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N79-24055

CHARACTERIZATION OF ELECTROMAGNETIC SIGNALS GENERATED BY ELECTRICAL BREAKDOWN OF SPACECRAFT INSULATING MATERIALS*

J. E. Nanevicz and R. C. Adamo
SRI International

B. L. Beers
Science Applications, Inc.

BACKGROUND

As part of a program to develop an understanding of the behavior of typical spacecraft insulating materials under exoatmospheric charging conditions, a series of exploratory measurements of the external transient electric and magnetic fields produced by electrical breakdown of materials was performed. Although the metal test chamber used for these early measurements was not ideally suited for detailed electromagnetic transient studies, the magnitudes of the observed fields were sufficiently large that the need for a concentrated effort to determine the true electromagnetic nature of discharge generated transients was recognized. A program was therefore initiated to conduct discharge characterization tests in an electromagnetically "clean" and clearly defined structure, in order that the data obtained be free of artifacts associated with the measurement setup.

The data presented in this paper were generated as part of a series of quick look experiments intended to verify the functioning of the experimental setup and to provide preliminary inputs for the development of analytical models of the discharge process. Thus, although it is planned that additional measurements will be made to carry out the complete program, it is felt that the results to date are significant in that they provide information on source characteristics in a form useful to the electromagnetic compatibility engineer.

EXPERIMENTAL SETUP

For the electromagnetic breakdown studies, the test samples were mounted in the middle of a ground plane within an electromagnetically transparent vacuum chamber in the general manner illustrated in figure 1. This arrangement simulates a region of charged dielectric mounted on the skin of a satellite. The electron gun is of a special type designed at SRI and uses a multipactor electron source to provide a large-area uniform beam over a wide range of energies and current densities as discussed in a companion paper.**

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*The work reported here was supported by the U.S. Air Force under contracts F49620-77-C-0113 and ~~SAI-77-C-0166.~~

**J. E. Nanevicz and R. C. Adamo, "Further Development of the Multipactor Discharge Electron Source."

The electron-gun circuitry includes a feedback system to maintain the electron-beam current density at a preset level over long periods of time.

This setup produces an environment similar to that existing on a satellite when breakdowns occur. These discharges on the outer surface generate transient electric fields above the skin and transient currents on the skin. The electric fields induce signals in wiring on the exterior of the satellite while both electric fields and skin currents excite apertures in the skin which excite wiring on the interior of the satellite. Thus an EMC engineer requires information about the time structure and spatial variation of the surface electric fields and skin currents generated by electrical discharges on the surface of the satellite. (It is worth noting that in this case, the electric field (E) and the magnetic field (H) are not generally related by the free-space impedance of 377 ohms as they would be in free space, so that it is necessary to measure both E and H.)

Measurements of E and H (H is equivalent to skin current) are being made using simple antennas located at varying distances from the discharge test panel as suggested in figure 1. The antennas being used are small electric dipoles and half loops. The electric dipole sensors measure E while the loop antennas respond to the H field. Although figure 1 shows E-field sensors and a signal from the target-material base as providing the outputs to an oscilloscope, other combinations of antennas are also being used.

Transient data generated to date were recorded using a Tektronix Model 7844 dual-beam oscilloscope equipped with 7A19 preamplifiers, providing a system bandwidth of 400 MHz. For future measurements, a Biomation Model 6500 waveform recorder will also be used. This system has a bandwidth of 100 MHz and allows the rapid digitization and storage of data for computer processing.

EXPERIMENTAL RESULTS

In generating the records presented here, the instrumentation system shown in figure 1 was configured so that target-material base current was displayed on one channel of the oscilloscope. The second oscilloscope channel was connected to a small E-field sensor located 30 cm from the center of the bell jar. All of the records presented here were generated by discharges that covered a large part of the dielectric surface and extended to the edge of the test sample. They generally are a representative sample of the higher amplitude signals generated for each particular material sample.

As the quick-look experiments progressed, various experimental shortcomings were uncovered, and appropriate improvements and modifications were systematically incorporated into the test setup. For example, it was found that the bell jar material was sufficiently insulating that the electron beam could deposit substantial charge on its inside surface. Charged particles generated by test sample breakdown neutralized this charge on the bell jar and produced a large change in dc field at the E-field sensor. Bell jar charging was eliminated by covering the inside of the bell jar with a high-resistance conductive coating which bleeds away dc charge but does not attenuate the high-frequency signals generated by the discharge. When the systematic data-gathering phase of this program begins, all of the measurements will be made with the conductive coating installed. Presently, however, data from many of the interesting test samples were obtained with the insulating bell jar, and certain precautions must be observed in using the results. It is felt that the waveforms and magnitudes of the signals generated by breakdown of the samples are of sufficient interest that the results should be presented at this time in spite of their imperfections. In particular the data in figure 2 were obtained with the conductively coated bell jar, while the rest of the records were obtained with an insulating bell jar.

Figure 2 shows a record generated by the breakdown of a second-surface quartz optical solar reflector (OSR) panel. A positive unipolar pulse is generated in the test sample base replacement-current circuit indicating that negative charge is driven away from the sample by the breakdown process. The current reaches its peak value of 1.7 A in roughly 100 ns and then decays monotonically. The behavior of the E-field can be explained by the following argument. The negative excursion, which is roughly a mirror image of the current waveform, is caused by the electrons generated in the breakdown plasma being driven upward from the surface, thereby increasing their dipole moment. A simple back-of-the-envelope calculation quickly verifies that the magnitude of the field change observed can be produced by the quantity of charge involved. In the first 100 ns, the average blow-off current is 0.87 A; thus the charge removed from the surface is 87×10^{-9} coul. If it is assumed that this charge is contained in a column extending to a height of 30 cm from the ground plane, the electric field at a point on the ground plane 30 cm from the dipole axis will be 7 kV/m which is consistent with the measured peak field excursion of 6 kV/m.

Figure 3 shows an early record generated by the breakdown of an OSR panel in the insulating bell jar. The positive unipolar replacement current pulse indicates that negative charge is driven away from the sample. The current reaches its peak value of 0.68 A in roughly 300 ns and then monotonically decays until, at roughly 1400 ns after the beginning of the discharge, another breakdown process occurs.

As before, the initial behavior of the E-field can be explained by the fact that the dipole moment of electrons driven upward by the discharge is greatly increased. In the first 100 ns, the average blow-off current is 0.25 A so that the charge removed from the surface is 25×10^{-9} coul. Thus we would expect an E-field change at the measurement point of 2.03 kV/m which is consistent with the measured peak negative field excursion of 2.8 kV/m.

As the breakdown proceeds, the negatively charged particles driven away from the sample surface arrive at the multipactor electron gun where they are collected so that they no longer contribute to the electric field at the ground plane. Removal of negatively charged particles from the plasma region leaves an expanding volume of positive charge which moves out and neutralizes the negative charges on the bell jar wall, so that after the first 100 ns, a positive-going field change is produced. The E-field at the sensor continues to become more positive until, at the end of the record, a total field change of 7.5 kV/m has been produced. This positive-going field change is an artifact of the early experimental setup and should be ignored.

To indicate the occurrence of bell jar wall effects, the E-field records in figure 3 and succeeding records have been shown dashed in the late-time regions where these effects become pronounced.

A record showing the signals generated by a discharge on a 10 cm by 15 cm (6" x 4") aluminized-Kapton test sample is presented in figure 4. The general form of the signals is the same as for the OSR panel of figure 3, but both the replacement current and the E-field-change magnitudes are an order of magnitude or more higher in figure 4. The replacement current to the base of the test sample reaches a peak magnitude of 65 A in 400 ns.

Again, the field change is initially negative in response to the blow-off of negative charge. The field reaches a negative peak of 9 kV/m in roughly 60 ns. Since the average replacement current during the first 60 ns is roughly 2.5 A, this means that the charge blown away is 100×10^{-9} coul. Thus we should expect a peak negative field change 4 times that observed with the OSR panel of figure 3, or the field change would be expected to be $4 \times 2.03 = 8.12$ kV/m in excellent agreement with the measured value.

It should be noted that 9 kV/m is a very substantial field change. Thus it is not surprising that spacecraft charging can cause transient-upset-level signals to be induced in spacecraft electronic systems.

Figure 5 shows another breakdown of the 10 cm by 15 cm (6" x 4") aluminized-Kapton sample in which three individual discharges separated by 400 ns in time occurred. Each of the individual discharges produced a current change of roughly 10 A and generated a burst of blow-off charge that drove the field roughly 7 to 8 kV/m more negative.

To investigate the importance of sample size in determining discharge characteristics, breakdown experiments were conducted using a 5 cm by 7.5 cm (2" x 3") aluminized-Kapton test sample. The signals generated by a discharge of this sample are shown in figure 6. Comparing figure 6 with figures 4 and 5 indicates that the duration of replacement current flow is roughly 1/2 as long with the half-size sample.

Again, the E-field signal is initially negative going, in response to the blow-off of charged material, reaching a negative peak of 15 kV/m in roughly 160 ns. Since the average current flowing in this period is 15 A, the charge blown off is 240×10^{-9} coul. Thus we would expect the field change to be $240/25 = 9.6$ times that observed with the OSR of figure 3 or $\Delta E = 9.6 \times 2.03 = 19.5$ kV/m. This is in reasonable agreement with the measured negative field change.

CONCLUSIONS

The breakdown characterization studies conducted thus far indicate that the electromagnetic signatures generated are highly material sensitive. For a given material, current-pulse length increases with sample size.

The absolute magnitudes of the signals generated are highly significant. Transient field changes of tens of kV/m occurring in a period of ≈ 200 ns have been measured with the sensor roughly 30 cm from the center of the test sample. Such transient fields are comparable to those normally associated with nuclear EMP events or nearby lightning. It has long been recognized that lightning and EMP can seriously affect unprotected electronic systems and that deliberate measures must be taken to harden systems against these electromagnetic threats. Since the transient noise signals generated as the result of satellite charging appear to be of comparable magnitude, it is important that this source be more completely characterized to allow the intelligent development of new or modified materials and design techniques having the necessary discharge immunity to ensure the required high reliability and long lifetime of future space systems.

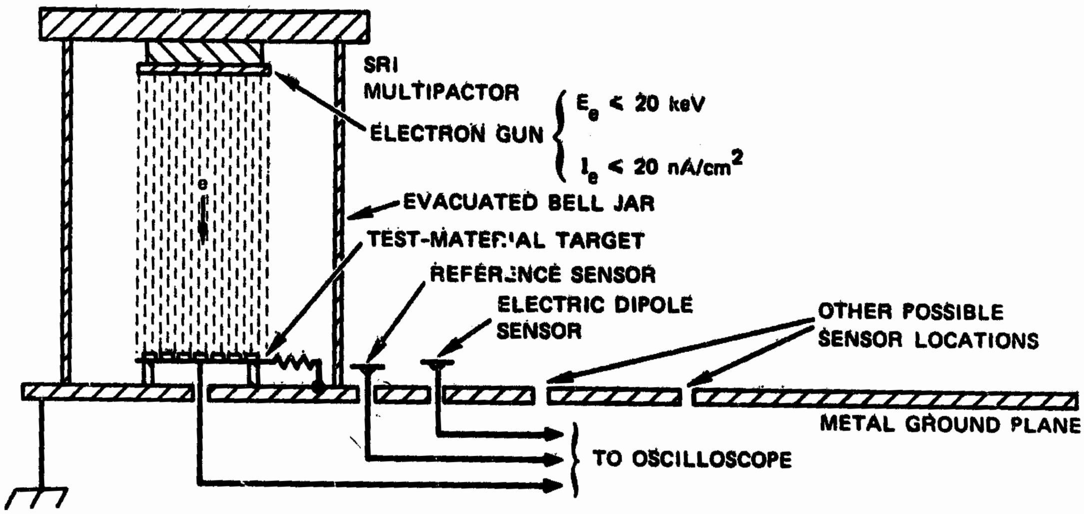


FIGURE 1 EXPERIMENTAL SETUP FOR BREAKDOWN PULSE CHARACTERIZATION

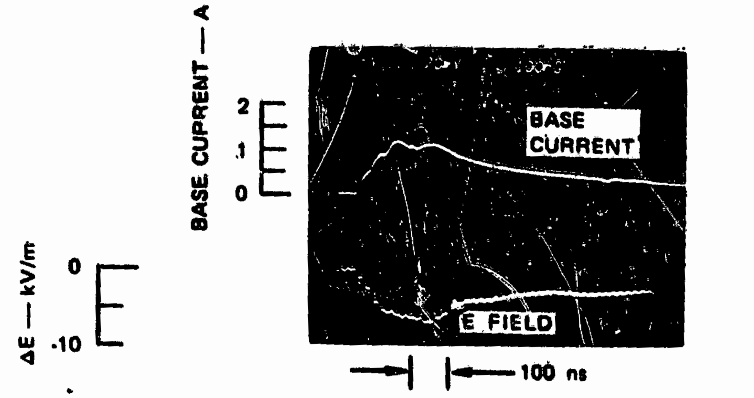
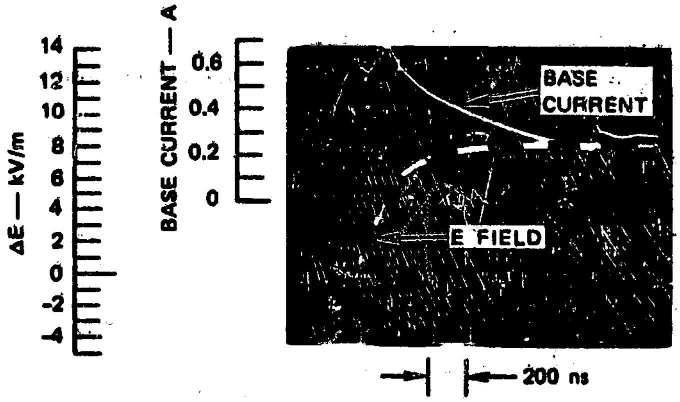
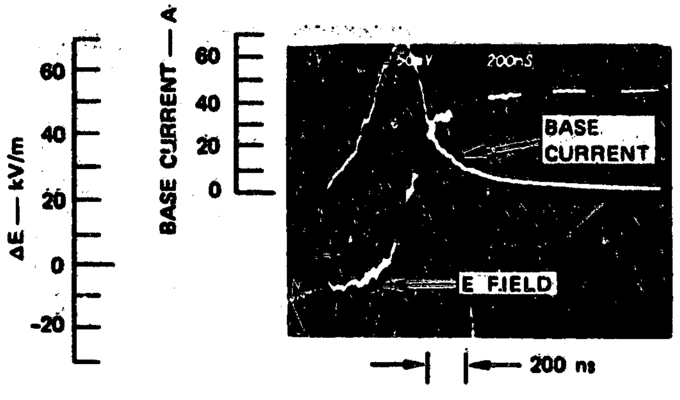


FIGURE 2 SIGNALS GENERATED BY OSR PANEL BREAKDOWN
(CONDUCTING BELL JAR)



12 in. x 12 in. OSR PANEL
10-keV BEAM
CURRENT DENSITY = 10 nA/cm^2

FIGURE 3 SIGNALS GENERATED BY OSR PANEL BREAKDOWN (INSULATING BELL JAR)



4 in. x 6 in. SILVERED KAPTON — 0.002 in. THICK
20-keV BEAM
CURRENT DENSITY = 10 nA/cm^2

FIGURE 4 SIGNALS GENERATED BY BREAKDOWN OF 4 in. x 6 in. ALUMINIZED KAPTON SAMPLE (INSULATING BELL JAR)

4 in. x 6 in. SILVERED KAPTON — 0.002 in. THICK
20-keV BEAM
CURRENT DENSITY = 10 nA/cm^2

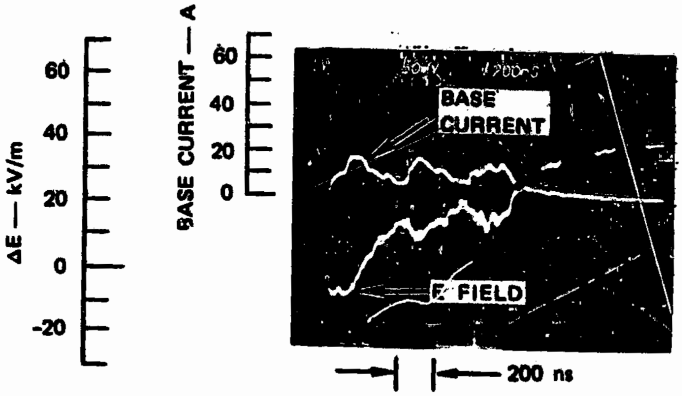


FIGURE 5 MULTIPLE BREAKDOWN OF ALUMINIZED KAPTON (INSULATING BELL JAR)

2 in. x 3 in. SILVERED KAPTON — 0.002 in. THICK
20-keV BEAM
CURRENT DENSITY = 10 nA/cm^2

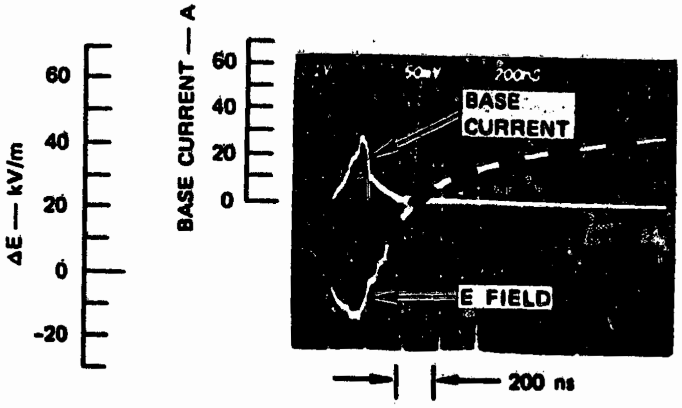


FIGURE 6 SIGNALS GENERATED BY BREAKDOWN OF 2 in. x 3 in. ALUMINIZED KAPTON SAMPLE (INSULATING BELL JAR)