LABORATORY STUDIES OF SPACECRAFT CHARGING MITIGATION TECHNIQUES

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INTRODUCTION

In the early 1970s, spacecraft charging was first suspected as the cause of numerous scientific and operational anomalies on synchronous orbit spacecraft. Since then, various tools and techniques have evolved in an effort to study and mitigate undesirable charging effects. These tools range from sophisticated, complex theoretical and computer model analyses and system-level tests to over-simplified paper studies and "band-aid fixes," several of which appear to have had, on occasion, some success.

Aside from single-event upsets (which are not addressed here), the most common spacecraft charging problems on nonscientific geosynchronous spacecraft result from differential static-charge buildup. When this differential charging, on the surface of (or interior to) the spacecraft, reaches a level sufficient to cause energetic electrostatic discharges (ESDs), circuit errors or damage may result.

As is true of virtually all electromagnetic transient interactions with systems, the undesirable effects of charging and subsequent discharging can best be mitigated by reducing or eliminating the electromagnetic sources themselves. If this procedure is not practical or possible, an alternative approach is to reduce the coupling of the troublesome transients to the sensitive systems by employing sound electromagnetic design techniques. Reducing the susceptibility of the systems themselves to the effects of electrical transients is still another poss'ble approach.

This paper deals with practical internal and surface discharge mitigation techniques developed and verified as part of SRI's ongoing spacecraft-charging studies.

All of the measurements described here were performed in the SRI Spacecraft Charging Simulation Facility (schematically illustrated, in one possible configuration, in Figure 1). This facility has evolved over the past two decades to include environment-simulation components (high-energy electrons, vacuum, and optical illumination) with electromagnetic and electrostatic measurement instrumentation. It provides a flexible environment for reliably measuring key parameters in charging studies of spacecraft materials and components [Nanevicz and Thayer, 1986; Thayer et al., 1987; and Nanevicz et al., 1988].

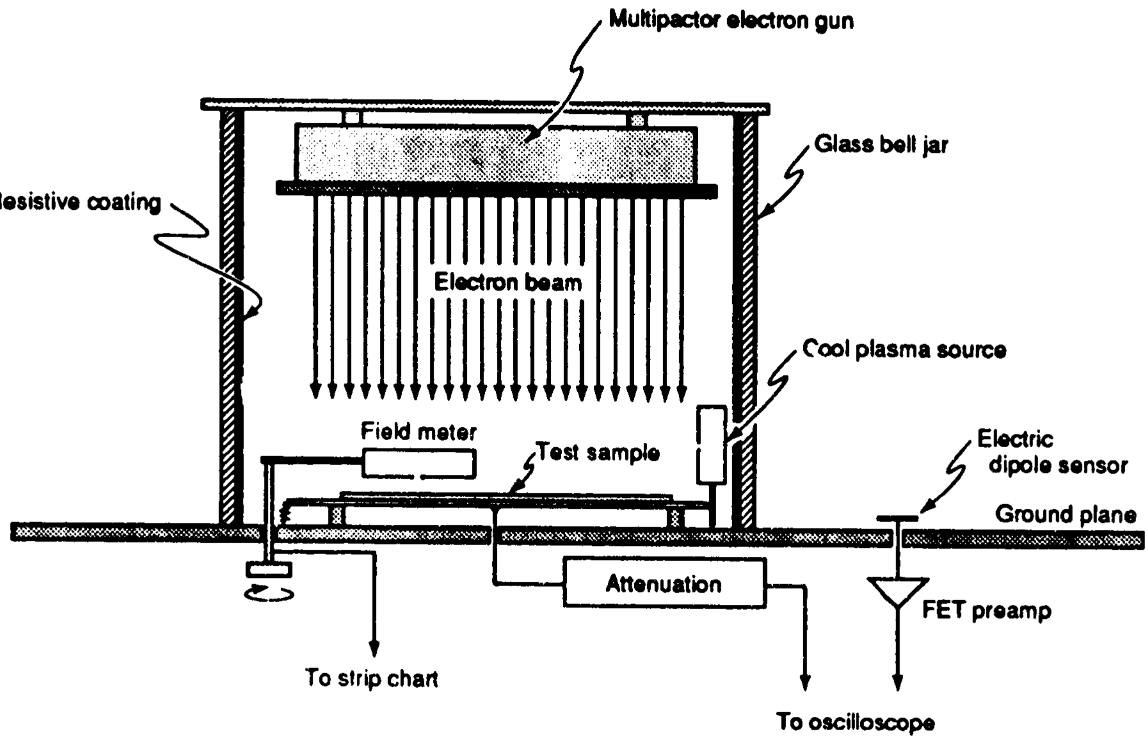

Figure 1 EXPERIMENTAL SETUP

Internal (Deep Dielectric) Charging and Discharging Mitigation

Internal charging is caused by high-energy charged particles (typically 0.3 to 5 MeV electrons) that penetrate the outer layers of spacecraft structures and collect in internal dielectric materials. If these materials are sufficiently good insulators, charge build-up may proceed faster than charge bleed-off, even at low incident flux densities (a few pA/cm^2). The resulting electrostatic fields and subsequent discharges from internal system components (such as fiberglass circuit-boards or Teflon-insulated wires) can couple very strongly to sensitive components causing system upset or damage.

The flux of energetic particles that can penetrate the satellite skin is much smaller than the flux of particles that can charge surface dielectrics to discharge levels. Thus, far fewer internal discharges are expected to occur. Those that do occur, however, are much more likely to affect internal systems, since the source and the victim-circuit are more closely coupled by their proximity.

Possible solutions to the internal discharge problem include (1) the use of additional conductive shielding material in the satellite skin and internal electronic boxes, and (2) the use of lower resistivity materials in internal assemblies. The first solution, however, often imposes unacceptable weight penalties, while the second is difficult to implement either due to functional requirements or to a lack of qualified materials and processes.

Perhaps the most widely used electronic-system component that can produce serious internal discharge problems is the ubiquitous printed circuit board. By nature of its primary function, the circuit board typically consists of large areas of excellent insulating material in intimate contact with sensitive electronic components. The experimental work described here was based on the conjecture that appropriate circuit board coatings could control the static field structure at the board's surface, thereby reducing the occurrence and severity of internal discharges without degrading the overall circuit-board function.

In our initial experiments, we used fiberglass/epoxy circuit cards, typical of those used in fabricating spacecraft instrumentation. Copper traces were etched on these circuit boards, but no components were installed. For each set of tests, three identical cards were prepared. One was left bare, one was coated with a standard conformal protective coating, and the third was flashed with an approximately 2000 Å layer of aluminum over a conformal coating.

Both the uncoated and the conformally coated circuit boards experienced many electrostatic discharges. The frequency of these ESDs increased with the test electron-beam current density. The morphology of these ESDs is such that electrons are thought to "blow off" the surface, causing radiated electric fields that propagate and possibly couple into sensitive systems. These discharge processes can be very energetic, with a typical blow-off current pulse peak of 4 A and a radiated electric field of 2 kV/m in the immediate vicinity of the discharge ($\leq$ 10 cm).

The vacuum-deposited aluminum coating on the third board constrained the charge embedded in the dielectric into either bleeding off or producing only minor discharges to the conductive aluminum. No discharges above the instrumentation thresholds were observed on the aluminum-coated circuit board [Nanevicz and Thayer, 1986].

An aluminum flash coating has been used and flown as a mitigation technique for some Los Alamos National Laboratory sensors that were experiencing frequent anomalies in space. The aluminum flash technique was successful in eliminating all such anomalies on later sensors. These results are detailed elsewhere in these proceedings in a paper by Berzins et al.

A follow-on experiment was performed at SRI on functioning microprocessor circuit boards. These were exposed in the vacuum chamber facility to particle-radiation conditions simulating the synchronous space environment. The boards (containing CMOS components) ran identical looping programs to write to and read from memory, while an external computer checked for errors. Again, uncoated, conformally coated, and specially treated circuit boards were tested. The special treatment in this case was a carbon-loaded acrylic topcoat over the conformal coating.

As before, the untreated and conformally coated circuit boards experienced ESDs that caused upset and latchup. The boards with a carbon-loaded topcoat, however, showed no evidence of discharges or circuit upset, even when exposed to the harshest beam conditions. The effectiveness of the resistive topcoat is believed to be due to the same mechanisms that worked for the aluminum flash coat: (1) the addition of the resistive topcoat may significantly reduce regions of high field concentration where discharges tend to be initiated, (2) the resistive coat may act as a sink that facilitates charge migration through the dielectric conformal coating, and (3) the resistive coat may limit the size or energy of the discharges such that the signals produced are below the threshold of detection and upset [Thayer et al., 1987].

External Charging and Discharge Mitigation

External discharge phenomena are caused by charged particles (typically 1 to 100 keV) that deposit in the outer dielectric materials of the spacecraft structure. Materials with sufficient insulating properties may readily charge in the space-plasma environment.

Spacecraft materials, such as optical solar reflectors (OSRs) or various types of multilayer insulation (MLI) that typically blanket the spacecraft, are chosen primarily for their excellent thermal-optical properties. Each material tends to charge and discharge at varying threshold energy and current flux levels. The presence of exposed conductors and other materials complicates the mechanisms of differential charging and discharging, as well as the strength, frequency, and location of surface ESDs. Furthermore, the susceptibility of interior components depends on the electromagnetic interference and compatibility protection offered by the satellite's design (i.e., whether the satellite acts like a good Faraday shield against externally generated electromagnetic radiation).

Mitigating external discharges is difficult because of the limited selection of materials that can provide the necessary thermal-optical properties. In addition, the design and fabrication of a Faraday barrier that is robust enough to exclude all external discharges from coupling to internal electronics may be logistically prohibitive or require too much added weight.

An effective and feasible means of controlling large surface discharges may be the introduction of a low-density cool plasma about the spacecraft. Studies performed in SRI's Spacecraft Charging Simulation Facility show that the presence of an ambient plasma greatly modifies the way in which charge collects on a dielectric surface. In particular, the addition of a low-density cool plasma reduced the charge residing on a Kapton sample surface to zero. The same sample readily charged and discharged in the absence of cool-plasma injection. This result may have important implications in the design of automatic systems for the discharge of satellites [Nanevicz et al., 1988].

Another mitigation technique that was experimentally tested at SRI was the use of thin thermal blankets. Very thin Kapton (< 1 mil, aluminized on the inside grounded surface) did not produce a detectable discharge, but thicker Kapton readily charged and discharged. Surface potential measurements of the very thin Kapton samples were very much below the high surface potential values of the thick Kapton. The lack of charge buildup in thin Kapton may be due to (1) the ability of the more energetic electrons to pass directly through the thickness of the samples, and (2) the reduction of the charge relaxation time for thin samples, whereby charged particles embedded in the Kapton can migrate quickly through to the conducting bottom surface [Adamo et al., 1987].

SRI also tested the charging and discharging characteristics of various other spacecraft materials. Flex cable made of copper interconnects embedded between two layers of Kapton produced discharges, some of which were dramatic and extended the entire length of the copper strip.

Conclusions

SRI's laboratory measurements verify that system anomalies, upset, or damage can be caused by electrical discharges that may occur on internal or external surfaces and couple large unwanted transient signals into satellite circuitry.

Internal circuit boards that may store charge, and subsequently discharge, constitute the most direct energy coupling available to damage components. Laboratory measurements also verify that conductive or resistive coatings applied on the surface of such boards minimize charging and eliminate discharges.

External dielectric surfaces such as Kapton and OSRs were observed to charge and discharge. Introduction of a low-density cool plasma eliminated these discharges. When using thin (< 1 mil) instead of thick Kapton, the discharges also disappeared.

Various types of materials, cables, and other exposed elements of satellite systems can be tested for charging or discharging characteristics in SRI's Spacecraft Charging Simulation Facility. Using laboratory measurements performed on a Los Alamos sensor experiencing anomalies, we proposed a "modification" that was later flown successfully in space.

An important step forward in the future of space experimentation will be the ability to verify laboratory and theoretical modeling studies with in situ experiments. A small, lightweight, low-power diagnostic package should be flown on many operational satellites to monitor the space-plasma environment, record the strength of any ESDs, and provide quasi real-time data on satellite interaction with the environment. Such data would enhance our understanding of the link between the space environment and satellite anomalies.

SRI's continued involvement in spacecraft charging and ESDs has led to the development of a prototype diagnostic package to monitor the environment and transients. The subsequent flight hardware will weigh an estimated 5 kg, consume approximately 7 W of power, and require about 4000 cm^3 of space.

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