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N79-24030

STATUS OF MATERIALS CHARACTERIZATION STUDIES

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SUMMARY

In the context of the spacecraft charging technology investigation, studies have been made to characterize the response of typical spacecraft surface materials to the charging environment. The objective is to obtain an understanding of the charging and discharging behavior of such materials for the reliable prediction of spacecraft response to charging environments and as a guide for the design of future spacecraft. Materials have been characterized in terms of such basic properties as resistivity and secondary emission and in terms of charging and discharging behavior in simulated charging environments. Both types of information are required to develop adequate predictive capabilities. This paper summarizes the results obtained to date, assesses the present understanding of charging and discharging behavior, and identifies areas in need of further study.

INTRODUCTION

The spacecraft charging technology investigation is being conducted to provide design guidelines and test standards for the control of absolute and differential charging of geosynchronous spacecraft (ref. 1). Attainment of this objective requires development of the capability to predict spacecraft response to charging environments. The phenomenology of spacecraft charging response consists basically of the electrostatic charging of spacecraft surfaces by the environment and the arc discharging of differentially charged spacecraft surfaces, including the coupling of the discharge energy into spacecraft electrical systems. During these processes, the spacecraft's surface materials interact with the environment, with each other, and with the spacecraft's structure and electrical systems - largely through the absorption, emission, and conduction of charge. The response of a given area of surface material depends on the environment, the properties of the material (resistivity, secondary yields, dielectric strength, etc.), and its configuration (i.e., its geometrical and electrical relationships to other portions of the spacecraft). Reliable prediction of spacecraft charging response thus requires accounting for the effects of both the basic properties of spacecraft materials and their configurations on their charging and arc discharging behavior.

Materials are characterized for spacecraft charging by identifying and describing their particular traits or features, in configurations typical of spacecraft construction, that determine a spacecraft's charging response in a given environment. Materials characterization studies have three objectives:

(1) to support model development by providing insights into the mechanisms that determine charging responses, (2) to identify the values of material property parameters that are needed as inputs to models, and (3) to provide the data required to validate models.

Three approaches have been taken: Literature reviews have been made to locate relevant information. Experiments have been performed in which samples of spacecraft materials in various configurations were exposed to charging environments (in general, to electron beams). Parametric studies have exercised models of the charging phenomena to identify the importance of various parameters in determining charging response.

For purposes of materials characterization, the spacecraft charging phenomena can be divided into two classes, charging and discharging. Charging characteristics are those that determine a surface's equilibrium potential in a specified environment and its charging rate. Discharging characteristics are those that determine the conditions causing an arc discharge to occur and the features of the discharge. Coupling of discharge energy into spacecraft systems depends on the features of the discharge and on spacecraft design. From the materials characterization standpoint, coupling does not constitute a separate area of investigation, but rather defines a requirement for an arc description in terms of the arc's electromagnetic signature. Both the charging and the discharging responses are affected by the properties of the materials, by their configurations, and by the environment. Identifying the roles of these effects and their relative importance in determining charging and discharging responses is an essential part of materials characterization.

The present paper summarizes the status of materials characterization studies in terms of progress toward attaining the three objectives for the two classes of response.

CHARGING RESPONSE

Mechanisms

Charging is the response by which a surface comes into equilibrium with its environment. The environment of interest consists of charged particles and photons incident on the surface. The surface interacts with this environment by absorbing, emitting, and conducting charge and thereby acquiring a potential relative to the environment such that, in equilibrium, the net current to the surface is zero. This must be true at each point on an insulating surface.

The mechanism by which orbiting spacecraft acquire nonzero potentials was known well before spacecraft charging became recognized as an operational hazard (ref. 2). The observed charging of geosynchronous spacecraft to negative kilovolt potentials is attributed to the same current-balance mechanism operating in the geomagnetic substorm environment, in which the plasmas are characterized by kilovolt temperatures (refs. 3 and 4). Charging-response models vary widely in the sophistication of techniques used to calculate incident, emitted, and conducted fluxes to surface elements but have in common the condition of zero net current to all surface elements in equilibrium (refs. 5 to 8). The time required to attain equilibrium depends on the net currents to various surfaces and the capacitances in the system (refs. 8 and 9).

The problem of determining charging response thus reduces to calculating net currents to surfaces. The net current to a particular surface element is simply the sum of incident, emitted, and conducted currents. These currents depend on the environment, the properties and potential of the surface element, and the effects of its surroundings.

Material Properties

The simplest case to consider is that of an isolated slab of insulation. In this case, a surface element interacts with the external environment and, if it is an insulator, with the metal structure directly beneath it. Current densities to a surface element of such an insulator are illustrated in figure 1. The current densities depicted are those considered significant for charging response in the geosynchronous substorm environment, in which electron and ion distributions are expected to have temperatures in the kilovolt range (refs. 2, 8, and 10).

In this simple case, current densities of incident ions and electrons (j_i and j_e, respectively) depend on the undisturbed environment and on the surface potential φ_S. All other current densities depend on the properties of the surface material as well as on environmental input (incident ions, electrons, and photons). The material properties required are evidently those that describe the yields of emitted electrons as functions of the energy and angle of incident particle impact and the bulk conductivity of the insulator.

Environmental effects on surface charging are illustrated in figure 2. Figure 2(a) depicts local effects of two adjacent surface elements at different potentials. If φ_2 is more negative than φ_1 (as illustrated), the resulting fields affect the trajectories of incoming electrons (and ions) so that the energy and angle distributions of environmental particles incident on each surface element depend on both φ_1 and φ_2. Trajectories of emitted electrons are also affected by these fields, so low-energy electrons emitted by surface 2 (at φ_2) can be collected by the more positive surface (at φ_1). These collected electrons then represent an additional source of incident current to surface 1. In addition, surface currents can flow between the two surface elements j_{s1}.

Figure 2(b) depicts a similar, but more global, effect in which a potential barrier results in the exclusion of low-energy environmental electrons from the distribution arriving at surface 1 (at φ_1) and in trapping of secondary electrons emitted by this surface. Such trapping reduces the effective secondary yield of surface 1. Formation of potential barriers can result from differences in the properties of surface materials (as depicted) or from anisotropies in the environment. The most obvious environmental anisotropy is solar illumination; formation of potential barriers due to illumination of one side of a spacecraft is expected (refs. 11 and 12). The ATS-6 data indicate that such potential barriers do develop in space (ref. 13).

In terms of material properties, the effects of surroundings indicate a need to know the surface conductivity and the energy and angle distributions of emitted electrons.

The material properties needed to calculate charging response then are basically the yields and distributions of electrons for electron, ion, and photon impact and conductivities. These yields and distributions in turn depend on physical and chemical properties and can also be functions of applied field, temperature, etc. Charging modelers have used methods to calculate the energy and angle dependence of electron yields that differ in the specific parameters required. Table I lists material properties commonly used in charging models. Specifically included in the table are properties required by the NASA charging analyzer program (NASCAP) code (refs. 8 and 14), which gives the most detailed treatment of material properties. Two of the listed properties, radiation-induced conductivity σ_R and dielectric strength E_D, are of more interest for discharging response than for charging response but are included in table I for completeness.

The materials whose properties are needed are those used for spacecraft surfaces. These include pure metals and alloys; polymer films; quartz; and a host of paints, coatings, composites, and fabrics developed particularly for space applications. The extent to which property information is available for these materials varies widely. In general, fairly complete characterizations are possible for pure metals, and many characteristics of quartz and of polymer films (Teflon, Kapton, and Mylar) have been measured. By contrast, very little is known about the properties of alloys and other spacecraft-specific materials.

To date, a comprehensive compilation of required material property information has not been made. A literature survey (ref. 15) has indicated that dielectric and electron interaction data are available for polymers. Conducting studies have been made for polymer films and quartz (refs. 16 to 18) and for some other spacecraft materials (refs. 19 to 21). Photoelectron emission has been measured for some spacecraft materials (ref. 22). Modelers of charging have compiled property data on materials of specific interest to their studies (refs. 2, 7, 8, and 23). Secondary-electron yield due to ion (H^+) impact appears to be the least available property for all materials of interest.

Thus, although material property information required to model the charging of spacecraft surfaces is available, it is both incomplete and scattered. An effort to compile the available information and to identify specific areas of deficiency is needed. Information on the influences of temperature, illumination-applied fields, surface condition, aging, etc., on the various properties should be included in such a compilation. Once specific areas of deficiency are identified, experimental programs to obtain the missing information can be devised.

Experimental Results

Ground studies of the charging of spacecraft surface materials have been reported by several investigators (refs. 24 to 31). Such tests generally involve exposing the surface of interest to normally incident monoenergetic electron beams in vacuum chambers. Two types of sample have been investigated: samples of single materials (polymer, paint, etc.) and samples in a "spacecraft configuration" (solar-a ray segments, thermal blankets, etc.). The single-material samples have generally been mounted on metal substrates that were electrically grounded to the facility. The spacecraft-configuration samples have generally been tested with their metallic portions grounded to the facility. Data reported include current in the ground line and surface potentials. A "typical data set" (fig. 1 of ref. 24) is reproduced in figure 3.

The most common method of summarizing charging test results is by plotting surface potential at equilibrium as a function of electron beam voltage, as illustrated in figure 4. The figure shows two types of response for insulators. Linear behavior is interpreted to indicate that the material's resistivity is large enough for leakage currents to be negligible. In this case the equilibrium potential is determined by surface emission characteristics (secondary-electron current due to electron impact j_{se} and backscattered electron current j_{bs}). Behavior in which the surface potential reaches a plateau beyond some beam voltage is interpreted to indicate that the equilibrium potential is determined by leakage current in the plateau region. The type of behavior observed depended on material thickness and beam current density as well as on resistivity and electron emission characteristics. This complicates comparison of results from different investigators, since the beam current densities used vary from one to another. With 1-nA/cm^2 beam current densities, 0.01-centimeter-thick Teflon and Kapton samples exhibited emission-dominated behavior to beam voltages of 12 and 14 kilovolts, respectively; in these tests, arcing occurred at higher beam voltages (ref. 24). Leakage-dominated equilibrium has been reported for thin ($<$0.0025 cm thick) Kapton and Mylar (ref. 29) and for S-13GLO paint (ref. 24) with 1-nA/cm^2 beams, and for 0.005-centimeter-thick Kapton at slightly higher current densities (ref. 28).

Equilibrium potential profiles of several surface-material samples exhibit irregularities that are probably due to configuration effects such as those illustrated in figure 2 (beam deflection, trapping of secondaries, etc.) (refs. 9, 24, and 29). Irregularities in equilibrium surface potential caused by the presence of small gaps between sections of a single type of insulation (e.g., solar-cell cover slides or strips of Teflon tape) were also observed. These became more pronounced for larger samples, apparently as a result of increased beam deflection by the larger samples (ref. 30).

Efforts to validate the NASCAP code by comparing its predictions with experimental data have begun (refs. 9 and 14). Agreement between prediction and experiment is generally very good when both material properties and test data are available (e.g., Teflon and Kapton). Additional experimental data for single-material samples are needed, since it is preferable to validate the models for individual materials before adding the complexity of surroundings effects.

Since experiments have been performed with normally incident monoenergetic electron beams, the data presently available do not permit models to be calibrated for the effects of distributed (in energy and angle) electron fluxes or for electron emission due to ion or photon impact. Experiments incorporating these additional environmental factors are needed, since the space environment consists of distributed fluxes of ions, electrons, and photons.

Ground testing of complex objects (spacecraft models), with concurrent modeling, is required to ensure that configuration effects are modeled adequately.

Parametric Studies

The two preceding sections identified the need for experimental efforts to obtain material properties and to provide model validation data for a variety of materials. The test matrix to examine each material in each environment, even without considering experiments to study configuration effects or discharge characteristics, is prohibitively large. Since charging models that incorporate material, configuration, and environmental factors are available, one approach to reducing the number of tests required is to conduct parametric studies. Such studies can be used to identify those material properties and configuration characteristics that are most important in determining charging response to various environments and how accurately the properties must be known for a given prediction accuracy.

As an example, effects of changing secondary-electron yields on predicted charging response to ground test and space environments are illustrated in figure 5. Figure 5(a) shows NASCAP predictions of the charging response of a metal plate in a 10-keV electron beam for three sets of secondary-electron-yield parameters. The metal plate is electrically floating and has a capacitance to its surroundings of 200 picofarads. No illumination or ions are present, so the currents to the plate are due to the beam and the emission of backscattered and secondary electrons by the plate. As shown in the figure, changing either the maximum yield δ_m or the energy for maximum yield E_m affects both the final plate potential and the rate at which charging occurs. From these curves, changing δ_m has a stronger effect on equilibrium potential than changing E_m: Using the middle curve ($\delta_m = 2.6$, $E_m = 300$) as a base and reducing δ_m by 63 percent (to 0.97) increase the final potential by 38 percent. Increasing E_m by 33 percent (to 400) decreases the final potential by only 9 percent. The dependence of final potential on beam voltage is linear, as shown in reference 14.

Figure 5(b) shows NASCAP predictions of the charging response of an ATS-5 model object (ref. 14) in a 5-keV, 1-particle/cm^3 Maxwellian "space environment." On the time scale of figure 5(b), differential charging is negligible, so the entire object is at the potential shown. The curves reflect effects of halving the secondary-electron yield for 1-keV proton impact δ_p for all surface materials. "Standard" δ_p's are those in the current version of NASCAP for Teflon, silicon dioxide, and aluminum, which are the surface materials of the ATS-5 object (ref. 14). With the curve for standard δ_p's as a base, a

50 percent reduction in δ_p's has resulted in a 58-percent increase in potential.

Secondary electron yield is expected to be an important factor in determining final potential in space substorm conditions, because secondary yields for protons with impact energies of tens of kilovolts are expected to be greater than unity and these effectively add to the proton fluxes (refs. 2 and 32). Figure 5 suggests that ion-generated secondary electrons are an important determinant of absolute spacecraft potential. Obviously, the information presented in figure 5 is insufficient to determine whether the relationships are linear and over what range of material and environmental parameters they are appropriate. It does, however, indicate the usefulness of parametric studies.

Although no comprehensive parametric studies of material property influences have been reported to date, some work has been done (ref. 33) and further results are expected (refs. 34 to 36). Such studies should be expanded to include configuration effects; it has been suggested (ref. 9) that the relative areas of different surface materials are an important consideration in determining charging rates and levels.

DISCHARGE RESPONSE

Mechanisms

Although charging response is adequately understood in terms of current balances, quantitative discharge mechanism models have yet to be devised. To attain a predictive capability it is necessary to identify the mechanisms responsible for initiation and propagation of arc discharges and to describe arcs in terms of their electromagnetic signatures.

Discharges of concern for spacecraft charging are those that can occur on dielectric surfaces charged by exposure to fluxes of kilovolt particles. The dielectric surface exposed to this environment is supposed to be charged negatively with respect to the underlying spacecraft structure. It thus acts as a cathode in a discharge. The situation differs from voltage breakdown of a dielectric between metal plates in that there is no dielectric-metal interface at the cathode, there is a limited supply of charge at the cathode, and the electric field in the dielectric is created by charges that are removed when discharge occurs. Little information on this type of discharge has been reported in the literature (ref. 15).

For calculating charging response it is sufficient to consider the absorption, emission, and conduction of charge to occur at material surfaces (since the depth of penetration of kilovolt particles is much less than the thickness of spacecraft surface materials). However, such a description is probably inadequate for considering discharge-response mechanisms.

Kilovolt electrons incident on a dielectric surface penetrate a distance of micrometers. Secondary electrons are emitted from a region within a few tens of angstroms from the surface. This results in a charge distribution inside the dielectric in which negative charge accumulates in some layer below the surface. The situation is sketched schematically in figure 6 for a dielectric slab mounted on a grounded metal substrate. Electrons are emitted from a region near the surface; incident electrons penetrate further into the dielectric, and a region of radiation-enhanced conductivity is formed; a distribution of negative charge (fig. 6) inside the dielectric results. The detailed shape of this distribution depends on material properties (bulk conductivity σ_B, radiation-induced conductivity σ_R, electron range R_E, and emission yields), on the distribution of incident electrons, and on irradiation time. Models now exist that describe such charge deposition profiles (refs. 8, 37, and 38), and techniques have been devised for their measurement (ref. 39).

Although no quantitative models of discharge mechanisms have yet been developed, mechanisms involving charge propagation in the radiation-enhanced region (refs. 40 and 41) and arc propagation by secondary emission (refs. 27 and 42) have been suggested. Such mechanisms have yet to be evaluated.

Experimental Results

In the absence of quantitative theoretical models for discharges, experiments must be relied on to provide both insights into discharge mechanisms and a data base from which empirical models can be constructed.

Investigations of the discharge response of electron-irradiated spacecraft dielectrics have been reported by a number of workers (refs. 24, 27, 28, 30, 41, and 43 to 47). For the most part, such investigations have involved exposure to monoenergetic electron beams of insulator samples mounted on grounded substrates or spacecraft-configuration samples (solar-array segments, thermal blankets, etc.) mounted with their metal portions grounded. Data taken include current in the ground line and surface potentials. In some experiments a scanning electron microscope has been used as both the electron source and the diagnostic (refs. 41 and 45). Typical current-to-ground and voltage-versus-time results are illustrated in figure 7. When a sample is exposed to an electron beam, charge and voltage build up on the dielectric surface and a corresponding current flows in the ground line. When a discharge occurs, a fast current pulse is observed (denoted by the arrow in fig. 7) that signifies net negative charge leaving the surface: The surface potential drops and charging resumes.

Charges transferred and a fast current pulse (return or reverse current pulse) observed during a discharge are illustrated in figure 8. In figure 8(a), charges are shown emanating from a trigger site. Charges Q_1 and Q_2 are transferred to the substrate, where they cancel with their image charges. The net charge Q_I leaves the surface and couples through the external circuit, which includes the vacuum facility and associated structures. Current flows in the ground line (meter I) and reflects the transfer Q_I (which is a negative charge). The horizontal arrows in figure 8(a) represent charge transferred on or near the surface to the trigger site, that is, arc propagation or a charge release mechanism.

A return current pulse is illustrated in figure 8(b), and Q_I is just the time integral of this current pulse. Such pulses exhibit a wide variety of detailed shapes (see, e.g., ref. 30) and may reflect multiple rather than truly single events. They are most easily characterized in terms of parameters such as peak current I_p, duration Δt, net charge $Q_I \equiv \int_{\Delta t} I_p \, dt$, and rise time $dI/dt|_i$. Results reported vary widely and depend on sample size and instrumentation as well as on sample material and configuration. The values of I_p, Q_I, and Δt all increase with increasing sample area for small samples (ref. 46); recent results indicate limitations on how large an area is affected in a single discharge (ref. 30). As an example, values given for samples of a few hundred square centimeters in area are Δt ~500 nanoseconds, I_p ~20 to 100 amperes, and Q_I ~20 to 60 μC for silvered-Teflon samples (ref. 24).

A critical aspect of instrumentation that must be considered in investigating return current pulses is the impedance to ground in the experimental setup. Typical surface potentials at discharge are about 10 kilovolts, and peak currents are about 100 amperes. Thus, a 50-ohm termination does not approximate a short circuit in this case, and test results may depend strongly on this impedance (ref. 30). This is of particular concern for application of results to the spacecraft situation.

In addition to descriptions of return current pulses, estimates have been made of the energy in a discharge, the charge transferred, and the area discharged (refs. 24 and 30). To date, no data have been reported on the radiated electromagnetic signature of such arcs. This information is important to calculations of electromagnetic interference (EMI) resulting from discharges. It is lacking because none of the experiments reported to date have been conducted in anechoic chambers so that facility resonances have made EMI measurements impossible.

The trigger mechanism for discharges is not understood, but data indicate that the observed discharges begin at gaps, holes, or edges and do not represent bulk dielectric breakdown (refs. 24, 27, 30, 43, and 44). Thus, discharges are observed at electric field stresses signficicantly less than the dielectric strengths of the insulators under study when gaps or edges are present. Some threshold condition, probably configuration dependent, other than insulator dielectric strength must be quantitatively defined for accurate arc prediction.

Experimental evidence to date indicates that discharges begin at gaps in insulation; that charge is removed from an area much larger than the trigger site; that a net negative charge is ejected from a surface during discharge; and that this charge ejection results in significant currents flowing in ground lines. Yet to be investigated are the EMI due to discharges and effects on discharge response of such environmental factors as distributed fluxes of electrons and the presence of ions. Experiments in which solar-array segments with flexible substrates of Kapton-fiberglass laminates have been illuminated during exposure to electron beams have indicated that arcing on such structures is greatly reduced during illumination, probably because of photoconductivity and the thermal enhancement of Kapton conductivity (refs. 24 and 46).

CONCLUDING REMARKS

The charging response of surfaces exposed to charged-particle and photon fluxes is understood in terms of current-density balance mechanisms. Models of charging response are available and predictions agree well with experimental results for cases in which material properties are adequately known. Material property information now available should be compiled to identify specific areas and materials for which data are lacking and to provide property values for use in prediction. A cursory examination of the information available indicates that the least well-known property for most materials of interest is secondary-electron yield due to ion impact and that the most poorly characterized materials are those that have been developed specifically for space applications. Also poorly known are property changes with time due to exposure, repeated arcing, etc. The experimentation required to determine material properties adequately for charging-response predictions can be significantly reduced by using parametric studies to identify those properties most important for determining charging response and how accurately these properties must be known for a specified prediction accuracy.

Data on charging response of spacecraft surface materials under monoenergetic electron irradiation are available for many, though not all, materials of interest. Data on the effects of additional environmental factors are needed. Of particular concern is information on the response to ion impact since this is expected to be an important determinant of spacecraft response. Effects of more complex geometries also need investigation to ensure that the modeling is adequate.

The mechanisms for initiation and propagation of arc discharges are not yet understood, although a number of their characteristics have been experimentally identified. The initiation mechanism is apparently configuration dependent: Arcs occur preferentially at gaps, seams, and edges. A net negative charge is emitted during discharges. Its measured magnitude depends on system instrumentation as well as on sample material and area. These dependencies are of particular interest in modeling arc propagation as well as in extrapolating ground test data to space conditions. Models of charge deposition and transport in electron-irradiated dielectrics have been devised, and they provide a necessary first step toward developing discharge mechanism models.

This paper has summarized the present status of materials characterization studies. Efforts are being made to develop empirical models for discharge pulses. Data on a wider variety of materials and configurations are needed to support this activity as well as mechanism model development. There is a growing data base on characteristics of return current pulses. Yet to be investigated are the electromagnetic interference spectra from arc discharges and the effects of such environmental factors as distributed fluxes of electrons and ions and temperature on discharge response.

REFERENCES

1. Lovell, R. R.; et al.: Spacecraft Charging Investigation: A Joint Research and Technology Program. Spacecraft Charging by Magnetospheric Plasmas, A. Rosen, ed., Progress in Astronautics and Aeronautics, vol. 47, American Institute of Aeronautics and Astronautics, Inc., 1976, pp. 3-14.

2. Whipple, Elden C., Jr.: The Equilibrium Electric Potential of a Body in the Upper Atmosphere and in Interplanetary Space. Ph.D. Thesis, George Washington Univ., 1965.

3. DeForest, Sherman E.: Spacecraft Charging at Geosynchronous Orbit. J. Geophys. Res., vol. 77, no. 4, Feb. 1, 1972, pp. 651-659.

4. Bartlett, R. D.; DeForest, S. E.; and Goldstein, R.: Spacecraft-Charging Control Demonstration at Geosynchronous Altitude. AIAA Paper 75-359, Mar. 1975.

5. Whipple, Elden C., Jr.: Modeling of Spacecraft Charging. Proceedings of the Spacecraft Charging Technology Conference, C. P. Pike and R. R. Lovell, eds., AFGL-TR-77-0051, NASA TM X-73537, 1977, pp. 225-235.

6. Inouye, G. T.: Spacecraft Charging Model. AIAA Paper 75-255, Jan. 1975.

7. Laframboise, J. G.; and Prokopenko, S. M. L.: Numerical Simulation of Spacecraft Charging Phenomena. Proceedings of the Spacecraft Charging Technology Conference, C. P. Pike and R. R. Lovell, eds., AFGL-TR-77-0051, NASA TM X-73537, 1977, pp. 309-318.

8. Katz, I.; et al.: A Three-Dimensional Dynamic Study of Electrostatic Charging in Materials. (SSS-R-77-3367, Systems Science and Software; NASA Contract NAS3-20119.) NASA CR-135256, 1977.

9. Purvis, C. K.; et al.: Charging Rates of Metal-Dielectric Structures. Spacecraft Charging Technology - 1978, NASA CP-2071, 1979.

10. Garrett, Henry B.: Spacecraft Potential Calculations - A Model. AFGL-TR-78-0116, Air Force Geophysical Lab., 1978.

11. Prokopenko, S. M. L.; and Laframboise, J. G.: Prediction of Large Negative Shaded-Side Spacecraft Potentials. Proceedings of the Spacecraft Charging Technology Conference, C. P. Pike and R. R. Lovell, eds., AFGL-TR-77-0051, NASA TM X-73537, 1977, pp. 369-387.

12. Mandell, M. J.; et al.: The Decrease in Effective Photocurrents due to Saddle Points in Electrostatic Potentials Near Differently Charged Spacecraft. Presented at 1978 IEEE Annual Conference on Nuclear and Space Radiation Effects, Albuquerque, N. Mex., July 18-21, 1978, Session C-4.

13. Whipple, E. C., Jr.: Observation of Photoelectrons and Secondary Electrons Reflected from a Potential Barrier in the Vicinity of ATS-6. J. Geophys. Res., vol. 81, Feb. 1, 1976, pp. 715-719.

14. Roche, J. C.; and Purvis, C. K.: Comparison of NASCAP Predictions with Experimental Data. Spacecraft Charging Technology - 1978, NASA CP-2071, 1979.

15. Wall, J. A.; Burke, E. A.; and Frederickson, A. R.: Results of Literature Search on Dielectric Properties and Electron Interaction Phenomena Related to Spacecraft Charging. Proceedings of the Spacecraft Charging Technology Conference, C. P. Pike and R. R. Lovell, eds., AFGL-TR-77-0051, NASA TM X-73537, 1977, pp. 569-591.

16. Coffey, H. T.; Nanevicz, J. E.; and Adamo, R. C.: Photoconductivity of High-Voltage Space Insulating Materials. (Stanford Research Inst.; NASA Contract NAS3-18912.) NASA CR-134995, 1975.

17. Adamo, R. C.; and Nanevicz, J. E.: Effects of Illumination on the Conductivity Properties of Spacecraft Insulating Materials. (Stanford Research Inst.; NASA Contract NAS3-20080.) NASA CR-135201, 1977.

18. Adamo, Richard C.; Nanevicz, Joseph E.; and Grier, Norman: Conductivity Effects in High Voltage Spacecraft Insulating Materials. Proceedings of the Spacecraft Charging Technology Conference, C. P. Pike and R. R. Lovell, eds., AFGL-TR-0051, NASA TM X-73537, 1977, pp. 669-686.

19. Gilligan, J. E.; Wolf, R. E.; and Ray C.: Electrically Conductive Paints for Satellites. Proceedings of the Spacecraft Charging Technology Conference, C P. Pike and R. R. Lovell, eds., AFGL-TR-77-0051, NASA TM X-73537, 1977, pp. 593-611.

20. Belanger, V. J.; and Eagles, A. E.: Secondary Emission Conductivity of High Purity Silica Fabric. Proceedings of the Spacecraft Charging Technology Conference, C. P. Pike and R. R. Lovell, eds., AFGL-TR-77-0031, NASA TM X-73537, 1977, pp. 655-668.

21. Viehmann, W.; Shai, C. M.; and Sanford, E. L.: Investigation of Conductive Thermal Control Coatings by a Contactless Method in Vacuo. Proceedings of the Spacecraft Charging Technology Conference, C. P. Pike and R. R. Lovell, eds., AFGL-TR-77-0051, NASA TM X-73537, 1977, pp. 687-698.

22. Feuerbacher, B.; and Fitton, B.: Experimental Investigation of Photoemission from Satellite Surface Materials. J. Appl. Phys., vol. 43, no. 4, 1972, pp. 1563-1572.

23. Grard, R. J. L.; Knott, K.; and Pedersen, A.: The Influence of Photoelectron and Secondary Electron Emission on Electric Field Measurements in the Magnetosphere and Solar Wind. Photon and Particle Interactions with Surfaces in Space. R. J. L. Grard, ed., D. Reidel Publishing Co., (Dordrecht) 1973, pp. 163-189.

24. Stevens, N. John; et al.: Testing of Typical Spacecraft Materials in a Simulated Substorm Environment. Proceedings of the Spacecraft Charging Technology Conference, C. P. Pike and R. R. Lovell, eds., AFGL-TR-77-0051, NASA TM X-73537, 1977, pp. 431-457.

25. Stevens, N. John; Klinect, Vernon W.; and Berkopec, Frank D.: Environmental Charging of Spacecraft Surfaces - Tests of Thermal Control Materials for Use on the Global Positioning System Flight Space Vehicle - Part 1: Specimens 1 to 5. NASA TM X-73467, 1976.

26. Stevens, N. John; Berkopec, Frank D.; and Blech, Richard A.: Environmental Charging of Spacecraft Surfaces - Tests of Thermal Control Materials for Use on the Global Positioning System Flight Space Vehicle - Part 2: Specimens 6 to 9. NASA TM X-734[illegible], 1976.

27. Robinson, James W.: Charge Distributions near Metal-Dielectric Interfaces before and after Dielectric Surface Flashover. Proceedings of the Spacecraft Charging Technology Conference, C. P. Pike and R. R. Lovell, eds., AFGL-TR-77-0051, NASA TM X-73537, 1977, pp. 503-515.

28. Robinson, P. A., Jr.: The Behavior of Partially Metallized Kapton for Spacecraft Charging Control. AIAA Paper 78-675, Apr. 1978.

29. Staskus, J. V.; and Berkopec, F. D.: Charging Test Results for Flexible Insulators and Composites. Spacecraft Charging Technology - 1978. NASA CP-2071, 1979.

30. Aron, P. R.; and Staskus, J. V.: Area Scaling Investigations of Charging Phenomenon. Spacecraft Charging Technology - 1978. NASA CP-2071, 1979.

31. Purvis, C. K.; Stevens, N. J.; and Oglebay, J. C.: Charging Characteristics of Materials: Comparison of Experimental Results with Simple Analytical Models. Proceedings of the Spacecraft Charging Technology Conference, C. P. Pike and R. R. Lovell, eds., AFGL-TR-77-0051, NASA TM X-73537, 1977, pp. 459-486.

32. Kaminsky, Manfred: Atomic and Ionic Impact Phenomena on Metal Surfaces. Academic Press, 1965.

33. Rubin, A. G.; Rothwell, P. L.; and Yates, G. K.: Reduction of Spacecraft Charging Using Highly Emissive Surface Materials. Presented at the 1978 Symposium on the Effect of the Ionosphere on Space and Terrestrial Systems, Naval Research Lab. and Office of Naval Research, Wash., D.C., Jan. 24-26, 1978, Session IV, Paper 4-7.

34. Suh, P. K.; and Stauber, M. C.: Material Parameter Dependence of Equilibrium Charging Potentials. Spacecraft Charging Technology - 1978. NASA CP-2071, 1979.

35. Sanders, N. L.; and Inouye, G. T.: Secondary Emission Effects on Spacecraft Charging Energy Distribution Considerations. Spacecraft Charging Technology - 1978. NASA CP-2071, 1979.

36. Haffner, J. W.: Secondary Electron Effects on Spacecraft Charging. Spacecraft Charging Technology - 1978. NASA CP-2071, 1979.

37. Beers, B. L.; Pine, V. W.; and Gore, J. V.: Electron Transport Model of Dielectric Charging. Spacecraft Charging Technology - 1978. NASA CP-2071, 1979.

38. Monteith, L. K.; and Hauser, J. R.: Space Charge Effects in Insulators Resulting from Electron Irradiation. J. Appl. Phys., vol. 38, no. 13, Dec. 1967, pp. 5355-5365.

39. Sessler, G. M.; West, J. E.; and Berkley, D. A.: Determination of Spatial Distribution of Charges in Thin Dielectrics. Phys. Rev. Lett., vol. 38, no. 7, Feb. 14, 1977, pp. 368-371.

40. Meulenberg, A., Jr.: Evidence for a New Discharge Mechanism for Dielectrics in a Plasma. Spacecraft Charging by Magnetospheric Plasmas, Progress in Astronautics and Aeronautics, vol. 47, A. Rosen, ed., American Institute of Aeronautics and Astronautics, 1976, pp. 237-246.

41. Balmain, K. G.; Orszag, M.; and Kremer, P.: Surface Discharges or Spacecraft Dielectrics in a Scanning Electron Microscope. Spacecraft Charging by Magnetospheric Plasmas, Progress in Astronautics and Aeronautics, vol. 47, A. Rosen, ed., American Institute of Aeronautics and Astronautics, 1976, pp. 213-223.

42. Inouye, G. T.; and Sellen, J. M.: A Proposed Mechanism for the Initiation and Propagation of Dielectric Surface Discharges. Presented at the 1978 Symposium on the Effect of the Ionosphere on Space and Terrestrial Systems, Naval Research Lab. and Office of Naval Research, Wash., D.C., Jan. 24-26, 1978, Session IV, Paper 4-8.

43. Adamo, R. C.; and Nanevicz, J. E.: Spacecraft Charging Studies of Voltage Breakdown Processes on Spacecraft Thermal Control Mirrors. Spacecraft Charging by Magnetospheric Plasmas, Progress in Astronautics and Aeronautics, vol. 47, A. Rosen, ed., American Institute of Aeronautics and Astronautics, 1976, pp. 225-235.

44. Yadlowsky, E. J.; Hazelton, R. C.; and Churchill, R. J.: Puncture Discharges in Surface Dielectrics as Contaminant Sources in Spacecraft Environments. (Colorado State Univ.; NASA Contract NSG-3145.) NASA CR-157105, 1978.

45. Balmain, K. G.; Kremer, P. C.; and Cuchanski, M.: Charged-Area Effects on Spacecraft Dielectric Arc Discharges. Presented at the 1978 Symposium on the Effect of the Ionosphere on Space and Terrestrial Systems, Naval

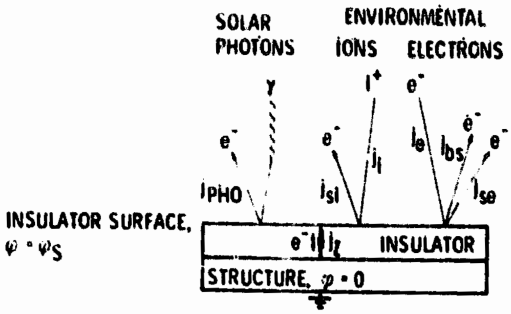
Research Lab. and Office of Naval Research, Wash., D.C., Jan. 24-26, 1978, Session IV, Paper 4-5.

46. Bogus, K. P.: Investigation of a CTS Solar Cell Test Patch under Simulated Geomagnetic Substorm Charging Conditions. Proceedings of the Spacecraft Charging Technology Conference, C. P. Pike and R. R. Lovell, eds., AFGL-TR-77-0051, NASA TM X-73537, 1977, pp. 487-501.

47. Hoffmaster, D. K.; Inouye, G. T.; and Sellen, J. M., Jr.: Surge Current and Electron Swarm Tunnel Tests of Thermal Blanket and Ground Strap Materials. Proceedings of the Spacecraft Charging Technology Conference, C. P. Pike and R. R. Lovell, eds., AFGL-TR-77-0051, NASA TM X-73537, 1977, pp. 527-547.

TABLE I. - MATERIAL PROPERTIES

Type of property	Property	Symbol
Physical and chemical	Density	ρ
	Chemical composition	CC
	Atomic number	A
	Atomic weight	Z
Electrical	Dielectric constant	ϵ
	Bulk conductivity	σ_B
	Surface conductivity	σ_S
	Radiation-induced conductivity	σ_R
	Dielectric strength	E_D
Particle penetration	Electron range	R_e
	Ion range	R_i
	Rate of energy loss for electrons	dE_e/dx
	Rate of energy loss for ions	dE_i/dx
Electron emission	Photoelectron yield	$\delta_{PHO}(E_{ph},\theta)$
	Secondary-electron yield due to electron impact:	$\delta_{se}(E_e,\theta)$
	Maximum yield	δ_m
	Energy for maximum yield	E_m
	Backscatter coefficient	$\eta(E_e,\theta)$
	Secondary-electron yield due to ion impact:	$\delta_{si}(E_i,\theta)$
	Yield at E_i = 1 keV (protons)	δ_p
	Energy for maximum yield (protons)	E_p
	Work function	W
	Distribution of emitted photoelectrons	$f_{PHO}(E,\theta)$
	Distribution of secondary electrons from electron impact	$f_{se}(E,\theta)$
	Distribution of secondary electrons from ion impact	$f_{si}(E,\theta)$



CURRENT DENSITY DUE TO -

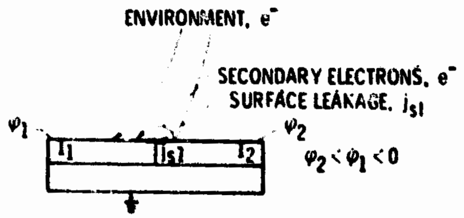
i_e	ENVIRONMENTAL ELECTRONS
i_i	ENVIRONMENTAL IONS
i_{PHO}	PHOTOELECTRON YIELD
i_{se}	SECONDARY ELECTRONS DUE TO ELECTRON IMPACT
i_{bs}	BACKSCATTERED ELECTRONS
i_{si}	SECONDARY ELECTRONS DUE TO ION IMPACT
i_ℓ	LEAKAGE THROUGH INSULATOR

EQUILIBRIUM CONDITION:

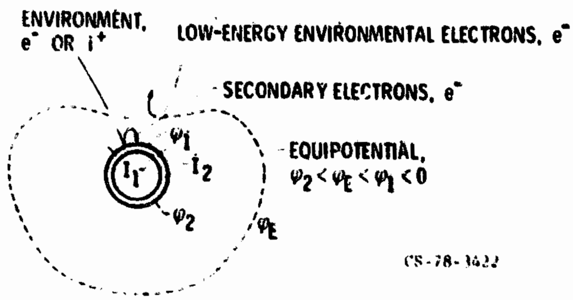
$$i_{net} = \sum_n i_n = 0$$

CS-78-3418

Figure 1. - Charging response - simple case (current densities to insulating surface element).

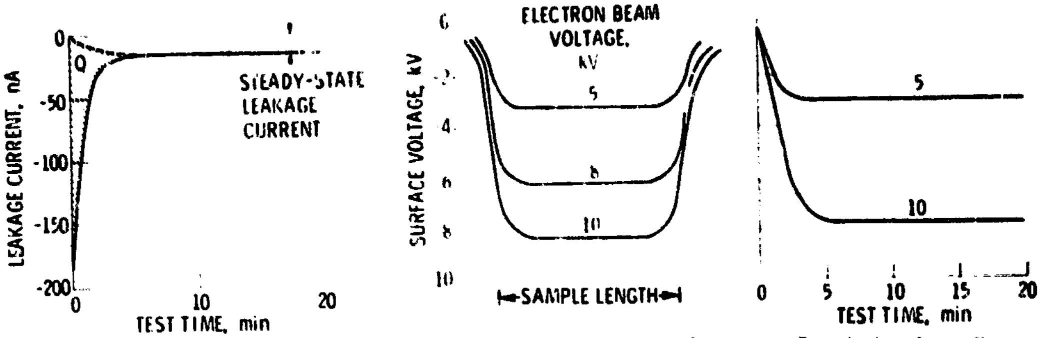


(a) Local effects.



(b) Global effects.

Figure 2. - Charging response - configuration effects.



(a) Transient leakage current. (b) Steady-state voltage profiles. (c) Transient surface voltage.

Figure 3. - Typical data set from materials characterization tests - charging data.

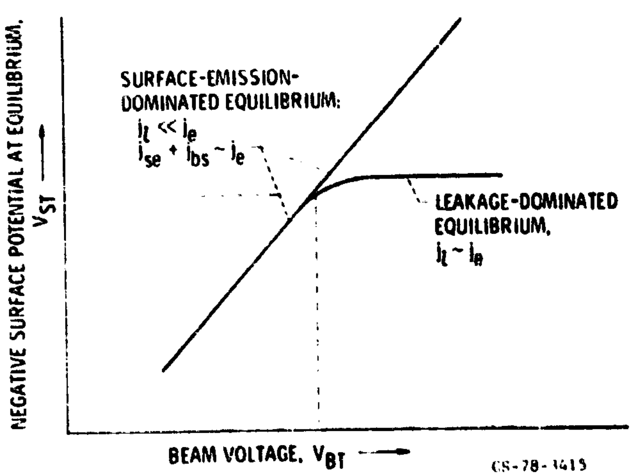
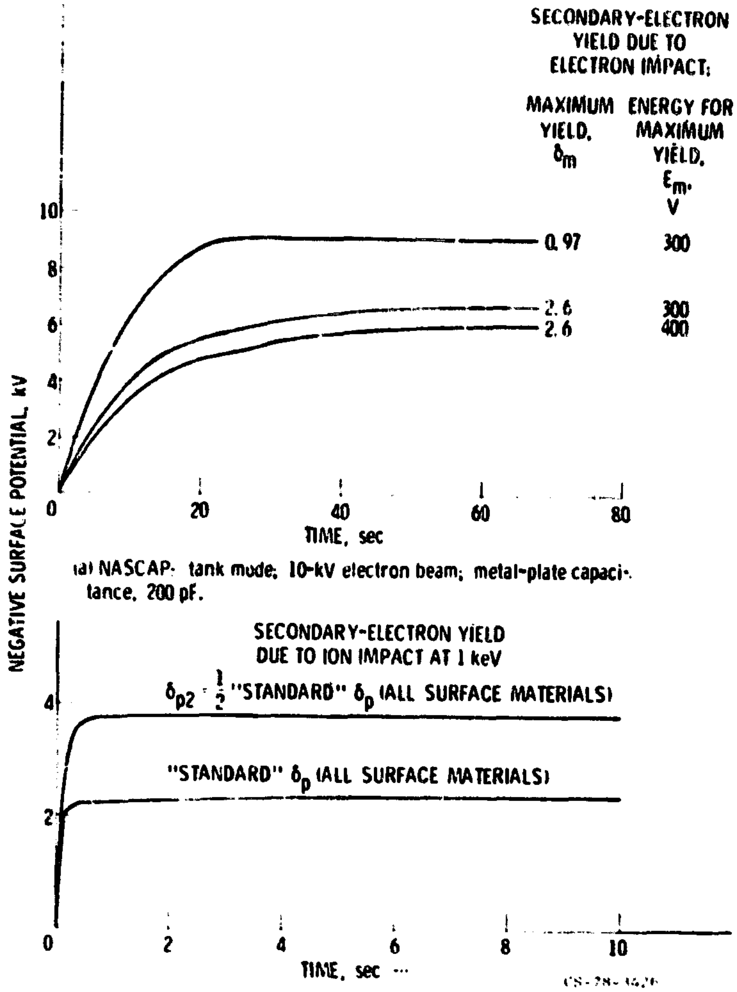


Figure 4. - Charging response - typical equilibrium surface voltage as function of beam voltage characteristics for insulators.



(a) NASCAP: tank mode; 10-kV electron beam; metal-plate capacitance, 200 pF.

(b) NASCAP: space mode (5 keV, 1 particle/cm^3); ATS-5 model object.

Figure 5. - Charging response - effects of changing secondary-electron-yield parameters.

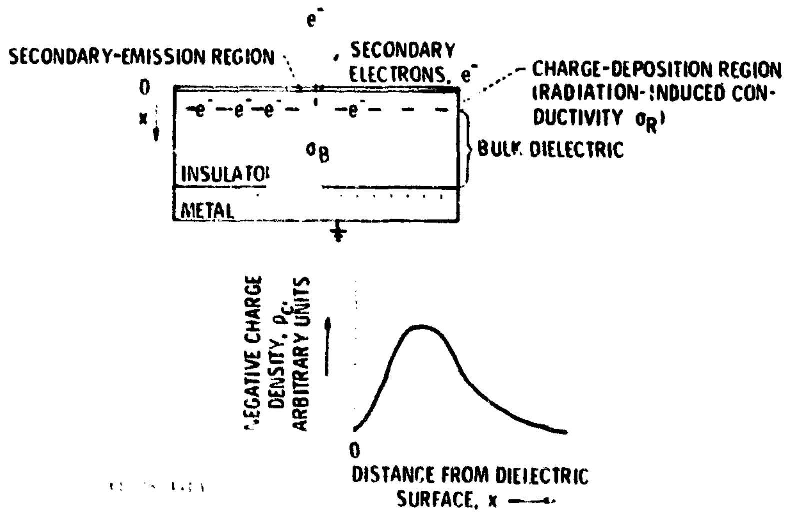


Figure 6. - Charge deposition.

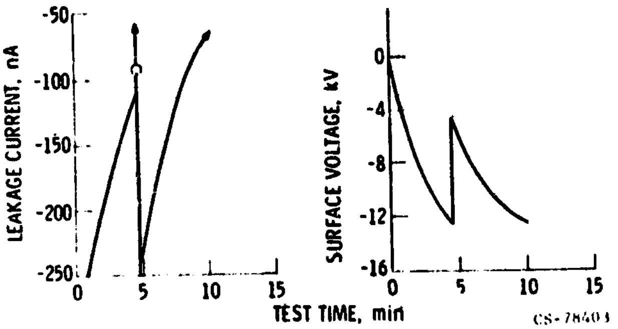
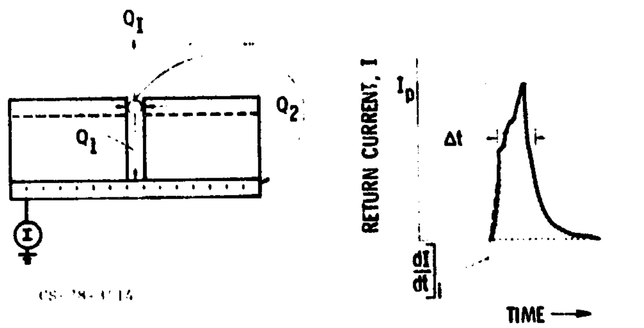


Figure 7. - Typical data set from materials characterization tests - discharging data.



(a) Charges transferred during discharge.

(b) Return curren. pulse.

Figure 8. - Discharge response.