IMPROVED TESTING PROCEDURES FOR SPACECRAFT DISCHARGE PULSES

A. R. Frederickson, Arthur.R.Frederickson@jpl.nasa.gov, 01-818-354-2105
C. E. Benson, Charles.E.Benson@jpl.nasa.gov, 01-818-354-2363
California Institute of Technology Jet Propulsion Laboratory
Pasadena, CA 91109, USA

ABSTRACT

A new set of discharge laws has been developed, if only qualitatively in some ways, which guides one to better develop testing procedures for spacecraft pulse discharge testing. Other papers indicate how the discharge is generated by a burst of gas. The physics of that gas discharge provides a set of discharge phenomena that must be considered when designing ground tests for insulator discharges for spacecraft systems. Most important, the amplitude of the discharge pulse is critically dependent on: the distribution of image charges prior to the discharge, the path of current through the gas discharge, the amount of gas issued in the event, and the electric field in the vacuum that drives the gas current avalanche. The amount of gas issued into the vacuum is critically dependent on the electric field inside the insulator. Thus, proper testing must simulate the electric field and image charge distributions that actually occur on structures in space.

INTRODUCTION

Quantitative analysis and prediction is the ultimate goal. If every component of the pulsing phenomenon were fully understood one could predict pulse shape, amplitude, distribution of current to spacecraft components, and frequency of occurrence. But full understanding is still far away. Based upon our experimental study the following analysis and prediction methodology seems to be appropriate. The method provides rough quantitative prediction with accuracy sufficient to reduce the uncertainties to much more manageable levels than in the past. For any required level of certainty, one can reduce the number of tests and safeguards relative to those that were needed in the past. Or, if one has been having unexplained problems on spacecraft, the analysis can better focus one to find the real causes.

Quantitative analysis allows one to perform much more focused testing on spacecraft (no more automotive spark coil testing), specify box-level requirements, correct only the truly threatening insulator structures and, in general, engineer more precisely. The analysis, however, must be performed before the goals can be achieved. Because we know little about most materials, testing is required to determine the value of parameters for each new material. The analysis must be performed in order to design the tests to find meaningful data for the parameters.

For example, electron beams at 25 kV and nanoamps per square centimeter make any insulator thinner that 0.4 mm pulse rapidly. When they pulse rapidly, the pulse waveforms are large. But on spacecraft, insulators seem to pulse infrequently. On the ground, when insulators pulse infrequently, the pulses are small. For example, on insulators thicker than 3 mm, 25 kV electron beams produce small infrequent pulses while more realistic high-energy space spectra can produce large pulses. Without good analysis, testing with arbitrary electron beams provides poor to bad guidance.

At this time, year 2000, the method is most profitable in designing ground test procedures to properly test insulator devices, and to evaluate material parameters. Among the important parameters we know the least about are the insulator material parameters that control both the electric fields and the gas discharge. Existing knowledge of these parameters only allows us to provide warnings of severe pulses in space, but not accurate pulse shape/amplitude prediction. By using the new method in ground testing, and comparing ground test results to space results, we will eventually build the knowledge of the material parameters and thereby empower us to make precise calculations.

IMPROVED TESTING PROCEDURE

The first component of the new procedure is to outline the conditions in space to which the insulator under test may be exposed. The important conditions are the electric fields inside and outside the insulator, and the distribution of image charges in nearby conductors. Steps 1-4 comprise the first component.

1. *Estimate the range of energy-spectra and intensities to which the insulator will be subjected.*
2. *Determine the range of electric field intensities that are expected* <u>*inside*</u> *the insulator. Usually one attempts to find a worst-case for the application.*
3. *Determine the range of electric field intensities that are expected* <u>*outside*</u> *the insulator, or the surface voltage on the insulator. Usually one attempts to find a worst-case for the application.*

4. *Determine the quantity of image charge residing on the wiring that is attached to the sensitive circuit just prior to a discharge. This is often the most critical factor, but not always.*

The second component of the new procedure is to determine the kind of pulse generated by the specific insulating material as described in step 5.

5. *Knowing the electric fields in 2 and 3 above, determine the magnitude of the pulse itself. The pulse itself is a current-time waveform that propagates in the vacuum space near the charged insulator surface due to the gas discharge that occurs there.*

One determines the magnitude of the pulse itself by testing the insulator with electric field stresses determined in 1-4 above. The worst case pulse generated by the insulator during these tests becomes a design-to condition.

One now returns to focus on the insulator in its actual configuration among circuit elements. When the insulator surface voltage discharges, it will cause image charges to flow, along with induced currents, inside the adjacent conductors. This can be described as step 6.

6. *Determine the size of the pulse that is induced on the wiring attached to the sensitive circuit. There are three components to this signal (other components also occur in a few special applications). They are: the image charge leaving the wire through the sensitive circuit, charge flowing through the discharge gas towards the sensitive wiring, and electromagnetic coupling of the discharge current loop into the sensitive circuit.*

Once step 6 has been achieved, one may analytically apply the predicted pulsed current to the circuit using codes like Spice to determine if it threatens the circuit.

It is possible that the circuit itself will limit the pulsed current, and save itself. But it must withstand very high voltage to do so. In most cases, the resistance of the gas discharge is large, from 1000 ohms to 1 megohm, and the voltage driving the currents through the gas is high, from 1000 volts to 50 kV. For most circuits, these conditions are equivalent to a constant-current source (high-voltage in series with very high impedance) and the circuit will not substantially alter the current generated by the gas discharge without developing high voltage across itself.

EXAMPLE OF IMPROVED TESTING PROCEDURE

Consider the classic 25 kV electron irradiation on a 200 micrometer insulator in a vacuum chamber with conductive, grounded walls. It is rare that such a condition occurs on spacecraft (low energy electrons, thin insulator, inside conductive box). But it is a common condition in ground tests. We will model this condition as if we had a spacecraft exposed to 25 keV electrons in its electronic boxes.

First, estimate the range of energy-spectra and intensities to which the insulator will be subjected.

Figure 1 provides the schematic for the problem. Electrons from the 25 kV gun bombard and stop inside the insulator within about 5 microns of the surface. For the most part, these electrons remain trapped where they stop. A few electrons, holes and ions drift in the resulting electric field to slowly deplete the field, but this can take days or longer in good insulators.

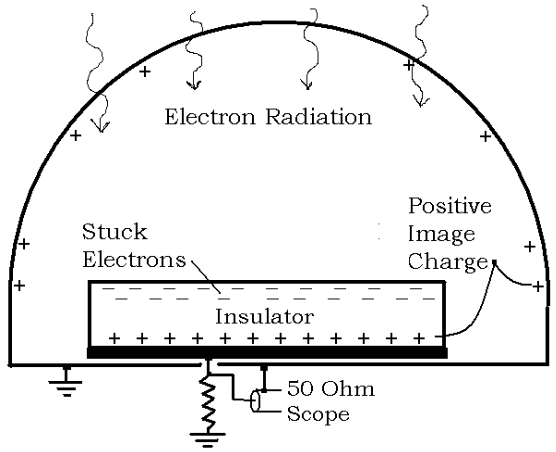

Figure 1. A 25-keV Electron-irradiated Thin Insulator in a Grounded Hemispherical Evacuated Box.

<u>Second,</u> Determine the range of electric field intensities that are expected <u>inside</u> the insulator. Usually one attempts to find a worst-case electric field for the application.

This is easy to do for the 25 keV electron beam normally incident. The surface voltage builds up negatively, as electrons accumulate, until the incident electrons bombard the surface at about 1 to 5 keV. Somewhere between 1 to 5 keV, depending on insulator material, a secondary electron is emitted for every incident electron and further accumulation ceases. Thus the surface achieves about +3 kV potential relative to the electron gun cathode or —22 kV relative to ground after very long irradiation time.

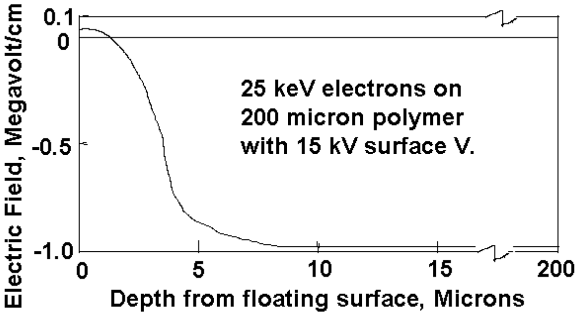

Figure 2. Electric field in a typical sample in 25 keV electron beam test.
Note the constant field between 15 and 200 microns.

Figure 2 is a snapshot of the electric field profile at the instant that the surface voltage attained —15 kV on a polymer sample 200 microns thick with the rear surface grounded. The maximum internal electric field is about 9E5 V/cm, and is close enough to the surface to cause a gas discharge to burst from the open surface.

<u>Third</u>, determine the range of electric field intensities that are expected <u>outside</u> the insulator, or the surface voltage on the insulator. Usually one attempts to find a worst-case for the application.

This is easy if one ignores 3-D geometry details. Assume the distance from the sample surface to the box wall is 5 cm. The electric field in the vacuum is roughly 15 kV/5 cm = 3 kV/cm. This electric field is planar and capable of generating a Townsend avalanche in the burst of gas.

<u>Fourth</u>, determine the quantity of image charge residing on the wiring that is attached to the sensitive circuit just prior to a discharge. This is often the most critical factor.

One can solve for the electric fields and images using an electrostatic field solver. We use our own code, NUMIT, to do so [1-3], but in one-dimensional approximation only. NUMIT follows the development of electric field, charge density, and surface voltage over time everywhere in the system by including effects due to conduction and secondary current flows along with the primary beam current. Often a simple calculation is sufficient based upon capacitance modeling as described in Fig.3. Refer to the electrostatics literature for information on determination of such electric fields. Figure 3 is used to describe a simple approximation.

Positive image charges are indicated in both Figs. 1 and 3. <u>One must determine the number and location of the image charges in order to estimate the discharge pulse current flows</u>. Electrons supplied by the electron gun cathode bombard and stop inside the insulator. Positive images also supplied by the gun cathode flow via ground to the electrode on the back of the insulator and to the nearby walls of the conductive vacuum chamber. When using mathematical field solvers, image charges are not usually tabulated but are implicit in the calculation.

The current flows on spacecraft are slightly different, but analogous. <u>One must effectively determine the position and number of images on the spacecraft as well.</u> The electrons are supplied by the high-energy flux in space. The positive image charges are supplied both from the space plasma and from the positive charge left on the spacecraft skin by emission of photoelectrons from the spacecraft.

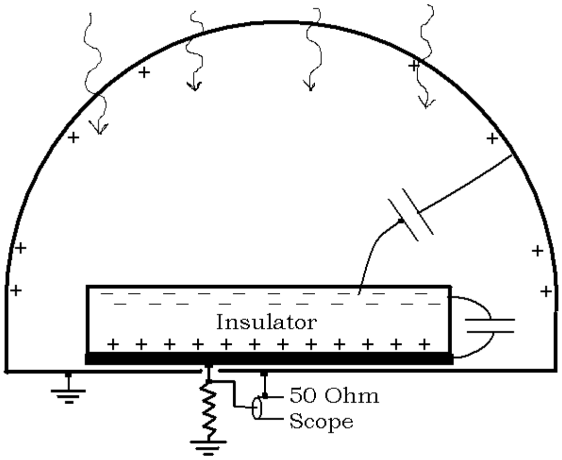

Figure 3. The Capacitor Approximation for Simple Charge Distributions. When the electrons are stopped in a thin layer such as near the surface, E-fields and voltages can be crudely estimated from the capacitance of that layer to ground.

Note that for every electron in the insulator there is somewhere a positive image charge of the same magnitude. When a spacecraft frame is charged, some of the images are located meters away in space plasma. On Earth, because the test chamber is grounded, and not charged relative to space, all of the image charges in the ground tests reside in the nearby conductors such as vacuum chamber walls.

For our typical polymer, there is roughly 0.2 microcoulombs/sq. cm of image charge on the rear electrode, and much less image charge on the box walls. This is the amount of charge associated with the electric field in the sample.

<u>Fifth</u>, knowing the electric fields in 2 and 3 above, determine the magnitude of the pulse itself. The pulse itself is a current-time waveform that propagates in the vacuum space near the charged insulator surface due to the gas discharge that occurs there.

The insulator is now charged and ready to spontaneously generate a discharge pulse. The electric field inside the insulator determines how much gas is released and thereby the total current that can flow. At this time we do not know the general functional relationship, but we can mine existing data to estimate the parameter for specific materials. Pulsing is infrequent (perhaps one per day per square cm or less) and with small gas evolution for fields of 1E5 V/cm. Below 1E5 V/cm pulsing is almost negligible, and nonexistent below 1E4 V/cm. Above 1E6 V/cm pulsing is frequent, approaching one per minute-sq.-cm of material above 2E6 V/cm, and the gas evolution is intense.

Given a sufficient injection of gas, the electric field outside the insulator determines whether the current pulse to circuits will be large. Figure 4 describes the situation. Typically a kilovolt surface potential is sufficient to generate large currents across the vacuum. In our test case there is 15 kV across the vacuum, sufficient to drive large currents.

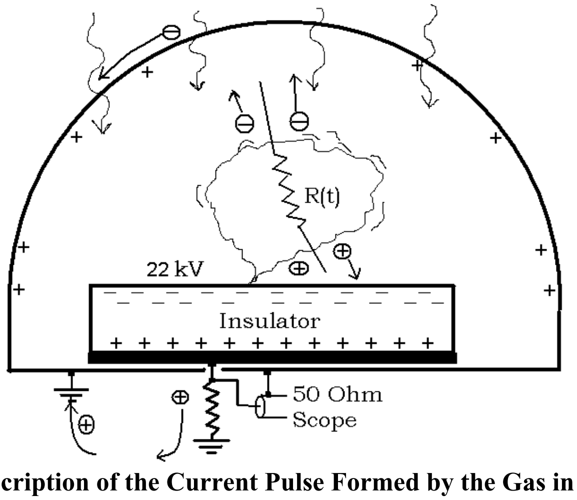

Figure 4. Description of the Current Pulse Formed by the Gas in the Vacuum.

The gas forms a resistive path, **R(t),** from the surface of the insulator to the walls of the chamber, and to any other surfaces in the vacuum. The pulsed current flow in the case depicted in Fig. 4 is comprised of positive images on the electrode flowing to ground (shown by arrows), then to the chamber walls, and finally images flowing from the chamber walls through the gas, R(t), and onto the surface of the insulator. This brings the images as close as they can be to the trapped electrons.

One must refer to ground tests on the material of interest in order to estimate R(t), or the current waveform. It depends on the electric fields inside the sample and outside the sample. R(t) has caused the electric field in the vacuum to be reduced. The change in surface voltage times the capacitance of the surface-to-ground is equal to the total charge that flowed. R(t) is not yet tabulated anywhere. At this time one must inspect ground test data in order to estimate R(t). For example, 1.6 mm thick circuit boards at 22 kV surface potential produce pulsed currents which peak around ten Amperes or less. The same surface voltage on 3.2 mm boards causes the discharge to peak at much lower currents by an order of magnitude. Because the thicker board has a smaller internal field, it produces less gas and thereby smaller peak current.

For our typical case, 22 kV/200 microns, ground tests indicate that FR4 circuit board will discharge nearly half of its surface voltage in one event with a peak current of perhaps 10 amperes or more, and lasting perhaps 200 nanoseconds. Because it discharges by half, 0.1 microcoulombs per sq. cm must flow from the rear electrode, to the box walls and through the gas to stop on the surface of the insulator. A current waveform from a test similar to our typical case is presented in Fig. 5.

As a result of the discharge, the distribution of charge immediately afterwards is depicted in Fig. 6. Compare the distribution of + and — charges in this figure with those in Figs 1 and 3 immediately prior to the discharge.

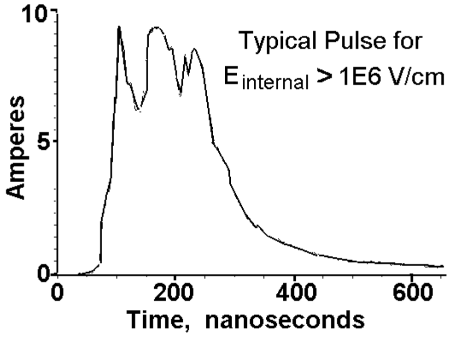

Figure 5. A Pulse Chosen from Data for Similar Samples in Similar Tests.

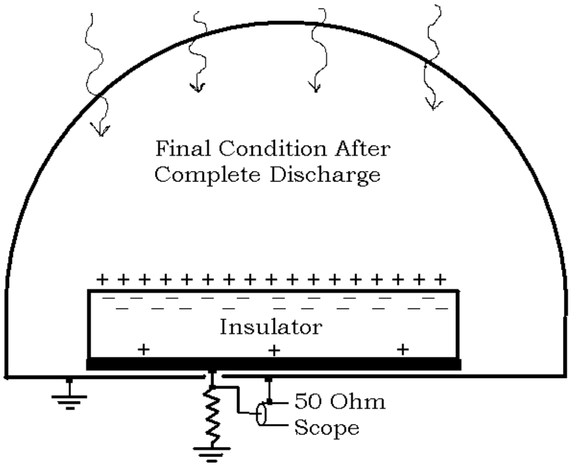

Figure 6. Charge Distribution After the Large Pulse of Current.

Sixth: determine the size of the pulse that is induced on the wiring attached to the sensitive circuit. There are three components of current that drive pulses into sensitive circuits.

The first component is the flow of image charges shown in Fig. 5 and depicted by the arrows in figure 4 as the primary discharge current. The second component occurs when another charged insulator in the vacuum drives current through the same discharge gas. Once emitted, the gas can conduct between any elements in the chamber. The third component is an electromagnetically induced signal from other circuits that couple to the discharge currents, and generate electromagnetic energy that is subsequently absorbed in the sensitive circuit.

The testing work needs only to determine the first component. As an example, consider the electronic box in Fig. 7. The circuit board is the source of the pulse. The signal ground plane may be 50 sq. cm in area, and the circuit trace may be 0.5 sq. cm in area. The discharge occurs from the circuit board to the box walls.

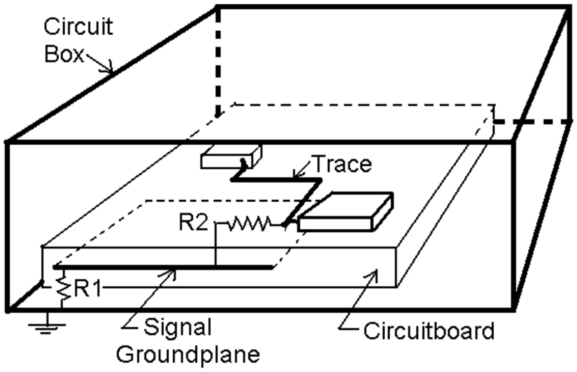

Figure 7. A typical Electronic Box, Simplified.

The signal ground plane experiences current pulses much like that shown in Fig. 5. The value of R1 may be 0.1 ohm, and thus the signal ground plane experiences a 1-volt pulse during the discharge. In some cases R1 may be large for the purpose of isolating a section of the board from ground. In these cases the voltage on the signal ground plane will be very large, but never more than the static voltage on the board prior to the discharge.

The trace has only 1% of the image charges that the ground plane has, and thus experiences only 1% of its current, or 0.1 Ampere peak. If R2 is 10 k-ohms, then the trace will experience 1 kilovolt peak. Since the circuit board probably has of order 10 kV surface voltage prior to the pulse, with larger R2 the trace would not be limited to 1-kV.

Until this point in the discussion we have applied the correct test procedure to the case of the classic laboratory irradiation using 25 keV electrons. The exceedingly threatening pulses are not simply the result of using 25 keV electrons. Instead, the threatening pulses are the result of exceedingly large electric fields primarily inside the insulator, and secondarily in the vacuum space. We proved that the problem is electric field, and not 25 keV electrons, by holding the energy at 25 keV and using much thicker test insulators. As the thickness increases, the electric field decreases and the discharge pulse amplitude decreases dramatically.

In space it is not realistic that inside a box the spectrum of high-energy electrons is equivalent to 25 keV electrons. The electric field inside the typical circuit board, and the image charges on the electrodes, are extreme with 25 keV radiation. The resulting discharge currents are unreasonably large compared to real boxes in space. What do we need to do to be realistic?

REALISTIC TESTING

Realistic testing simulates the electric fields expected in the insulators in actual space conditions. It is electrons above 100 keV that penetrate a box and radiate the circuit boards. Consider the electric field developed in a slab of circuit board 1.62 mm thick with grounded surfaces, irradiated by 1-MeV electrons. Figure 8 shows the electric field predicted in a laboratory test of FR4 board assuming that it has infinite dark resistivity.

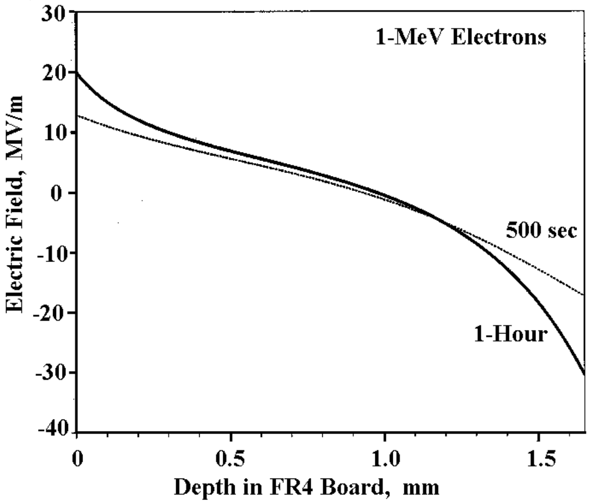

Figure 8. Electric Field in FR4 Circuit Board.
The 1-hour curve is true for all times beyond 1-hour as the field is at steady state. This is the maximum field possible for any 1 MeV electron flux that is less than this laboratory level of 0.5 nA/cm^2.

It is clear that the laboratory testing of FR4 circuit boards should use radiations that produce electric fields of less than 3E5 V/cm. Such testing generates discharge pulses that are at least a factor of ten smaller than that in Fig 5. And, the experimenter needs to wait hours or longer for the few pulses to occur. We have gone as long as two days with only one small pulse occurring in one of our tests on thick insulators with 25 keV electrons simulating field strengths of 1E5 V/cm.

Proper laboratory testing must use electric fields similar to those occurring in space. It is necessary to estimate the electric fields in the insulators that actually occur in space. Armed with this knowledge, one can use, say, 25 keV test electrons on a properly sized sample of the material under investigation in order to simulate the electric field that occurs in space.

Better Test Spectra

The first requirement for a ground simulation is to develop electric fields similar to those encountered in space. It might be possible to do this by using the exact spectrum encountered by the samples in space, but it is doubtful. The spectrum is ever changing and at very low intensity requiring years of ground test for each sample. One should, instead, consider the likely electric fields developed in space, and then test using slightly larger field strength on the ground. Any electron energy spectrum is satisfactory as long as one achieves the goal of simulating the electric field strength.

Further, the recent data on FR4 circuit board, and the older data on Teflon materials indicate that the electric field strength and/or the propensity to pulse at a particular field strength is dependent on dose-related changes in the material. FR4 pulses stronger and more frequently after receiving dose, and Teflon pulses less frequently and weakly as it accumulates dose. Teflon is also known to become more conductive with dose exposure and thereby bleeds off the more intense electric field as dose is accumulated. The test spectrum must be chosen to develop a reasonable simulation of the dose history of samples in space.

The CRRES spacecraft demonstrated the advantage of in-space tests. Much cheaper and better quality testing of insulator sample pulsing could be achieved in space in the future. As materials and spacecraft technologies are developed in the future, they can be tested with worst-case methods on the ground. Materials and technologies that remain most problematic can then be tested in space.

SUMMARY

The following concepts and test procedures seem to be important.

1. The insulator under study must be analyzed to determine how it charges, and which surfaces may be discharged by a burst of gas in adjacent vacuum. An equivalent circuit (Fig.4) must be generated which shows the path of the discharge current, the location of all charges injected by radiation, and the locations of image charges in nearby conductors.

2. The location of the possible gas discharge is considered. Based on the flow of the gas discharge current, one determines the image currents that must simultaneously flow in the surrounding electrodes. Usually, the image currents are the actual threat to the spacecraft, not the current in the gas itself.

3. One must consider the divergence of the electric field in vacuum into which the gas will evolve from the initial discharge. The ground tests should reproduce this condition, and not dramatically change the divergence over a large region of space.

4. One can protect circuits by the use of series resistance to limit peak pulse current, but the series resistance must greatly exceed the resistance of the discharge gas. Thus, ground tests must properly determine the impedance internal to the discharge by creating gas bursts similar to those that will occur in space.

5. The most critical parameter that controls the pulse current waveform is the electric field inside the insulator. It is this electric field that controls the amount of gas evolved, and the amount of gas controls the pulse current. In spacecraft situations, higher internal fields generate more gas that, in turn, generates more peak current. Ground tests must simulate the real internal electric field.

6. The pulse rate can be used as a crude indicator of the internal electric field. Many experimenters were impatient and drove the internal electric fields to exceed 1E6 V/cm in order to generate sufficient data before lunch. This produces misleading data with excessively large pulse size, and excessively frequent pulsing.

7. Pulse amplitude has only small dependence upon beam current density. Only in cases where conductivity in the sample affects the internal electric field will beam current density affect pulse amplitude. It still appears reasonable to use enhanced beam current in order to more rapidly charge surfaces. But test fidelity will be sacrificed if this affects maximum internal electric fields.

8. Radiation dose can affect the rate and size of gas bursts. FR4 circuit board pulsed more frequently after six months in space, PTFE pulsed less frequently. Ground tests indicate that this was due in both cases to total dose, not due to evacuation, drying out or beam current effects. Gradient of the dose may be very important as having an effect on the size and frequency of gas bursts. Therefore, good testing must include the effects of dose.

9. It can be very important to consider the actual path through which the gas carries the discharge current. Coupling into external circuits may be critically dependent on the path of the discharge current. The gas can carry current through tortuous paths.

References.

1. A. R. Frederickson, "Radiation-Induced Electrical Current and Voltage in Dielectric Structures", AFCRL-TR-74-0582, 41 pgs. (1974)
2) A. R. Frederickson, "Charge Deposition, Photoconduction, and Replacement Current in Irradiated Multilayer Structures", IEEE Trans. Nuc. Sci. NS22, 2556-2561 (1975)
3) A. R. Frederickson, S. Woolf and J. C. Garth, "Model for Space Charge Evolution and Dose in Irradiated Insulators at High Electric Fields," IEEE Trans. Nuc. Sci. 40, No. 6, 1393-1401, Dec., 1993.

Keywords: Spacecraft, EMC Testing, Electrostatic Discharge, Insulator Breakdown, Vacuum High-voltage Breakdown, Radiation

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration and the NASA SEE Space Environment Effects Program.