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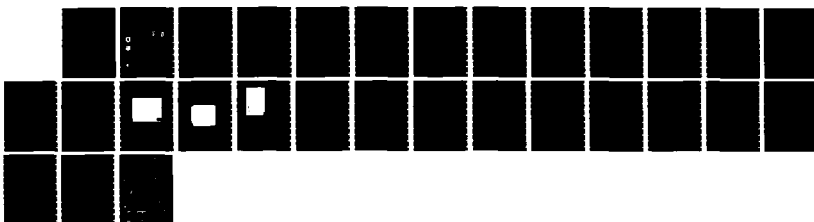
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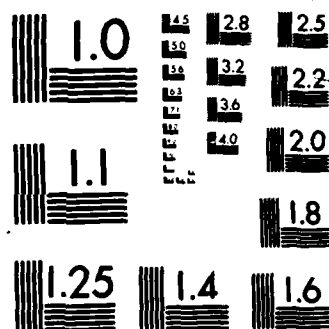
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Deep-Dielectric Charging — A Review

W. F. DENIG
A. R. FREDERICKSON

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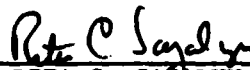
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Deep-Dielectric Charging – A Review

1. INTRODUCTION

Deep-dielectric charging is the process whereby energetic charged particles, which are incident to a dielectric material, penetrate a finite distance into the medium before coming to rest. The nature of most dielectrics is such that these particles have a greatly limited mobility within the volume. If radiated with a continuous flux of these particles, say 20-keV electrons at 10^{-9} A cm⁻², a significant spacecharge can be deposited within the dielectric establishing internal electric fields of order 10^6 V cm⁻¹ within several minutes. Subsequent to the termination of this particle flux the spacecharge and electric fields can remain within the material for several days, perhaps weeks. Under such conditions an electrical breakdown or arc may occur in response to the electrostatic fields thus affecting the spacecharge configuration and electric field pattern. These processes are expected to occur on spacecraft having exposed insulating surfaces which, at times, may be subject to energetic charged particle fluxes. The arcing due to dielectric discharging is a source of EMI (ElectroMagnetic Interference), light, and enhanced surface contamination to the spacecraft as well as being a potential hazard to the astronauts and the mission objectives.

(Received for publication 15 May 1985)

This presentation covers the topics of deep-dielectric charging and discharging as related to manned spaceflight, especially to polar-orbiting Shuttle missions. The high-latitude auroral region is a hostile environment for spacecraft due to the presence of intense fluxes of energetic charged particles. Section 2 of this article describes common laboratory experiments and computer models which are used to study the buildup of spacecharge and electrostatic fields within a dielectric irradiated with auroral-type electrons. The physics of the breakdown phenomena as currently understood, and the detrimental effects of arcing are covered next. Photographic examples are presented which show the tendency for arcing to occur at regions of high electric field concentration and also show the residual effects of these discharges on polymers, in the form of Lichtenberg patterns and blowoff channels. Finally, a recommendation on how to minimize this dielectric charging is presented and the consequences of not following this recommendation are discussed.

2. LABORATORY STUDIES AND COMPUTER SIMULATIONS

A schematic of a typical laboratory configuration used to study deep-dielectric charging by energetic particles is shown in Figure 1. In such an experiment incident electrons of energy 1 keV to 20 keV impact the front surface of a dielectric and penetrate to several microns within the material thus causing an increase in the trapped negative spacecharge density. This situation approximates that of a space vehicle in darkness which has dielectric surfaces exposed to energetic auroral electrons. In the absence of sunlight there are no photoelectrons created at the dielectric surface which would affect the electric field configuration. The opposite case (not shown)—that of a sunlit space vehicle—can be approximated in the laboratory by covering the irradiated sample with a thin grounded conducting layer (aquadag). The grounded electrode simulates the effects of solar UV and soft X-rays which cause emission of, typically, $\approx 10^{-9}$ A cm⁻² of low-energy (< 50 eV) electrons. These low energy electrons "clamp" the surface of an irradiated dielectric at ground potential as long as the incident high-energy current density does not exceed this level. These two differing experimental configurations are now considered in more detail in terms of the temporal buildup of this internal spacecharge and the electrostatic fields.

The experimental geometry shown in Figure 1 is that of an electron-irradiated dielectric with a floating front surface. The negative spacecharge initially deposited within the material will cause the surface potential, that is, referenced to zero at infinity or the ambient plasma potential, to attain a steady-state magnitude such that there is a balance between the incident particle flux and losses due to backscattered and secondary electrons. For monoenergetic, say 20 keV, electrons on polymers,

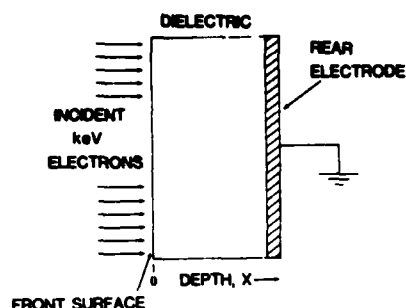


Figure 1. Experimental Configuration for an Electron-Irradiated Dielectric With an Ungrounded Front Surface

for example, mylar, kapton, and teflon, the secondary electron second crossover point is approximately 2 keV so that the steady-state surface potential is 18 keV. In other words, the polymer surface "sees" an incident flux of 2-keV electrons where the difference in energy, that is, 18 kV, was used by the particles in overcoming this surface potential. The time-dependent spacecharge density plotted as a function of depth within a thick (0.1-mm) mylar sample irradiated with 20-keV electrons at 10^{-9} A cm $^{-2}$ is shown in Figure 2. These are the results of a computer simulation of the interaction of incident electrons with the dielectric using an appropriate electron stopping-power formulation (Berger and Seltzer¹) combined with a Poisson's equation solver which includes electronic conduction in the dielectric (Frederickson and Woolf²). Considered in the simulation are the effects of bremsstrahlung (braking) radiation and X-rays generated within the mylar; however, the contributions from these processes are negligibly small. Notice that Figure 2 depicts the development of a trough in the negative spacecharge density after approximately 4 minutes of irradiation. The spacecharge actually becomes positive within a subregion of the dielectric. This positive spacecharge occurs because of transient radiation-induced changes in the conductivity of the material. The thickness of the dielectric affects, in part, the distribution of internal charge as well as the internal electric field configuration. For this 0.1-mm mylar sample, the equilibrium electric field at depths beyond the penetration of the auroral-type electrons is approximately 1.8×10^6 V cm $^{-1}$, that is, 18 kV over 0.1 mm. Prebreakdown pulses can be expected to occur within the dielectric near the surface where the electric field strength exceeds the experimentally determined prebreakdown level of $\approx 10^5$ V cm $^{-1}$ for polymers. As an aside, a comparison of this

1. Berger, M. J., and Seltzer, S. M. (1964) Tables of electron-losses and ranges of electrons and positrons, in Studies in Penetration of Charged Particles in Matter, edited by U. Fano, Publ. 1133, National Academy of Sciences - Material Research Council, pp. 205-284, Washington, D. C.
2. Frederickson, A. R., and Woolf, S. (1982) Electric fields in keV electron irradiated polymers, IEEE Trans. Nucl. Sci., NS-29:2004-2011.

spacecharge-induced electrostatic field to the electron stopping power of typical polymers, that is $\geq 2 \times 10^7 \text{ V cm}^{-1}$, shows that the internal electric field has a minimal effect on the trajectories of 0.1 to 1 MeV electrons.

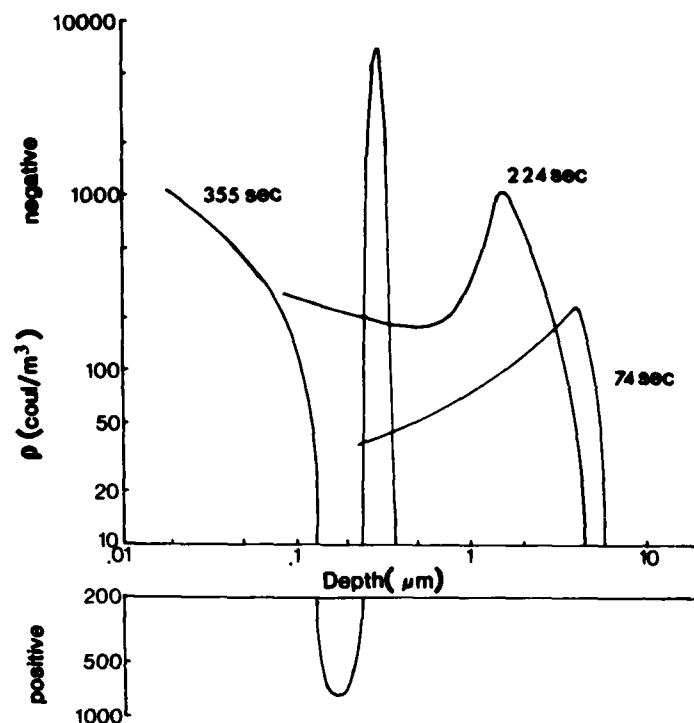


Figure 2. Results of a Computer Simulation for the Internal Charge Density vs Depth of an Ungrounded-Front-Surface Dielectric. The different curves show the temporal buildup of the space charge distribution within a 0.1-mm mylar sample irradiated with 20-keV electrons at $10^{-9} \text{ A cm}^{-2}$ (Frederickson and Woolf²)

A second experimental configuration (not shown) used to study electron-irradiated dielectrics has a grounded front surface, that is, a thin grounded conducting layer ($\approx 1 \text{ mg cm}^{-2}$ carbon) covering the front surface of the dielectric (Frederickson^{3,4}).

3. Frederickson, A. R. (1982) Electric fields in irradiated dielectrics, in Spacecraft Charging Technology Conference - 1978, edited by Robert Finke and Charles P. Pike, AFGL-TR-79-0082, AD A084626, Air Force Geophysics Laboratory, pp. 554-568.
4. Frederickson, A. R. (1983) Electric discharge pulses in irradiated solid dielectrics in space, IEEE Trans. Elec. Insul., EI-18:337-347.

This situation resembles that of a dielectric surface in sunlight where photon radiation in the visible and ultraviolet parts of the spectrum induces photoelectron emission from the material. These low-energy electrons are sufficient in number to compensate the incoming flux of electrons and thus prevent the buildup of external electric fields in front of the dielectric. Incident 20-keV electrons retain their full kinetic energy, penetrate the dielectric surface, and are embedded within the dielectric to greater depths than in the floating front surface case. In this simulation the effects of bremsstrahlung radiation and X-ray are considered. The trapped spacecharge induces large electric fields just below the surface of the dielectric as shown in Figure 3, specifically for 20-keV electrons at a flux of $10^{-9} \text{ A cm}^{-2}$ onto a 25-micron sample of mylar. The intense electric fields, capable of inducing an arc, are also present throughout most of the material in this grounded configuration.

3. RADIATION-INDUCED ELECTRICAL BREAKDOWNS IN POLYMERS

In Section 2 it was shown that an electron-irradiated dielectric can accumulate a significant amount of internal spacecharge resulting in large electrostatic fields within the bulk and near the surface of the material. The magnitude of these fields can surpass 10^5 V cm^{-1} which has been found to be sufficient to induce electrical arcing within the dielectric. The physics of this breakdown phenomenon, as it is currently understood, is discussed in this section. It is felt here that the internal discharge pulsing of a naturally-irradiated dielectric in space may be the most important source of spacecraft arcing surpassing the surface differential charging mechanism commonly discussed for space vehicles.

The internal discharging of an irradiated dielectric is not the more-or-less intuitive mechanism whereby positive or negative spacecharge is torn free, in a cascading manner, from the dielectric by intense electrostatic fields. Such a process is not consistent with currently-understood physics or with laboratory measurements which indicate (Budenstein⁵) that prior to the main discharge phase, or the voltage collapse, the breakdown channel becomes luminous. In addition the morphology of this channel, examined post-irradiation, does not have the damage paths expected from a wide-area sheet-cascade breakdown. It is believed—and experiments have borne this out—that the electrical discharging of an irradiated dielectric is due to the formation of highly conductive gaseous, that is, plasma channels within the polymer. A speculation is that these conductive paths are

5. Budenstein, P.P. (1980) On the mechanism of dielectric breakdown of solids, IEEE Trans. Elec. Insul., EI-15:225-240.

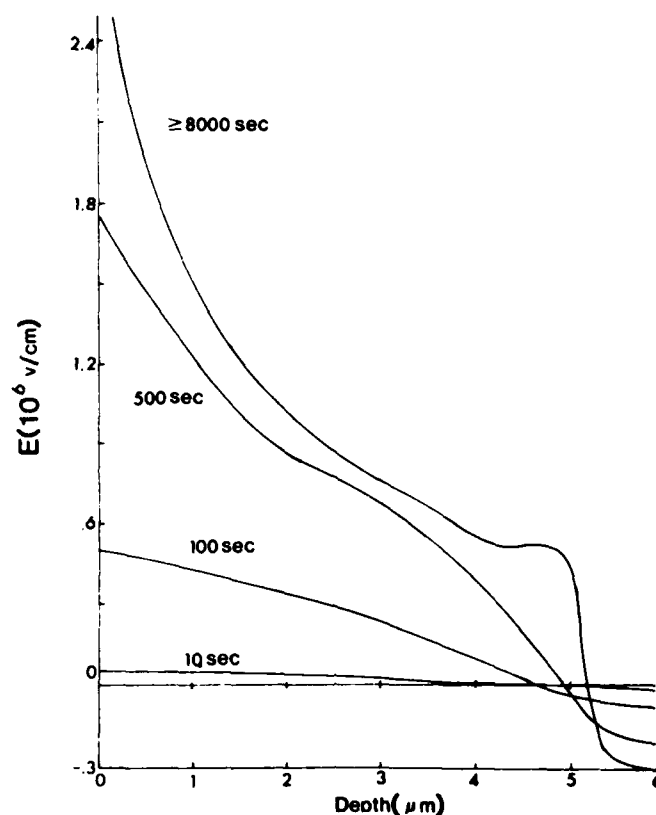


Figure 3. Results of a Computer Simulation for the Internal Electric Field vs Depth of a Grounded-Front-Surface Dielectric. The different curves show the temporal development of the electric field distribution within a 25-micron mylar sample irradiated with 20-keV electrons at 10^9 A cm^{-2} . Laboratory measurements indicate that electrical arcing occurs when this internal field is greater than about $\approx 10^5 \text{ V cm}^{-1}$ (Frederickson and Woolf²)

created due to modifications of the electronic states within the polymer chain by the internal electric fields and the availability of charge carriers. A detailed analysis of this theoretical aspect is not yet available. The current discussion will deal, however, with the experimental observations and a phenomenological description of the breakdown.

Most of the laboratory work on irradiated dielectrics to date have used geometries similar to Figure 1, that is, that of an electrically-floating-front-surface dielectric. The case of a grounded front electrode has been considered and these results are discussed here. Basically, the grounded front surface not only changes the internal

charge deposition and electric field pattern but, in addition, prevents the explosive loss of charged particles at the intersection of the dielectric surface and the vacuum as occurs in the ungrounded case. In other words, the large current spikes ($> 10^2$ A) that are observed in ammeters connected to the rear electrode of Figure 1 are not seen in the grounded case. The ungrounded front surface dielectric is discussed first.

Figure 4 shows schematically a cross section of a negatively charged dielectric which has undergone an internal arc discharge and has created a blowoff channel at the interface of the dielectric and the vacuum. Blowoff arcs occur most readily at discontinuities, for example, edges, holes, and imperfections in the insulators where the electrostatic fields are greatest. The larger geometry is that of an ungrounded front surface dielectric undergoing electron irradiation as shown in Figure 1. It is important to realize that the arc erupts from the surface on the irradiated side, that is, the anode, and that the subsurface discharge tunnels are primarily in the plane of the buried charge near the one-electron penetration depth (5 to 8 μm). This mechanism is often called a prebreakdown event since the discharge is not a full breakdown of the dielectric property of the material. A full breakdown has never been obtained in any radiation-induced discharge of a polymer. The prebreakdown does, however, leave a permanent Lichtenberg pattern or hollow tree within the dielectric as a remnant of the discharge. These small discharges are not detrimental to the insulating property of the material. Further, for a given sample under continuous irradiation with a monoenergetic flux of electrons, the frequency of breakdowns decreases with time—an annealing effect—indicating that arcing is associated with imperfections of the sample. Finally, the breakdown characteristics of polymers; for example, mylar, teflon, and kapton, are less dependent on their chemical composition than on the manufacturing process. That is, the composition is of second order or of less importance.

The blowoff arc as shown in Figure 4 highlights several important features of the front-surface discharge and channel formation. Prior to detailed post-irradiation studies of the breakdown morphology (Lichtenberg patterns) it was assumed that this discharge was a result of a punchthrough of the surface charge to the rear electrode of the dielectric (see Figure 1). Figure 4 shows that in the present model a plasma is emitted from the blowoff channel with sufficient density, that is, conductivity, to neutralize the electric field near the surface. Particle measurements of scattered electrons and excess ions are in agreement with this proposed mechanism. In addition, this concept of a plasma being generated within the breakdown channel is consistent with the formation of plasma-filled tunnels or streamers within the dielectric as mentioned earlier.

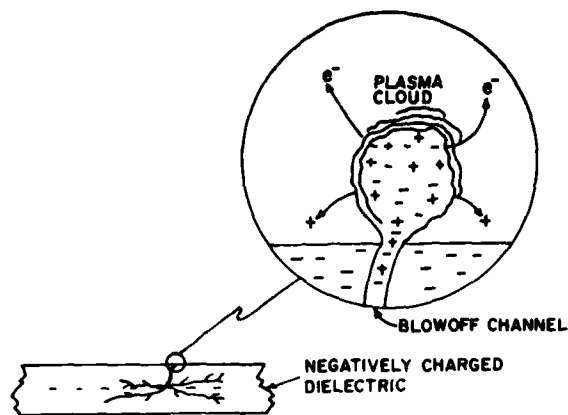


Figure 4. The Intersection of a Streamer and the Surface of a Dielectric Results in a Blow-off Arc. The hot plasma within the blowoff channel electrically couples the external surfaces and the channel path thus neutralizing the surface charge and creating an equipotential path within the material. A typical tree or Lichtenberg pattern, which is created within the dielectric, is shown schematically at the left

Figure 5 is a schematic of a streamer propagating within a dielectric in response to the large internal electric fields. For the case described above, these ionization paths intersect the front surface and the highly-conductive plasma along the streamer causes the tunnels to be approximate equipotentials. In addition, the plasma emitted at the blowoff point electrically couples the head of the streamer and the tunnels to the vacuum, the dielectric surface, the vacuum chamber walls, and so on. This highly-ionized hot gas is created within the tunnel (at the head of the streamer) by a change of state of the dielectric material. The small amount of excess charge or spacecharge trapped within the dielectric can escape along this ionized path. The propagation speed of the streamer determines, in part, how fast the prebreakdown pulsing proceeds. Measurements yield an approximate speed of order 10^5 m sec^{-1} (Balmain⁶). Although only a small amount of spacecharge can be released by this mechanism—since the tunnels are so small—transient currents in excess of 10^2 A are often observed at the rear electrode of Figure 1. Such large currents are primarily due to the emitted plasma which neutralizes the electric fields in the vacuum region. These image currents at the rear electrode can flow

6. Balmain, K. G. (1980) Surface discharge effects, in *Space Systems and Their Interactions With Earth's Space Environment*, edited by Henry B. Garrett and Charles P. Pike, *Progress in Astronautics and Aeronautics*, V71, pp. 276-298.

between adjacent materials and can propagate below the insulator within the body of a space vehicle. It is these large currents that can be quite hazardous to sensitive electronic equipment on spacecraft.

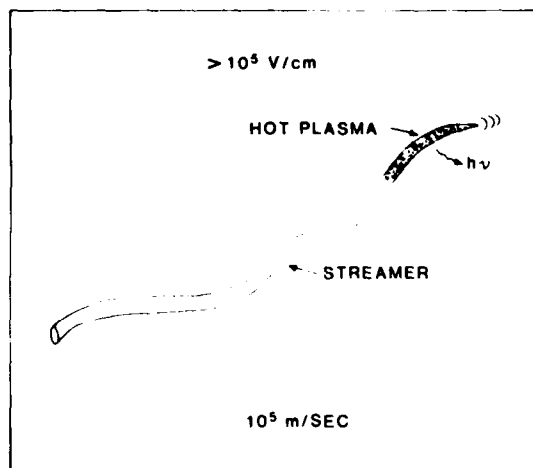


Figure 5. Schematic of a Subsurface Dielectric Streamer. This mechanism is the manifestation of a pre-breakdown arc which can occur when the internal electric field is greater than 10^5 V cm^{-1} . At the head of the streamer is a gaseous light-emitting plasma. The experimentally determined (Balmain⁶) velocity of the streamer head is about 10^5 m sec^{-1} .

An example of a series of subsurface discharge tunnels is shown in the photograph of Figure 6. This scanning electron micrograph is of a Kapton sample following irradiation with energetic electrons. Note, in particular, the surface eruptions at the right indicating the locations where blowoffs have occurred. These features are permanent scars within the sample and an analysis of these scars suggests the following facts:

- The discharge tunnels are located at a subsurface depth of ≈ 0 to $8 \mu\text{m}$ within one penetration length for energetic (10's of keV) electrons.
- These tunnels are hollow—evidence that the formation process is not electron cascade throughout the material. Instead, a plasma is created within the tunnel which is emitted at the blowoff points.

- The surface blowoff occurs at the irradiated (anode) side of the sample even though the electric fields are larger at the rear (see Frederickson⁴, Figure 6).
- The presence of old discharge tunnels does not noticeably affect the insulating property of the dielectric.



Figure 6. The Resulting Subsurface Lichtenberg Pattern Observed in an Electron-Irradiated Kapton Sample Following the Occurrence of a Pre-Breakdown Event or Arc. Note the surface eruptions at the right of the photograph indicating the locations of blowoff arcs (Photomicrograph courtesy K. Balmain, University of Toronto)

Typical space-qualified materials under irradiation by electrons are shown in Figures 7 and 8 where it is evident that electrical arcing is occurring at the edges, corners, or near holes in the samples. The typical construction of a thermal blanket uses aluminized mylar sheets separated by layers of tulle (wedding veil material). In order to prevent differential charging and to minimize surface charging these sheets are sewn together using conducting wire. Figure 7 shows that the exposed mylar undergoes significant arcing at the pinholes. Presumably this is

due to the larger electric fields present at these locations which preferentially induce arcing within the sample. A similar process occurs in an electron-irradiated solar cell array as shown in Figure 8. The insulating glass (fused silica) covers undergo significant arcing at the corners between adjacent cells. The two examples presented above show that arcing readily occurs for electron-irradiated dielectrics especially at imperfections; for example, holes, corners, cracks, and so on, within the sample. Again, it is stressed that this arcing is non-destructive to the dielectric's insulating properties but can induce large transient currents in the surrounding medium.



Figure 7. A Well Defined Pattern of Electrical Breakdowns at the Points Where a Sewing Needle Penetrated the Surface of an Electron-Irradiated Thermal Blanket. Such a pattern demonstrates that the breakdowns tend to occur more often where there are material imperfections. (Photo courtesy of N.J. Stevens, NASA Lewis Research Center, Cleveland, Ohio)

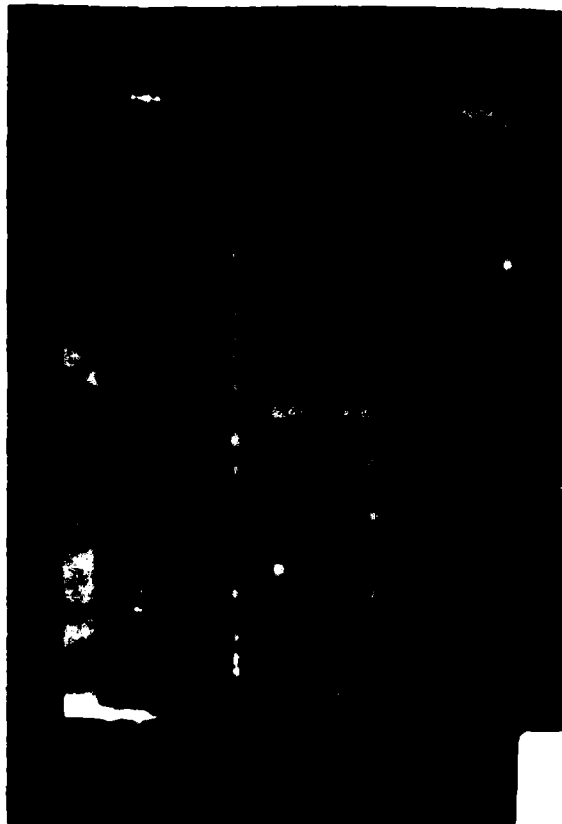


Figure 8. Light Flashes at the Corners and Within the Bulk of an Electron-Irradiated Solar Cell Array. These flashes result from the electrical breakdown of the glass (fused silica) dielectric. Very fine streamer patterns can be seen in the original photograph throughout the bulk of the glass. Blowoff occurs preferentially at the edges between individual cells. (Photo courtesy of N. J. Stevens, NASA Lewis Research Center, Cleveland, Ohio)

Arcing within a grounded-front-surface dielectric under irradiation differs from that of an exposed dielectric (Figure 1) in that the currents measured at the rear electrode are smaller in the former than in the latter. These currents are generated by the subsurface discharge tunnels which reorient the charge distribution and electric fields within the tunnel. Only a limited amount of published data exists for electron-irradiated dielectrics with grounded front surfaces and, then, only at energies of several hundred keV to 1 MeV. Note that these energies are significantly greater than typical auroral particle energies (10's of keV). The increased energy causes the incident particles to be deposited to greater depths within the dielectric than at lesser energies; however, calculations of the internal electric field strengths established by the spacecharge are comparable at the different energies (see Figure 4 and Frederickson,⁷ Figure 13). Figure 4 also shows that the electric field strengths in the steady state are sufficient, that is, $> 10^5 \text{ V cm}^{-1}$.

7. Frederickson, A. R. (1980) Radiation induced dielectric charging, in Space Systems and Their Interactions With Earth's Space Environment, edited by Henry B. Garrett and Charles P. Pike, Progress in Astronautics and Aeronautics, 71:386-412.

to induce arcing near both the front and rear surfaces of the dielectric. The polarity of the discharge current detected in the rear electrode (only one electrode assumed connected to an ammeter) segregates front-surface discharges from those near the rear electrode. The temporal development of the internal electric fields for polymers has been modeled and compared to measurements of the temporal onset of arcing and of the currents at the front and rear electrodes. The results agree and the following facts accrue:

- high field strengths do not guarantee breakdowns,
- no breakdowns occurred below $\approx 10^5 \text{ V cm}^{-1}$,
- field-enhanced conduction occurs but is not important for preventing microdischarges,
- breakdowns release infinitesimal amounts of the initially trapped spacecharge from the dielectric,
- the decay of bulk charge requires long time periods, for example, days,
- the rate of arcing within materials under constant irradiation decreases with time, and
- changes in the particle energy distribution can induce renewed high arcing rates.

All the above findings do not conflict with high voltage experiments using applied electric fields without radiation.

In an experiment especially relevant to future polar-orbiting space shuttle missions, a typical Orbiter tile (Lockheed Company LI-900 All Silica Insulating material) was irradiated with very energetic electrons to study the charging and discharging characteristics of the tile. The shuttle has 30,000 of these tiles with varying surface areas of 10 cm^2 to 400 cm^2 . In the ionosphere these tiles may be exposed to large dose rates of energetic electrons which are then imbedded within the tile material. This spacecharge can remain up to several days. It is fairly certain that these irradiated tiles will undergo some degree of arcing in space, however, the size and frequency of the discharges will depend on conditions that are quite complex. The experiment described here is covered in more detail in an article by Frederickson and Chesley.⁸

A typical shuttle tile has a borosilicate glass cover surrounding a sintered array of silica fibers. This glass cover has a variable thickness of 0.23 mm to 0.38 mm while the internal fibers are less than 3.2 mm long and 1.2μ to 4μ in diameter. For the sample used in this experiment the tile was tested in a

8. Frederickson, A.R., and Chesley, A.L. (1983) Charging/discharging of space shuttle tile material under irradiation, IEEE Trans. Nucl. Sci. NS-30:4296-4301.

floating-front-surface configuration and irradiated with electrons of energy 50 keV to 350 keV and at a flux level of $3 \times 10^{-6} \text{ A m}^{-2}$. The back of the sample tile, that is, a fiber surface, was mounted against the rear electrode and the tile held in place by a grounded brass support. An annular brass ring mounted slightly in front of the sample was used as a beam monitor. Electrometers measured currents flowing within the rear electrode and the beam monitor ring. Both electrometers were sensitive to arcing within the tile and typical plots of current versus time are shown in Figure 9. Model calculations show that arcing occurs when local electric fields within the borosilicate glass cover exceed $\approx 10^5 \text{ V cm}^{-1}$. This sample was irradiated, at different times, with two types of electron radiation having separate energy distributions.

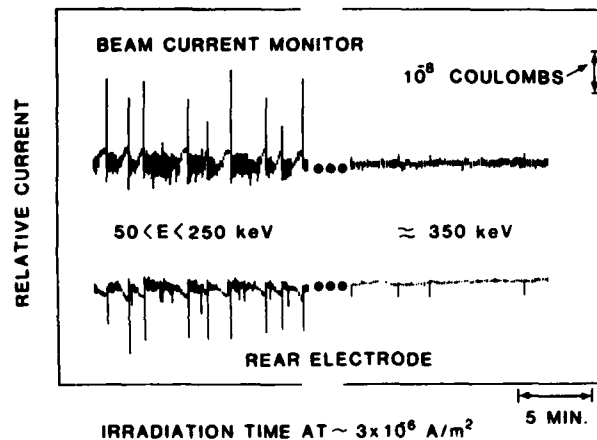


Figure 9. Electrometer Record for Currents in the Back Electrode and in the Front Beam Monitor Ring for an Electron-Irradiated Sample of a Space Shuttle Tile. The large spikes correspond to surface eruptions and the small spikes are due to changes in the internal charge configuration. The height of a pulse corresponds to the charge (note the 10^{-8} Coulomb fiduciary) flowing through a calibrated resistor. It should be noted that the 1-sec response time of the chart recorder was not sufficient to determine the shape of the actual pulse (lasting less than 1 sec). However, the authors believe that the pulse average is correctly monitored. (Frederickson and Chesley⁸)

The first radiation had a broad energy spectrum of electrons from 50 eV to 250 keV. Figure 9 shows that under these conditions the current monitors detected larger pulses or arcs occurring within or on the surface of the tile. Presumably these currents were due to blowoff-type discharges at the glass-vacuum interface, similar to those discussed earlier. At the blowoff channel a plasma was emitted from the dielectric which neutralized the external electric fields. Small pulses or microdischarges were also detected, corresponding to arcs within the bulk of the glass cover. Very few of the primary electrons were sufficiently energetic to completely penetrate the borosilicate cover and only negligible spacecharge was imbedded within the tile fibers.

A monoenergetic population of 350-keV electrons caused only intermittent microdischarges. At this energy some of the incident electrons penetrated the borosilicate cover and were imbedded within the fibers. Smaller electric fields, relative to the previous case, would be expected in the bulk of the glass with a reduced probability of arcing. In addition, secondary electron emission among the silica fibers inhibited large (organized) electrostatic fields of arcing strength from occurring here. It is probable, however, that extremely small discharges occurred at edges and corners of the fibers where local electric fields could exceed 10^5 V cm^{-1} . Indeed, post-irradiated measurements with sensitive electrometers did show evidence of such arcing subsequent to the termination of the radiation. These tiny discharges persisted for several days.

This experiment has shown that arcing within space shuttle tiles can be induced by fluxes of energetic electrons. Within the auroral zones, discharging of the tiles will probably include a substantial number of blowoff arcs—especially in the absence of sunlight. The large transient currents associated with this form of discharge may disrupt electronic instrumentation as well as being an undesirable source of EMI and optical contamination. There is also a question regarding astronaut safety during EVA (ExtraVehicular Activity) since dielectric discharging can be induced by changes in the material's surface pressure, for example, by an astronaut accidentally touching an exposed insulator. Only a limited amount of information (Gross et al.⁹) is available in this regard and, clearly, more work is needed.

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4. SUMMARY AND CONCLUSION

The processes of deep-dielectric charging and discharging are especially relevant for low-altitude spacecraft which traverse the auroral zones. The energetic particle populations that are present in these regions of space can deposit spacecharge within the materials which, in turn, induces large internal electric fields. Above $\approx 10^5 \text{ V cm}^{-1}$ these local fields are sufficient to support dielectric discharging or arcing of irradiated materials. Although such arcing does not seriously affect the insulating property of dielectrics, transient currents of order 10^2 A may be generated at the surface of exposed dielectrics in darkness. Lesser currents are likely for surfaces having sufficient photoelectrons to compensate the incoming charged particle flux. A polar-orbiting shuttle with its large insulating surface area is expected to undergo dielectric discharging which may impact astronaut EVA.

In order to reduce the potential hazard of dielectric arcing it would be advisable to use "leaky" material ($< 10^{12} \Omega \text{ cm}$) which would prevent the internal electric fields from exceeding 10^4 V cm^{-1} . Since this may not be possible or practical the following consequences may occur:

- trapped spacecharge and internal fields may persist for weeks subsequent to the radiation exposure; lying in wait to affect the spacecraft activities,
- surface voltage pulses of $\leq 20 \text{ kV}$ may occur during breakdown; sufficient to adversely affect electronics in the vicinity,
- $>$ microcoulomb plasma ejections may occur randomly at blowoff points producing unpredictable EMI problems,
- spacecraft electrostatic fields external to the dielectric may focus incoming charged particles and cause increased doses to specific areas around the spacecraft, and
- EVA astronauts may set off these discharges (whether or not the astronaut is grounded) by touching an exposed dielectric. The discharge might disrupt the EVA.

QUESTIONS AND ANSWERS

- Question: Why wasn't deep-dielectric charging a concern during the Apollo program? (W. Sinclair)
- Answer: The Apollo capsules were subjected to an environment that was not as extreme as that expected for a polar-orbiting shuttle. Within the auroral zones, the Orbiter will be routinely subjected to multi-keV particles at flux levels reaching 10^{-9} A cm⁻². The Apollo capsules, on the other hand, were embedded within a low energy (< 100 eV) plasma at flux levels of $\approx 10^{-14}$ A cm⁻². Calculations I have made show that, under these latter conditions, the probability of arcing is extremely small. In addition, the capsule was almost always within sunlight and therefore surrounded by an abundance of low-energy photoelectrons which reduced the electric fields at the surface of dielectrics.
- Question: Can breakdowns be triggered by high-energy, high-Z particles, that is, cosmic rays? (R. Filz)
- Answer: Contrary to the intellectual appeal of such a mechanism, the passage of high LET (Linear Energy Transfer) particles has not been found to be a problem by the electric insulation industry. The high ionization trail does not turn into a plasma. However, a gaseous void within the dielectric or at the surface causes a material defect which may initiate the breakdown in the electric insulating material.
- Question: Can such a breakdown occur within a biological system? (M. Elkind)
- Answer: The electric conductivity within biological systems is high enough, in most situations, to prevent the establishment of large internal electric fields. Perhaps more pertinent is that a dose in excess of 10^4 rads is needed to build up the spacecharge within the system before arcing would become a problem. The biological system would in fact be killed by such a dose prior to any arcing concerns.

Question: What would the effect of 8-MeV to 10-MeV electrons?
(R. Sagalyn)

Answer: In most space scenarios there is an insufficient current density of such particles to build up a significant spacecharge within the dielectrics; that is, the dark current of the insulator is high enough to "leak off" the deposited charge. If, however, the flux of these high-energy particles exceeds $\approx 10^{-14}$ A cm⁻² the problem must be investigated for the specific dielectric material. In most cases the problem would be equally acute for 10-MeV electrons as for the 10-keV electrons discussed in this presentation. As an aside, at the RADC/ESRE labs we have created Lichtenberg discharge trees with dielectrics irradiated with 10-MeV electrons. These trees were created in a variety of dielectrics of thickness both $>$ and $<$ one - electron penetration depth and for extremely high dose rates, for example, 10^3 rads/sec over 100 sec.

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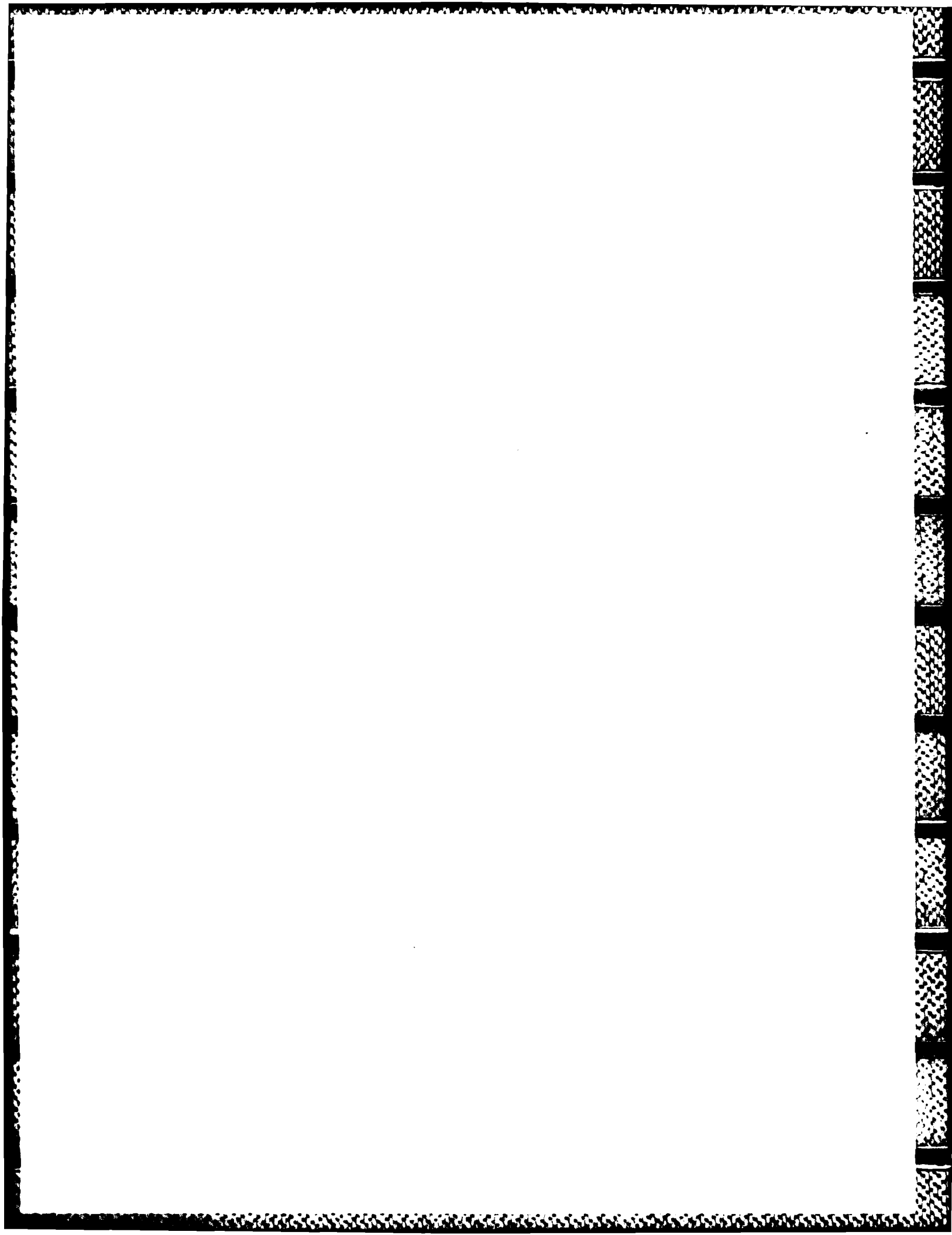
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