GAS DISCHARGE PHENOMENA IN SPACECRAFT DISCHARGE PULSES

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ABSTRACT

Various experiments are performed to determine that the typical pulsed discharge current is controlled by a low-pressure gas discharge. Although not broadly accepted, this has been mentioned often by previous investigators. The phenomenon has important technical implications that are only now being investigated. We find that both the spatial arrangement of the vacuum chamber grounds and the divergence of the space-charge electric fields strongly modify the pulsed-current waveform. The results are consistent with the interpretation that the pulse of current is carried by a Townsend gas discharge, and not by electrons emitted from the insulator. The amplitude, duration, slew-rate, polarity and total charge in the pulse can be dramatically changed by changing the spatial arrangement of grounded surfaces in the vacuum chamber. As a result, the pulsed energy delivered to a threatened circuit element is varied by an order of magnitude or more by seemingly unimportant parameters such as the "geometry" of the discharge space. Useful quantitative distinctions can now be made.

EXPERIMENTAL METHOD

Multi-keV electron beams are used to charge the front surface of FR4 epoxy fiberglass planar circuit board material and other materials to high voltage, typically of order 20 to 30 kV. The back surface is metalized with copper, and grounded through 50-ohms as shown in Fig. 1. Pulsed currents are measured flowing from the copper to ground through the 50-ohm circuit in this standard charging/discharging experiment configuration. Beam energies from 5- to 35-keV are employed at 0.5 nA/cm2. In one instance a thin strip of copper on the front surface is also monitored.

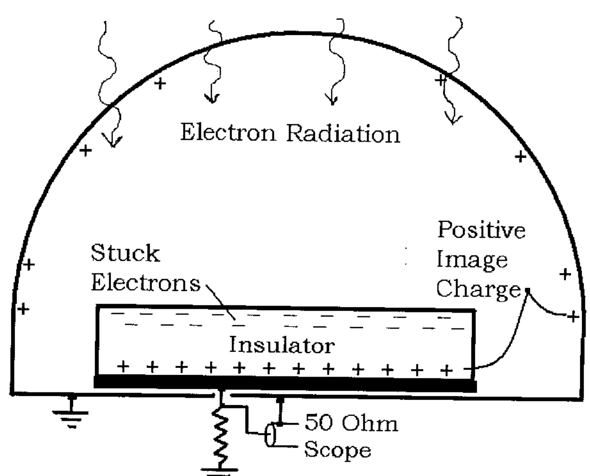


Figure 1. A multi-keV Electron-irradiated Thin Insulator in a Grounded Vacuum Chamber. The actual chamber is a 75 cm diameter cylinder with the front of the

sample at 74 cm from the broad-beam electron gun. In this arrangement the oscilloscope always registered a positive pulse.

Various grounded wire grids are sometimes placed approximately 2.5 cm above the front surface so that the keV electron beams must pass through the grid in order to bombard the front surface of the sample. The charged sample surface voltage (typically 10 to 20 kV) produces a strong electric field between the surface and the grid. Negligible electric field penetrates beyond the grid into the remainder of the vacuum chamber. The high-voltage on the sample produces a strong electric field in the sample and occasionally generates a spontaneous discharge tree in/on the sample. The discharge tree issues a burst of gas into the evacuated space above the sample.

DETAILED EXPERIMENTS

The experimental arrangements of materials and vacuum electric field profiles are varied as depicted in the figures below. The discharge pulses associated with each arrangement are described with an illustrative example along with a table describing each of the many pulses for that arrangement. The first group of tests is performed with the 0.165cm X 7.6cm X 7.6cm FR4 samples.

USING GRIDS TO CONTROL THE GAS DISCHARGE

First Arrangement

The first arrangement generates nearly parallel electric field in the vacuum with a 90% transmission grounded grid placed 2.5 cm from the surface. The incident electrons arrive at the surface in the normal direction, and the surface achieves up to –27 kV when bombarded by the initially 30 keV electrons. Most of the vacuum field is plane-parallel as shown by the arrows in Fig.2.

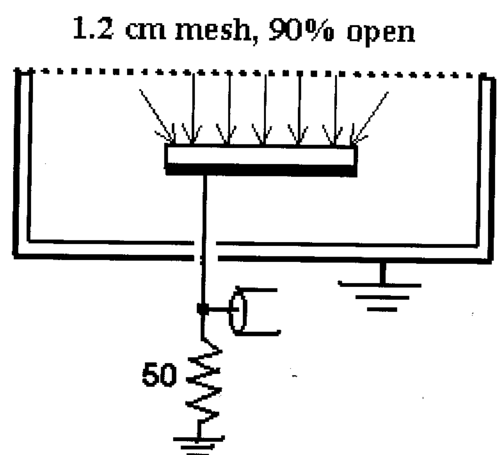


Fig. 2. Planar Sample Under Planar Open Grid. The charged sample produces mostly parallel electric field as depicted by the arrows.

All of the pulses captured in one run are listed in Table 1. The trigger level on the scope was set so that nearly all pulses were fully recorded. Prior tests had taught us that by setting the scope to be more sensitive, very few small pulses are seen and most of the pulses are then off scale. Another full eight hour run found no negative pulses. Negative pulses would occur when the discharge passes through the fringing field region onto the sample electrode thus causing positive image charges originally in the aluminum sample holder to flow through the scope onto the sample copper electrode. We monitored for 8-hours and no negative pulses occurred.

Table 1. Pulses under 90% Transmission Grid.

Pulse number 10/04/99	Width at Half Peak (ns)	Peak current 50 ohms (A)	Charge (Coulombs)	Energy in 50 ohms (mJ)
1:48:48	160	8.8	1.67E-06	0.46
1:57:03	172	7.0	1.29E-06	0.31
2:08:08	236	5.7	1.35E-06	0.26
2:11:58	260	5.4	1.25E-06	0.21
2:15:58	138	11.4	1.41E-06	0.41
2:22:21	116	7.6	1.05E-06	0.20
2:27:06	224	6.3	1.55E-06	0.29
2:33:09	190	5.1	1.10E-06	0.17
2:36:24	278	4.0	1.28E-06	0.16
2:41:56	248	5.1	1.32E-06	0.21
2:48:27	196	5.7	1.52E-06	0.24
2:55:55	250	5.1	1.37E-06	0.21
3:00:10	236	5.1	1.10E-06	0.15
3:07:37	260	4.6	1.30E-06	0.18
3:12:26	316	3.8	1.25E-06	0.15
3:18:07	264	4.4	1.33E-06	0.17
3:38:34	300	4.4	1.42E-06	0.17
4:39:41	264	5.1	1.43E-06	0.21
Average	228	5.8	1.33E-06	0.23

The beam current was approximately 0.5 nanoamps/cm^2. Over the three orders of magnitude of beam current used on our tests the discharge pulse shape and amplitude do not depend upon beam current. It is instructive to roughly estimate the time to charge the sample. Pulses are identified in Table 1 by their times of occurrence during the two hour test. The surface capacitance, C, to "ground" is 2.33 pF/cm^2. Assume that, on average during charging, half of the incident current is backemitted and half is absorbed near the front surface of the insulator. Using $dV/dt = I/C$, $I = 0.25$ nA/cm2, one finds that $dV/dT = 107$ V/s, approximately. Thus a discharge of 12 kV requires about 2 minutes to recharge. Therefore, the time to recharge the samples will play a role in the pulse history when pulses occur within about five minutes of each other.

It is also instructive to evaluate the amount of surface voltage eliminated by the discharges. The capacitance of the surfaces of these insulator samples to the copper substrate is 2.33 picofarads/cm^2, and for the entire sample is 135 pF. From the equation CV=Q we find that the average pulse in Table 1 changed the surface voltage by 9.85 kV. The pulse with largest total current dropped the voltage by 12.37 kV.

A typical pulse is shown in Fig. 3. The pulses with the plane-parallel 90% transmission grid are often jagged. It appears that the discharge is not well organized, as if the discharge process nearly quenches several times during the pulse. Despite the fact that the electric field is large, perhaps 10 kV/cm at the beginning of the pulse, the discharge process is "weak." A strong discharge would drop the surface well below a kilovolt. The fact that the surface voltage typically decays by only 10 kV when the surface was initially above 20 kV is further evidence that the discharge process is "weak." Such a discharge is reminiscent of a diffuse gas discharge, or other weak process. Certainly this is not strong like a gas arc switch, nor a lightning arrestor, nor a voltage regulator tube!

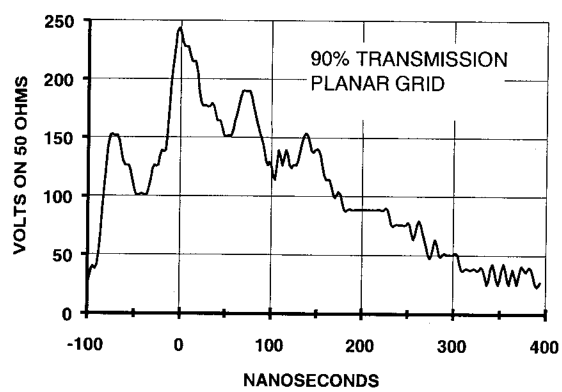


Figure 3. A Typical Pulse Using the 90% Transmission Plane-Parallel Grid at 2.5 cm Above the Sample Surface.

What might be the cause for the quenching and weakness of the pulses in the presence of the 90% transmission grid? The effect of the grid might be to allow neutral gas molecules to pass through the grid and out of the high-field region before becoming ionized in the Townsend avalanche. The escaping molecules would not contribute to discharge current. This idea can be investigated by making the grid much more dense in order to block much of the out-diffusion of gas and keep it in the high-field region longer. The second arrangement tests this idea.

Electrons and ions having passed through the plane of the grid have fully contributed to the discharge current independent of whether they stop on the grid or continue to the far walls of the chamber, or forever drift between the chamber walls and the grid. It is the image charges in the grid and chamber and other "grounded" objects that constitute the current flows in the ground circuit. For nearly every charged particle which passes from the surface of the insulator to the plane of the grid, there is an oppositely charged image charge flowing from the sample electrode through the 50 ohm scope and onto the system of grounded electrodes (which includes the vacuum chamber, grounded grids, earth ground, etc).

Second Arrangement

A similar experiment was performed on the same samples with a dense grid of 32% transmission also placed 2.5 cm above the sample surface, shown in Fig. 4. Because the grid blocks some incident electrons, the electron beam intensity is adjusted to produce the same intensity at the surface of the sample. In this arrangement the dense mesh will strongly delay the escape of 2/3 of the neutral gas molecules.

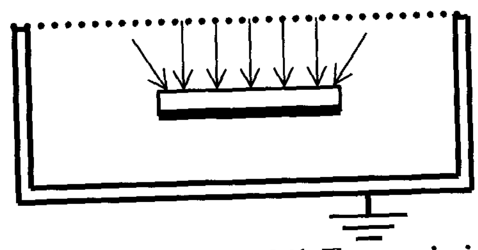


Figure 4. Arrangement for Plane Parallel 32% Transmission Grid, similar to Fig 2. Arrows indicate E-field.

Figure 5 succinctly describes how the results changed. Table 2 lists all of the pulses in one test using the dense grid. It is very clear that partial confinement of the neutral gas provided the following results on average:

1. More complete discharge of the surface voltage, here an average of 13.7 kV compared to 9.85 kV.
2. A stronger gas discharge current with much less evidence of quenching.
3. Higher average peak pulse current by a factor of 3.6, here an average of 20.7 A compared to 5.8 A.

Thus the average pulse reduced the surface voltage by 13,700 volts and the largest pulse reduced it by 16,100 volts.

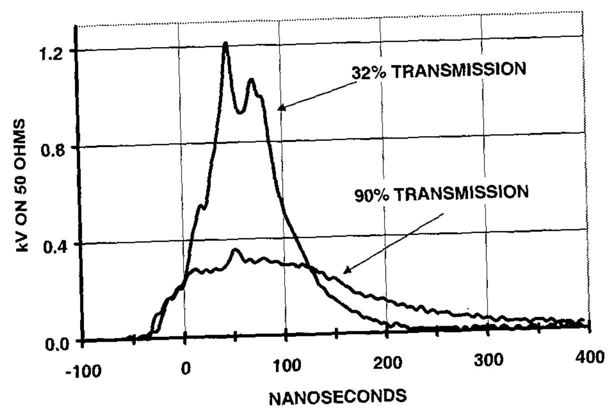


Figure 5. Comparison of A Pulse Using the 90% Transmission Plane-Parallel Grid to A Pulse Using the 32% Transmission Plane-Parallel Grid.

Table 2. Pulses under 32% Transmission Grid.

Pulse number 9/21/99	Width at Half Peak (ns)	Peak current 50 ohms (A)	Charge (Coulombs)	Energy in 50 ohms (mJ)
1:00:38	64	28.4	2.17E-06	1.92
1:03:18	66	24.0	2.03E-06	1.48
1:06:00	80	24.0	1.97E-06	1.56
1:09:22	86	23.4	2.02E-06	1.57
1:14:27	82	22.1	2.02E-06	1.46
1:17:51	76	22.1	2.00E-06	1.37
1:26:05	92	22.1	1.97E-06	1.35
1:32:50	94	20.2	1.96E-06	1.16
1:36:10	104	17.7	1.80E-06	1.10
1:48:22	38	26.5	1.83E-06	1.20
1:57:49	108	15.2	1.83E-06	0.81
2:12:10	48	20.2	1.80E-06	0.93
2:27:20	58	20.2	1.76E-06	1.01
2:40:01	58	17.1	1.67E-06	0.79
2:49:58	98	16.4	1.69E-06	0.84
2:57:18	66	17.7	1.61E-06	0.85
3:08:35	76	17.1	1.63E-06	0.78
3:32:52	92	17.7	1.63E-06	0.67
Average	77	20.7	1.85E-06	1.10

Before continuing with gas discharge studies, it is important to consider the practical implications of these results. The circuit board is a model of a typical electronic board, or IC package, or antenna insulator substrate. The 50 ohm oscilloscope is a model of a sensitive circuit on the spacecraft. Although the many spacecraft circuits have many impedances to ground, it is instructive to directly use the 50 ohm data for the moment. Changing only the escape of neutral gas molecules from the discharge region while maintaining the same sample, the same electric fields and the same radiation parameters strongly affected the following engineering parameters:

1. The peak voltage delivered to the sensitive circuit. (290V vs. 1035V)
2. The peak current flowing in the circuit. (5.8 A vs. 20.7A)
3. The power radiated into radio frequencies and its distribution in frequency. See Fig. 6 for indication of this effect.
4. The power/energy delivered to the sensitive circuit. (1.7E3 Watts peak vs. 2.1E4 Watts peak; or integrated over the time-waveforms, 0.23 mJ vs. 1.1 mJ.)

Thus, such a change in the spatial arrangement of the test chamber electrodes has a large effect upon the threat developed by discharge pulses. Such geometrical effects are not normally considered when evaluating the threat to spacecraft.

The following tests were performed to more thoroughly evaluate the threat as geometry is changed. In addition such studies help one to evaluate the relation of testing geometry to the real geometry.

Third Arrangement

The effect of smaller electric field in vacuum might be important. The grids in the prior two tests, being placed only 2.5 cm from the sample surfaces and parallel to the surfaces produce high vacuum electric fields, 27 kV/2.5 cm = 11 kV/cm.

The electric field was made smaller by removing the grid, and placing the sample as far from all grounds as possible. However, the back sample electrode, which is at ground potential when a pulse is not occurring, remains at the sample and one can visualize strong fringing fields to this electrode. The arrangement is depicted in Fig. 6, and only one sample is mounted.

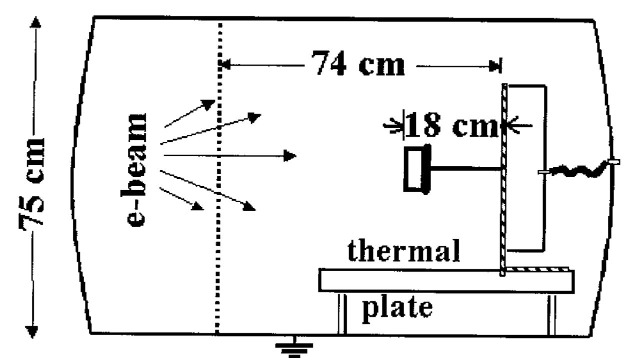


Figure 6. A single sample is mounted 18 cm from the nearest vacuum chamber grounds to reduce the electric field in vacuum.

The sample is roughly 18 cm from both its mounting plate, and from the thermal base plate grounds. Presumably the maximum charging voltage is 25 kV so that the field strength averages roughly 20/18 = 1.1 kV/cm, much lower than the previous 11 kV/cm. Of course the field distribution is complex, being largest near the sample, but has not been analyzed.

If the strength of the discharge is proportional to electric field strength, and to physical confinement of neutral gas, one should see diminished pulse amplitudes relative to both prior experiments. The results are presented in Table 3, and a typical pulse for the third arrangement is seen in Fig. 7. It is clear that the pulses in the third arrangement are as strong (or stronger) as those in the second arrangement. The surface voltage lost in a discharge is 15,500 V on average, and 16,300 V in the largest pulse.

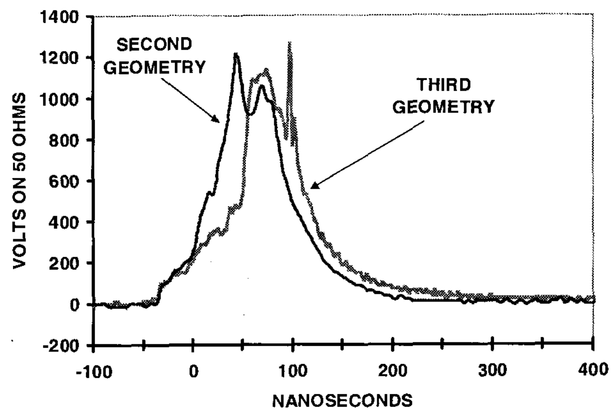


Figure7. Pulse Under Fully Open Arrangement of Fig. 6 Compared to Pulse Under 32% Transmission Planar Grid

Table 3. Pulses from Sample Suspended Mid-chamber Without Grids.

Pulse number 7/16/99	Width at Half Peak (ns)	Peak current 50 ohms (A)	Charge (Coulombs)	Energy in 50 ohms (mJ)
9.31.57	40	18	1.4E-06	0.6
9.34.05	50	18	2.0E-06	0.8
9.39.54	48	23	1.9E-06	1.1
10.19.06	36	24	2.2E-06	1.0
10.25.05	40	28	2.0E-06	1.3
10.29.20	80	17	2.1E-06	0.9
10.40.58	82	23	2.1E-06	1.2
10.45.47	76	21	2.2E-06	0.9
10.48.26	96	18	2.2E-06	1.0
11.04.40	56	19	2.1E-06	0.9
11.10.24	46	32	2.2E-06	1.7
11.20.33	54	25	2.2E-06	1.4
11.25.41	34	32	2.1E-06	1.5
11.36.14	36	32	2.2E-06	1.5
11.40.17	48	25	2.2E-06	1.2
11.44.36	60	26	2.1E-06	1.3
11.56.29	42	30	2.1E-06	1.5
12.00.25	56	26	2.1E-06	1.4
12.09.57	44	30	2.1E-06	1.5
Average	54	25	2.1E-06	1.2

Moving the sample far from a planar grid or other planar electrode may cause the divergence of the vacuum electric field to become important. A divergent electric field produces a force on a polarizable neutral gas molecule proportional to the divergence of the electric field. As neutral gas atoms leave the sample surface they initially experience negligible divergence of the electric field. Since the planar sample surface is roughly 7 cm wide, the divergence of electric field will have maximum effect several cm to 10 cm from the surface. (Fringing fields have much stronger divergence but occupy small spatial volume and thus affect fewer gas molecules.) The diverging fields may prevent the polarizable gas molecules from escaping beyond a few cm from the surface of the charged sample. Perhaps the divergent static electric fields confine much of the gases that escape from FR4 circuit board during discharge events. Order of magnitude estimate on this effect is provided in the appendix of Ref. 1.

Additionally, one might hypothesize that the thermalized neutral molecules take time to transit to the walls of the vacuum chamber and thus are longer exposed to the current avalanche process in the arrangement without any grid. The results of tests in the fourth arrangement indicate that this may not be as important as the hypothesis of gas confinement by field gradient, but these tests do not rule out the argument.

Fourth Arrangement

Based on the previous three experiments, and the previous phenomenological explanations, a fourth arrangement is proposed as a worse situation. A conical grid is placed near the sample in order to maximize both the field strength and its divergence, and thereby hold the neutral molecules close to the sample and expose them to a more active Townsend avalanche. Figure 9 displays the conical grid arrangement.

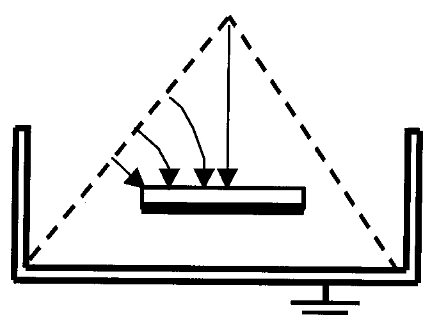


Figure 8. Experiment with the 60% Transmission Conical Grid. The peak of the cone is 5.5 cm above the sample surface. The arrows indicate a divergent E-field with maximum strength near the sample surface.

The results for the conical grid are presented in detail in Ref. 1. The samples were different, so testing with the planar grid was repeated for these relatively thin samples. The thin samples were 0.06cm X 6.7cm X 6.7cm FR4 circuit board under 30keV electrons, 0.1nA/cm2, edges of boards wrapped with Kapton tape. Typical pulses for the thin samples under planar and conical screens are shown in fig. 9.

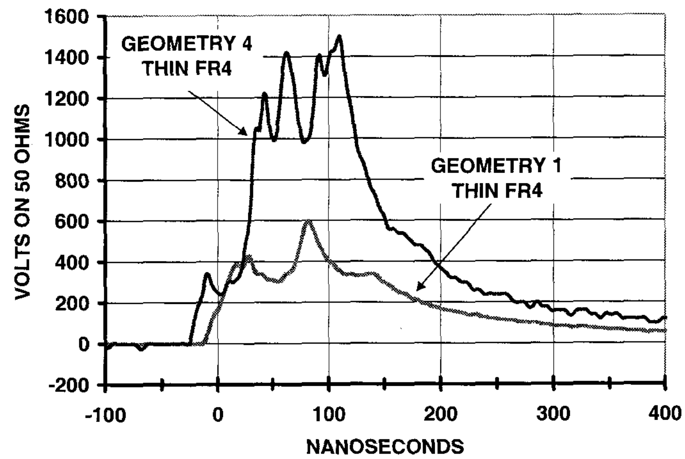
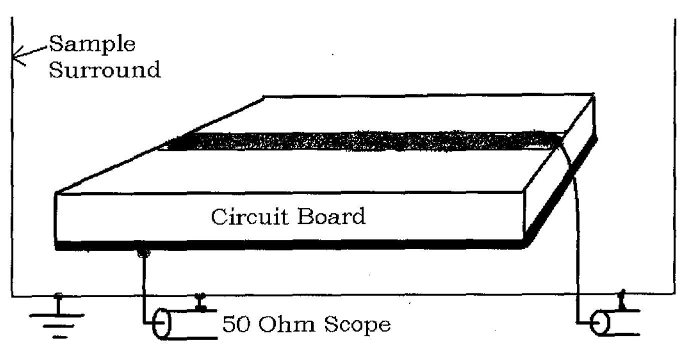


Figure 9. Comparison of Pulse Under Arrangement 1 (planar open grid) with Pulse Under Arrangement 4 (conical grid) for 0.06 cm FR4.

What happens when the insulator under consideration is surrounded by other components that are covered with insulation? How does the discharge get to ground? Does all of the discharge go to the nearest grounded object? What if we physically constrain the movement of gas molecules? In summary, the discharge spreads widely to all surfaces that can be accessed by a gas. If necessary, it appears that the discharge may even evolve to wend through a maze of insulation to find ground.

Unconstrained Gas Avalanche

First consider the following circuit board that is not surrounded by insulation. Discharges were generated by electron radiation from 10 keV up to 1 MeV. The results of interest here did not depend on the beam energy. (Of course pulse amplitude, pulse frequency and surface voltage did depend on beam energy.) The boards were approximately 7 cm x 7 cm in size, and both Duroid and FR4 boards were tested. The observed phenomena are adequately explained by the gas discharge concept.



The pulses on the rear electrode were large and positive because as the surface of the insulator discharged, the positive image charge in the rear electrode went to ground through the scope.

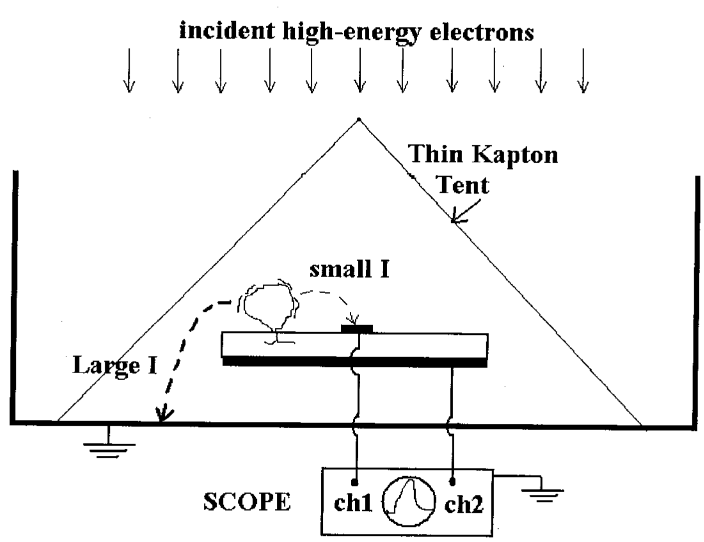
The pulses on the strip of copper at the front of the board, however, were always small, sometimes only positive, and often bipolar. A small amount of positive image charge also resides on the copper strip prior to each discharge. Sometimes the gas of the discharge did not connect to the copper strip, and in this case only a small positive pulse would be seen from the copper strip. But other times the gas would connect to the copper strip and turn the initially positive pulse rapidly into a negative pulse as the negative potential of the insulator surface drove current through the gas onto the copper strip. The total charge in the negative-going pulses was often larger than the charge in the positive-only pulses.

The charge in the rear electrode pulse was always much larger than the charge in the copper strip pulse. Thus, it appears that the plasma spreads out widely in the chamber and delivers the discharge current over a wide region in the chamber. When it is not constrained, the gas avalanche distributes current widely.

Other insulated surfaces will be either further-charged or partially discharged depending on their potential relative to the potential of the avalanching gas and the initial discharging surface. Thus, some current will be delivered (capacitively) to electrodes that underlay those other insulated surfaces.

Partially Constrained Gas Avalanche (data of 12/14,15/99)

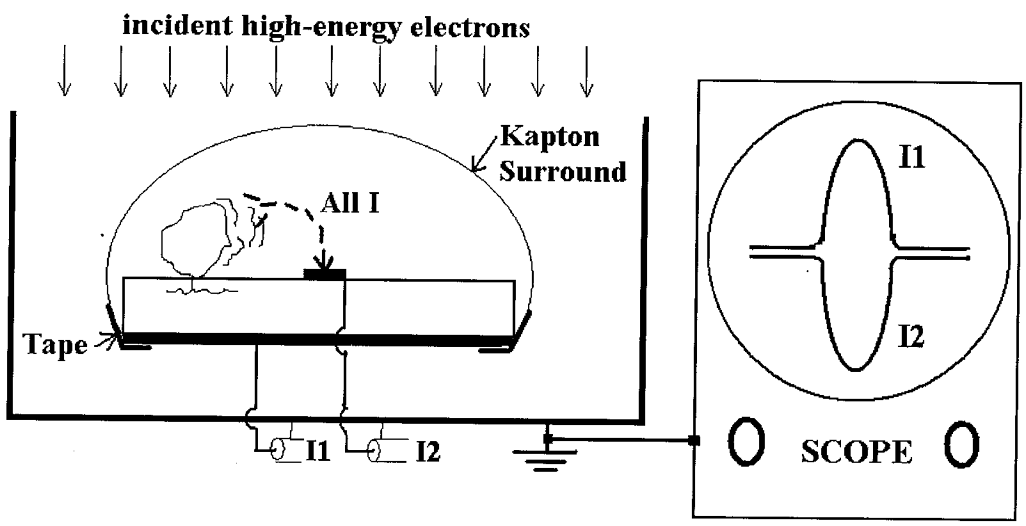
The gas may be constrained to flow to ground via a tortuous path by other insulators. The following figure describes how a (25 micron) Kapton blanket was used to investigate the effect. The Kapton was not metal coated. Electron beams from 100 keV to 1 MeV were used to penetrate the Kapton and bombard the circuit boards. The figure is an approximate cross sectional drawing of the test apparatus.



The pulsing results were not significantly changed relative to the results discussed above for the unconstrained gas discharges. The majority of the discharge current flowed through the gas to the ground behind the samples. Only small discharge current went to the copper strip on the front of the boards.

Fully Constrained Gas Avalanche (data of September, 2000)

The gas discharge can be constrained so that it may discharge the insulator surface only through the copper strip. The following drawing describes the test geometry. The 25 micron Kapton blanket constrains the gas. A small hole was punched into the Kapton for vacuum purposes. Electron beams from 100 keV to 1 MeV were used to penetrate the Kapton. The samples were the same samples as in the prior tests.



The gas is not able to carry current to any grounded object except for the copper strip. Thus, in this experiment every one of the pulses had the copper strip current equal and opposite to the rear electrode current. The oscilloscope traces were more complex than shown in this drawing. The traces were not unlike those of tests described in other chapters. No matter what the pulse shape, I1 and I2 were nearly perfect mirror images of each other.

SUMMARY AND DISCUSSION OF RESULTS.

The gridded results are briefly outlined as follows. A very transparent planar grid (90% open) allows the neutral gas molecules and atoms to escape the region of electric field and thus not contribute to the Townsend avalanche. This produces "weak" discharge pulses with small peak currents that discharge a small fraction of the surface potential because the quantity of gas is not sufficient to maintain a strong discharge. A very dense grid (30% open) confines the much of the gas to remain within the electric field region and thereby contribute to a strong Townsend avalanche. This produces pulsed currents of large peak amplitude and short duration that more fully discharge the sample surface. With the dense grid, the energy deposited in the 50-ohm resistor, or in a sensitive spacecraft circuit element, is up to ten times larger than that with the transparent grid. Yet the initial static electric fields and voltages are the same in both cases. Tests with divergent electric fields developed by conical grids find that the strong pulses are also developed in this case.

The results of the gridded tests are summarized in Table 4. The data for thick samples should not be compared directly to data for thin samples. Thin samples have more capacitance and stored energy for the same surface voltage. Additionally, the electric field inside the thin FR4 material is larger than that inside the thicker FR4 causing the thin FR4 to generate more gas in its pulses. For each type of sample one compares the effects of the changes in electrode/chamber arrangement. Fraction of voltage lost cannot be estimated for the thin samples because the initial static voltage on the kapton tape at the rear of the samples was not determined.

Table 4. Summary of Average Pulse Results.

Arrangement And Sample	Peak Current (Amps)	Pulse Width Half Max (ns)	Pulse Energy in 50 Ohms (mJ)	Charge (Coulombs)	Estimated Fraction Surface Volts Lost
Planar Grid 90% Xmsn Thick FR4	5.8	228	0.23	1.33E-06	0.36
Planar Grid 32% Xmsn Thick FR4	20.7	77	1.10	1.85E-06	0.51
Fully Open Center Chmbr Thick FR4	25.0	54	1.20	2.1E-06	0.77
Planar Grid 90% Xmsn Thin FR4	10.0	136	0.47	1.8E-06	?
Conical Grid 60% Xmsn Thin FR4	31	122	3.9	2.9E-06	?

Real cases rarely have grids. But real cases such as in the third row of Table 4 have divergent electric fields. Divergent electric fields operating over sufficient distances can also constrain neutral gas molecules within the high electric field region in a vacuum as discussed in [1]. The divergence of the electric field in typical large vacuum chambers also constrains neutral molecules to produce strong discharges.

The most important parameters for spacecraft design purposes are the peak current and the energy delivered to the (50 ohm) circuit. Peak current changes a factor of four, and energy to the load changes a factor of eight as the chamber electrode arrangement changes.

One can also constrain gas molecules with thin films such as thermal blankets that allow passage of the high-energy electrons to charge insulators. Tests with this configuration also develop strong current flows by causing the more complete avalanching of the gas discharge. Additionally, constraining the gas in this manner allows all of the gas current to become concentrated on a small conductor. Traditional test procedures would not discover this phenomenon.

It is evident that the pulsed current waveform depends upon the interplay between the arrangement of electrodes and (gas?) discharge phenomena. Contrary to some reports, the pulses cannot be explained by spontaneous emission of electrons from the insulator accelerating across the vacuum space. If simple electron emission were the discharge process, one would expect the highest field arrangement, Fig. 2, to produce the fastest and strongest pulses, yet this arrangement produces the weakest pulses.

The discharges occur such that the pulses often do not become well organized. Instead, the discharge process extinguishes prior to fully discharging the surfaces. Consistently after the pulse, samples maintain 3kV or more as noted by many workers, yet this parameter has never been systematically tabulated in the literature. How the arrangements of electrodes and insulators on actual spacecraft affect the level of threat presented to spacecraft by the discharges is yet to be determined.

Such studies require considerable patience. Time in vacuum and under radiation is often important for the production of consistent pulsing. Some materials produce no pulses for the first few days of irradiation until conductive ions such as OH out-gas from the sample. Often during the first few days in vacuum the samples produce small pulses amongst the larger pulses. FR4 requires some unknown radiation effect to develop before pulsing begins under reasonable (space-like) electric field stress. But with Teflon-based materials the pulses start as soon as the electric field reaches threshold, and diminish later as radiation induces long-term conductivty.

These findings have strong implications for real spacecraft experiencing internal or external charging threats. They provide guidance for improved spacecraft design standards, and for design and interpretation of ground tests.

REFERENCES.
This conference paper serves two purposes. 1) It introduces the ideas that are discussed at more length in Ref. 1. Please refer to Ref. 1 for complete discussions and references. 2) Also, it discloses the dramatic finding relative to the kapton tent surrounding the sample.

1. A. R. Frederickson, C. E. Benson and E. M. Cooke, "Gaseous Discharge Plasmas Produced by High-energy Electron-irradiated Insulators for Spacecraft," IEEE Trans. Plasma Science 28, 2037-47, Dec. 2000.

Keywords: Gas discharge, solid dielectric, dielectric discharge, vacuum breakdown, spacecraft charging, radiation-induced breakdown, electrical breakdown, high-voltage.

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