47 $\mu A/m^2$, 1 MeV

Figure 7 describes the results for this sample of polycarbonate which is approximately 30% thicker than the range of 1 MeV electrons. The small discrepancy between theory and experiment at zero seconds is probably due to incident intensity calibration errors. Again we have predicted the polarity of the initial breakdown correctly. At the first breakdown (which occurred near the front) the predicted front surface field is 6×10^7 V/m while the rear surface field is 3×10^7 V/m. At approximately 1000 seconds the rear surface began arcing at 6×10^7 V/m at which time the front surface field is predicted to be 1×10^8 V/m.

The coefficient of radiation induced conductivity, k, (ref. 6, 1) controls the slope of the current vs. time curve. For polycarbonate there is no choice of k which could provide a perfect fit because at early times the response shows first a slow decrease in the current followed by a more rapid decrease. The theory which assumes a constant value for k predicts that the rate of decrease in current is maximum immediately after the irradiation begins. One probable answer is that field enhanced conduction plays a large role, perhaps doubling the conductivity after 400 seconds. All materials show this effect to some extent to date but thick polycarbonate seems to have the largest apparent field enhanced conduction of those materials tested.

This is an excellent time to describe a major finding. Note the breakdown pulses: they never change the slope or value of the meter current except briefly during the pulse (<0.1 sec). If any significant current had flowed during the pulse charge would have been removed, the meter would have gone off-scale and the measured current would then return somewhat closer to the initial (time zero) current. We have probably seen tens of thousands of pulses but they have <u>never</u>* displaced the measured current except for the brief period of the pulse. <u>Breakdowns do not remove much bulk charge</u>, even at irradiation intensities ten times as large as shown in these figures. From the data presented so far breakdowns remove not more than one percent of the charge; later we see that they remove virtually <u>no</u> charge.

Lichtenberg patterns are produced by breakdowns. We have looked for the patterns in fewer than ten samples and have seen extensive patterns in one polycarbonate and one polystyrene sample. The irradiation history of these samples is not well documented and the number of meter pulses was not recorded

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* "never" means: not even once!

so we don't know how large a lichtenberg pattern results from only one or a few pulses. The entire diameter of the samples contained the pattern; thus large patterns result from small total current flows.

This major finding also describes why many experimenters see almost continuous light pulsing after a dielectric has been irradiated to the breakdown "threshold". Virtually no bulk charge is removed by each breakdown pulse and the large internal fields remain to cause further pulses.

F) Decay of the bulk space charge.

Figures 8 and 9 describe the bleeding off of space charge in polypropylene after the irradiation ends. No theoretical work has been done yet on this problem. The meter current in figure 8 was not monitored continuously, each dot represents one reading. On some samples currents were still non-zero a day later.

Several samples were re-irradiated a number of times under similar conditions. The initial current in the initial irradiation is indicative of a sample response with no internal space charge. Figure 9 shows that a polypropylene sample which has rested 4 or 5 days will "lose" some of its charge, returning to within 10% of its initial t = 0 value. This doesn't mean that the sample lost 90% of its irradiation space charge but it does imply that the charge was at least severely redistributed.

G) .620 cm, Polyvinylchloride, 4.63 $\mu A/m^2$, 1 MeV.

Figure 10 is typical of PVC but includes shifts in the irradiation energy at late times. At early times we again see the apparent field dependent conduction effect. The initial breakdowns are in the front surface as predicted by the model and occur at 4×10^7 V/m. The rear surface breakdowns begin later as predicted but the first one occurred at 2×10^7 V/m. Other samples have broken-down at this level but this is the lowest field at which we have ever seen a breakdown. The theoretical slope is due to a value $k = 2.3 \times 10^{-16}$ sec/ohm-m-rad, typical of such polymers.

The interesting point here is the results for small incident energy changes. At 3600 seconds the energy was lowered to 0.93 MeV while maintaining constant incident current. A seven percent change in energy changes the range of incident electrons only 7% so that if this change had occurred at t = 0 only a small ($\approx$7%) measured current change would have occurred. However, at late times there are various bulk currents all partially canceling each other and a small change in one can severely alter the net measured current as we see here at 3600 seconds.

It has been predicted (ref. 2) that a change in irradiation spectrum could cause breakdowns. Such spectral changes are certainly seen in space routinely. The prediction is dramatically reinforced in fig. 10. However it occurred only by lowering the energy. At 4220 seconds the beam energy was raised to 1.06 MeV but not without some excursions to other energies over a two minute period. For a small change in energy we again saw a large change in

current but we saw no breakdowns. It would be nice to try to predict these results using the theory but we haven't done so to date.

In this irradiation we also dramatically see the cessation of breakdowns even though high fields exist. Most samples show a tendency to decreasing frequency of breakdowns under continued irradiation. However, some samples, having not shown any breakdowns in a first irradiation, show many breakdowns in a similar irradiation repeated days later. Obviously we do not understand the breakdown process and its causes. We are simply developing a large statistical sample.

H) .607 cm, Polyphenylene Sulfide (glass filled)* 5.0 $\mu A/m^2$ at 0.6 MeV.

Figure 11 describes the results of the breakdown champion of the samples tested to date. This data could not be redrawn in ink so the original chart recording is used directly. All four samples showed similar results.

The theoretical prediction is in excellent agreement with the measured current. For this sample $k = 1.7 \times 10^{-16}$ sec/ohm-m-rad. Even with all those breakdowns having occurred, virtually no charge was lost in the breakdown process. However, the polarity of the first many breakdowns is not as predicted.

Only the first third of the sample is penetrated by the primary radiation and thus the fields at the front surface must usually be larger than at the back surface. Yet the rear surface breakdowns occur earlier and at lower fields. Front surface breakdowns hardly occur at all, only after 2000 seconds and after field build-up to 2×10^8 V/m.

Perhaps the glass fibres and/or the many small voids are playing a dominant role here. In the irradiated front part of the sample the glass fibres are held in good electrical contact with the polymer molecules by the super hot conduction electrons (and holes) created by the radiation. This radiation induced conductivity may prevent fields of breakdown strength from occurring at the glass-polymer interface in the irradiated region. In the unirradiated region or in the transition zone between irradiated and unirradiated regions many small breakdowns may occur at glass-polymer interfaces. This is all conjecture and it would be nice to really understand these results.

As with the other samples, there is a definite tendency for breakdowns to become less probable as the irradiation continued. In this case the breakdown rate decreased at least a factor of four and the meter stopped going off scale after 2000 seconds. However, this material is different in one significant way: after the irradiation ends, breakdowns continue to occur for more than one day. Breakdowns become smaller and less probable as the hours pass but nevertheless this is a surprising result. Several polyphenylene sulfide samples have been tested and all show the same effects.

This particular sample provided a clue to solving the surface blowoff

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* Phillips Chemical Co. "RYTON" trademark.

problem. All samples have had electrodes painted on the front surface but this sample's electrode had a hole (by accident) of roughly 20μ diameter. After 2000 seconds some arcing was occurring in the front surface region and we were surprised to see current pulses on the beam current monitor ring. Electrons were being emitted in pulses from the front surface, presumably from the hole, into the vacuum space. Sometimes these were accompanied by a current pulse in the rear electrode meter, sometimes not. In any case, even though all breakdown pulses are small, surface blowoff currents are to be seen (ref. 15) associated with these small internal discharges. We will return to the blowoff problem later.

I) .318 cm polytetrafluoroethylene (PTFE), 1.2 MeV, 6.15 $\mu A/m^2$

PTFE is severely different from all the other polymers tested*. Three differences dominate:

(a) The coefficient of radiation induced conductivity $k \approx 5 \times 10^{-15}$ sec/ohm-m-rad is typically twenty times larger than the other polymers.

(b) This material structurally degrades at irradiation doses of less than 10^6 rads (equivalent to only a few thousand seconds in these typical runs).

(c) Significant conductivity is added by a radiation induced damage process at only 10^5 or less rads dose.

I was not so clearly aware of (a) and (c) until 1979, so it was unfortunate that ref. 7 improperly assigns typical polymer parameter values to a dielectric called "teflon". Apparently others are finding similar results (ref.8). Values for k available in the literature vary widely (probably due to experimental error more than to sample differences) and improved values are only now becoming available.

Figure 12 describes typical results for PTFE when the electrons do not penetrate to any great extent. The initial current decay rate is indicative of the large value of k (5×10^{-15} sec/ohm-m-rad). Field enhanced conductivity can be seen but is not significant. What is significant is the measured current reversal after roughly ten minutes. This reversal is probably due to enhanced conduction produced by the high dose rate over the first 70% of the primary electron range. This enhanced conduction allows the space charge to relax back to the front surface. We can test for this enhanced conduction days later by repeating the irradiation and noticing the initial measured current decay is very fast indicating a vastly increased conduction relative to the earlier irradiation. We have repeated this test several times and find that the enhanced conduction lasts at least a week. I guess that the enhanced conduction is related to the known chemical degradation of PTFE under this level of irradiation.

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* As well as the polymers reported above we tested nylon, delrin, polymethylmethacrylate and polyethylene.

Breakdowns have been seen in PTFE but only a few and they are slow, lasting nearly two seconds*. Such breakdowns may not cause problems like faster breakdowns do. I believe we have recorded only one probable fast breakdown in about 8 teflon sample runs. See ref. 15 for data on pressure actuated breakdowns.

We have attempted to fit the teflon data with a conduction term due to total dose (not delayed conductivity but instead permanent dose related conduction) as shown by the dots. The prediction uses the theory (ref. 2) with values for conductivity given by:

$$\sigma(x,t) = \sigma_{dark} + kD(x,t) + k_1 D(x,t)t \text{ where D is}$$

dose rate in rads/second

$$k = 5 \times 10^{-15} \text{ sec/ohm-m-rad}$$

$$k_1 = 5 \times 10^{-16} \text{ (ohm-m-rad)}^{-1}$$

$$t = \text{irradiation time in seconds.}$$

By this simple theory we have not yet been able to reproduce the change in current polarity experimentally observed because the computer algorithm blows up at the zero crossing.

Teflon is substantially different than the other samples but how much different? These samples were only irradiated to 10^6 rads. What if we went to 10^9 rads to simulate more time in space? We don't know what we would see! Maybe the annealing effect would go away and breakdowns would reoccur with renewed vigor; related effects have been seen with 10 to 40 keV electrons (ref. 15).

IV. Proposal for Blowoff Currents

Combining the findings of this paper with reports from the 1978 conference and references 9-14, and with vague notions concerning breakdown propagation, let me propose the following model for blowoff currents.

We now know that very little net charge moves in a breakdown tunnel or streamer but that a lichtenberg pattern results. We know that light is emitted so there probably is a plasma. The material is not heated severely or melted locally outside the channel so the plasma must travel as a wave front rather than a repeating process or continuous wave. The lichtenberg channels exit a surface in many cases.

So I propose that a nearly net neutral plasma bursts from the surface at the channel-surface intersection as shown in figure 13. If the net charge

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* In private discussions J. West, Bell Laboratories, disclosed that he sees the fast type breakdown pulses in his FEP teflon samples (Dec 1980).

in the dielectric is negative, the plasma will partially separate: electrons will rapidly move away from the dielectric and positive ions will return to the dielectric surface partially neutralizing the trapped charge fields external to the dielectric. The process is dynamic containing force terms due to E-M cavity oscillations, $\partial B/\partial t$ terms, and self shielding in the plasma region. Thus full neutralization of the dielectric space charge fields external to the dielectric will not usually occur, just 50% or 80% neutralization. The amount of net current flow from the plasma will depend on the total dielectric trapped charge along with the time dependent vacuum chamber cavity fields -- thus we would have the so called "surface area scaling laws". But the trapped dielectric charge remains in the bulk so that further breakdowns are likely to reoccur soon in rapid succession even though the surface potential appears mostly neutralized; light pulses would continue to occur. And I predict a new observable -- the net neutral plasma will produce microwave bursts when it exits the surface in the classical plasma oscillation character. From the radio frequency of these bursts we can obtain the plasma density, or vice-versa. Of course the density and the total charge are decaying rapidly so the R.F. bursts are both amplitude and frequency modulated.

V. CONCLUSIONS

The results discussed above are quite extensive and have been reported as briefly as possible. These results are boiled down from many experiments and represent the major patterns. New patterns would probably emerge as more samples and longer irradiations are performed. The following is a list of the major findings or concepts. Please return to the text for discussion of these points.

MAJOR FINDINGS

1. High field strength does not guarantee breakdowns.

2. No breakdowns seen below 2×10^7 V/m.

3. Teflon less likely to break down and extended irradiation severely increases dark conductivity.

4. Breakdown pulses last less than 100 ms except in Teflon where they can last 2 seconds.

5. Field enhanced conduction occurs but is not important for mitigating breakdowns

6. Breakdowns do not remove any bulk space charge.

7. Lichtenberg patterns occur, even at these very low intensities.

8. Decay of bulk charge requires at least a week, if not years.

9. Most materials radiation anneal to decrease breakdowns under continued irradiation; this is due to some effect other than increased conductivity.

10. Spectral changes reintroduce breakdowns.

11. Glass filled polyphenylene sulphide (and perhaps other filled polymers) shows enhanced breakdowns.

12. Penetrating radiations also cause breakdowns so that broad spectra will not significantly reduce breakdown probabilities.

13. I propose a net neutral plasma pulse as driving function for blowoff currents. such a model can explain the results seen here as well as other results published elsewhere.

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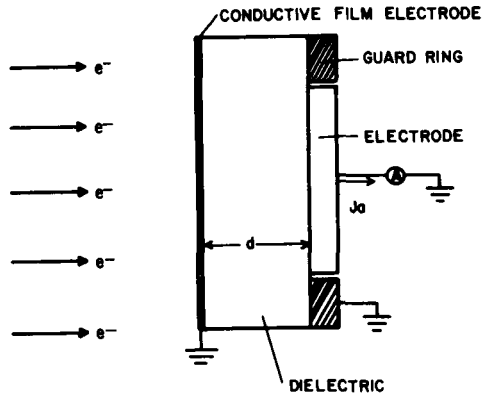

Figure 1 Typical Dielectric Irradiation Geometry.

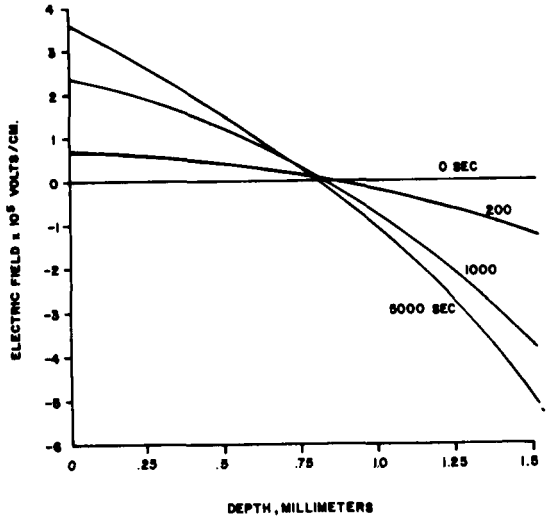

Figure 2 Electric fields as a function of depth at various times after initiation of a constant 1 MeV electron irradiation of intensity 3.9×10^{-6} A/m^2 in polyvinylchloride 1.5mm thick. No further changes in field occur after 5000 seconds. Note the electric field is bipolar. These calculations are based on the model described in reference 2.

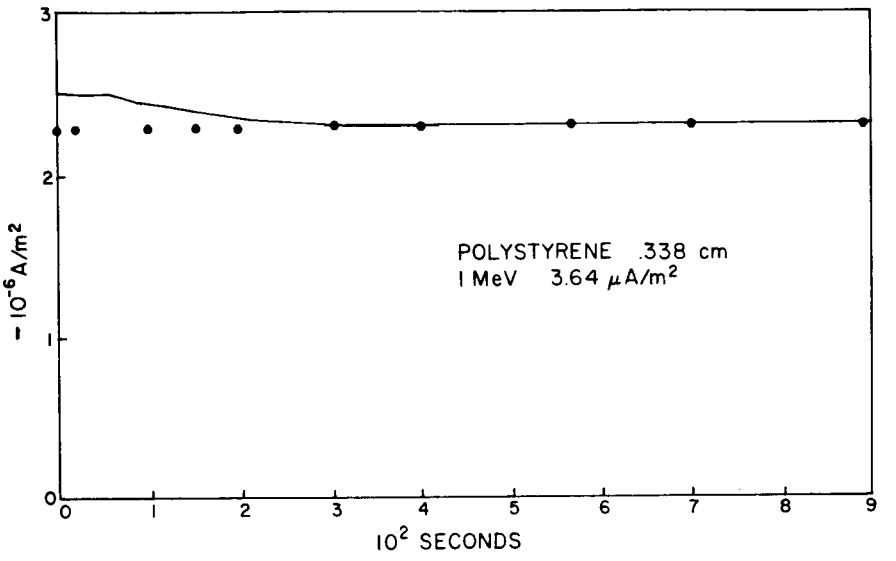

Figure 3 Measured current density by meter A vs. time in .338cm thick Polystyrene, irradiated by 1 MeV electrons at 3.64 $\mu A/m^2$. Solid line is the experiment, dots are the theoretical prediction.

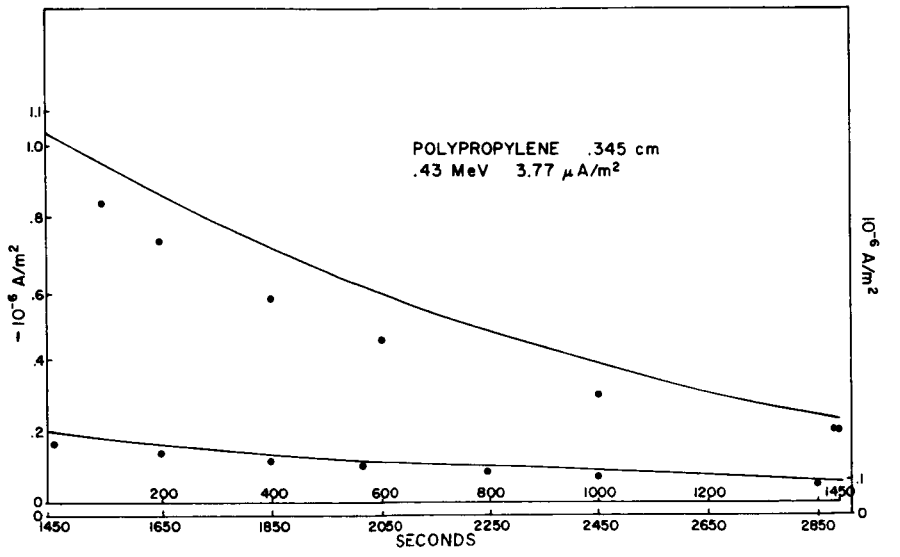

Figure 4 Measured current density by meter A vs. time in .345cm Polypropylene irradiated by 0.43 MeV electrons at 3.77 $\mu A/m^2$. The lower curve is the continuation of the upper curve with displaced axes. The dots are theoretical predictions.

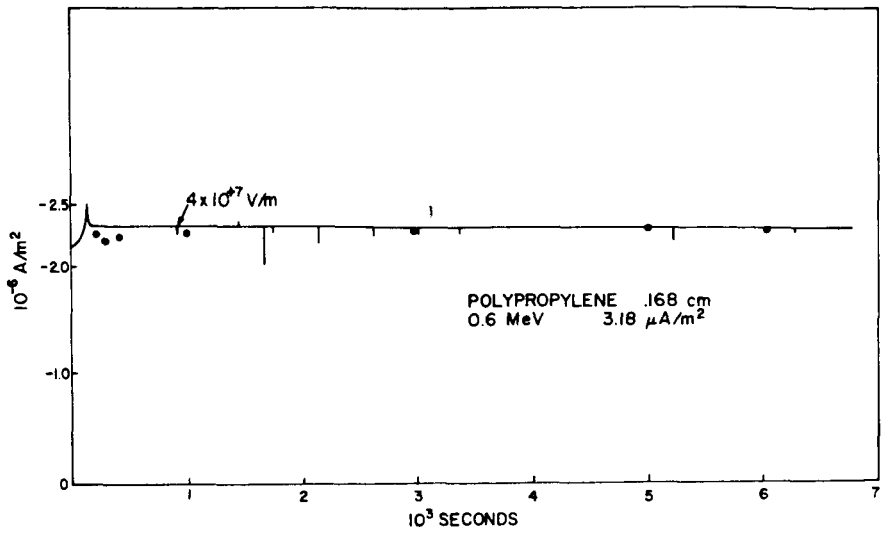

Figure 5 Measured current density by meter A vs. time in 0.168cm Polypropylene irradiated by .6 MeV electrons at 3.18 $\mu A/m^2$. Dots are theoretical predictions. The first breakdown pulse occurred at nearly 1000 seconds and the polarity indicates it occurred near the left (front) electrode (inspect figs. 1 and 2). The early rise and fall is not a breakdown pulse, it took tens of seconds to occur. At 1000 seconds the electric field adjacent to the front electrode was theoretically estimated to be 4×10^4 V/m.

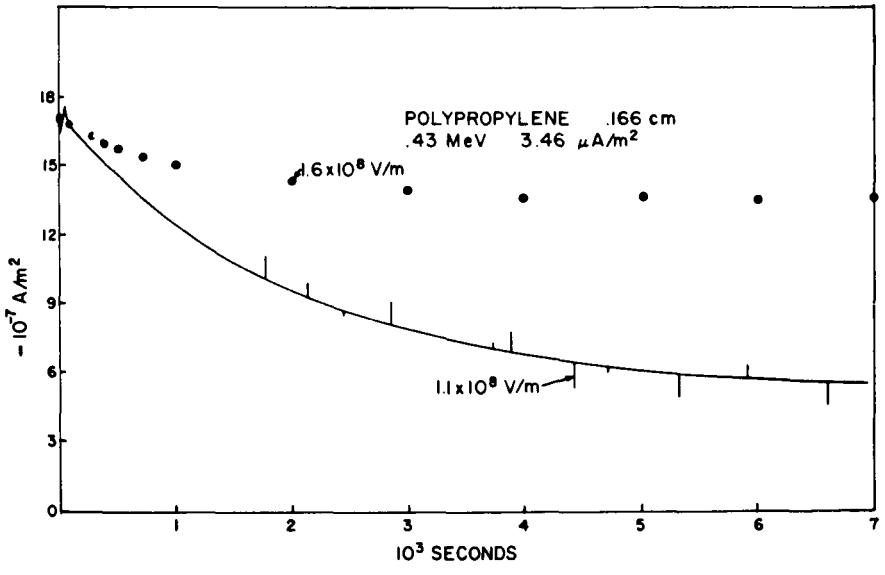

Figure 6 Measured current density by meter A vs. time in 0.166cm Polypropylene irradiated by 3.46 $\mu A/m^2$ electrons at 0.43 MeV. Dots are theoretical predictions. At nearly 1800 seconds we see the first breakdown pulse. Qualitative inspection of figure 2 and the polarity of this first pulse indicate that this breakdown occurred in the right portion of the sample where the field was negative. At 2000 seconds the theory estimated the electric field adjacent to the rear electrode to be 1.6×10^8 V/m. At 4400 seconds the field adjacent to the front electrode was roughly 1.1×10^8 V/m.

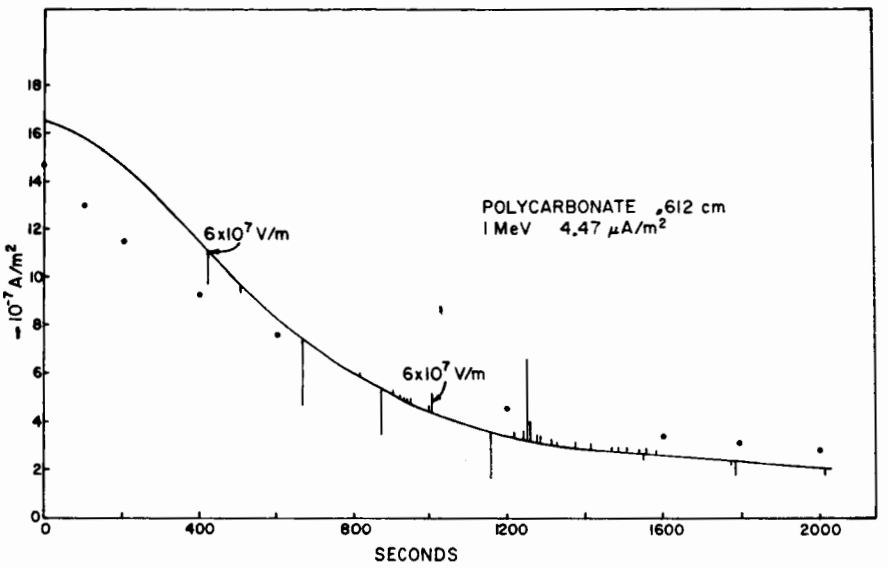

Figure 7 Measured current density by meter A vs. time in 0.612cm thick Polycarbonate irradiated by 4.47 $\mu A/m^2$ of 1 MeV electrons. Dots are theoretical predictions.

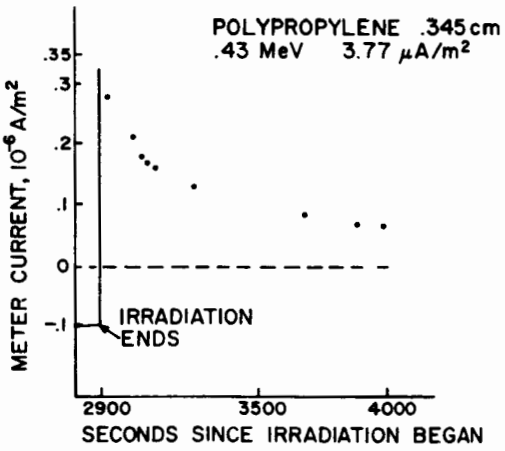

Figure 8 Space charge decay meter current after end of irradiation.

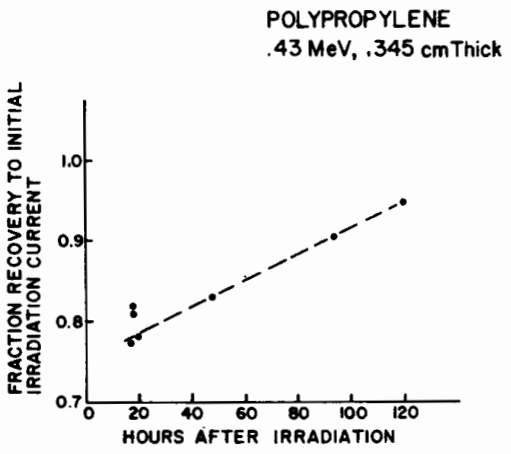

Figure 9 Sample recovery days after irradiation.

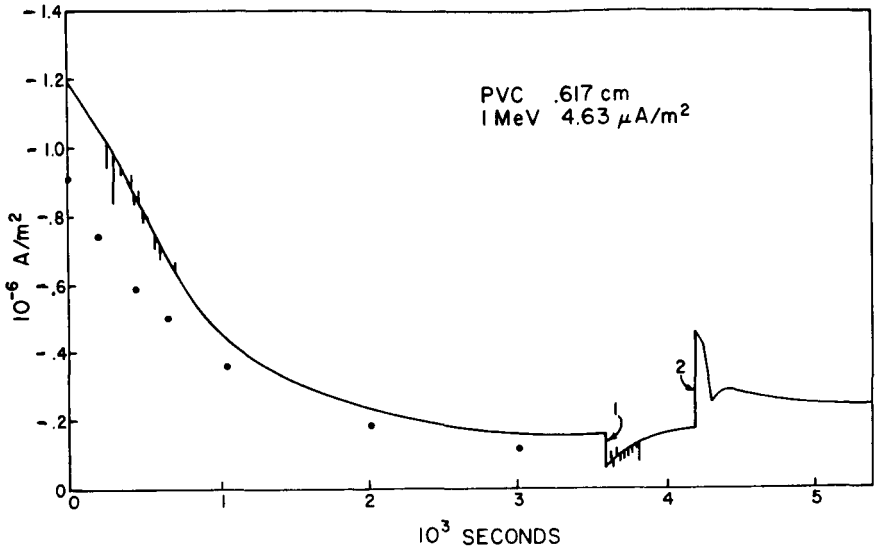

Figure 10 Measured current density by meter A vs. time in .617cm Polyvinylchloride irradiated by 4.63 $\mu A/m^2$ of 1 MeV electrons. Dots are the theoretical predictions. Incident energy was changed after 3600 seconds. At 3600 seconds, step 1, the energy was quickly lowered to 0.93 MeV and remained constant until step 2 at 4220 seconds when the energy was raised. Note that the initial breakdowns ceased after 700 seconds but reoccured after step 1 and then later ceased again.

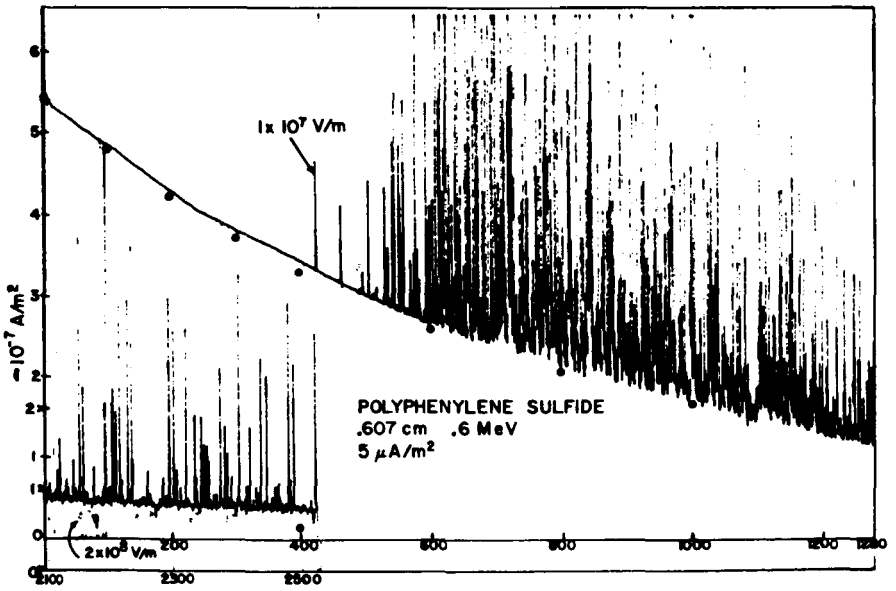

Figure 11 Results for Polyphenylene Sulfide, glass filled. Dots are theoretical predictions. It is not obvious from the chart recording but at 2200 seconds small breakdowns of positive polarity (downward) began when the field adjacent to the front surface was estimated to be 2 x 10^8 V/m. At this time blowoff current pulses began to be monitored by an electrode mounted in front of the sample (but not blocking the incident beam).

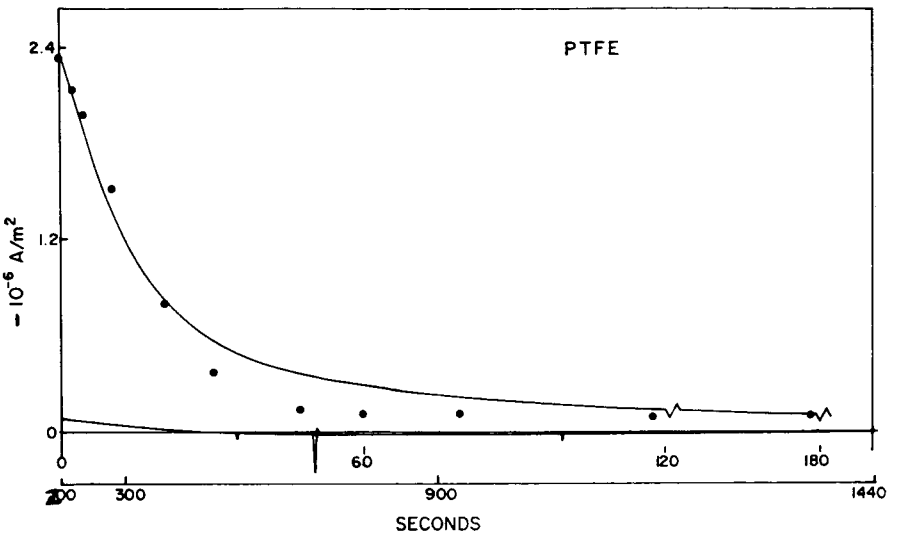

Figure 12 Typical results for Polytetrafluoroethylene. Dots are theoretical predictions including radiation damage induced conduction. Note the breaks in the time scale at 180 and 120 seconds, and the slow pulse at 700 sec.

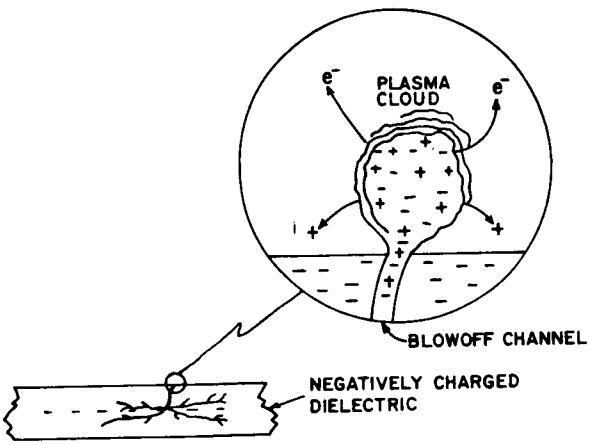

Figure 13 Proposed surface blowoff current source function -- a net neutral plasma.