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PROCEEDINGS OF THE SPACECRAFT CHARGING TECHNOLOGY CONFERENCE

Executive Summary

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SESSION I. ENVIRONMENT

DeForest reviewed the geosynchronous plasma environment including the high energy tail, the thermal background plasma, the low temperature "warm plasma," locally produced secondaries, substorm injection events, field aligned currents

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and magnetopause crossings. A synchronous environment plasma model was presented that includes omnidirectional and unidirectional electron fluxes. Charging in cavities located at the ends of a spacecraft can be dominated by the intense field aligned fluxes. Johnson et al reported observations of field aligned fluxes of O^+ and H^+ ions. Fluxes of 10^8 ions/cm sec sr and with keV energies are seen. Sagalyn and Burke reported on vehicle potential and plasma density and temperature measurements. At 2500 km altitude in polar orbit, vehicle potentials of up to -40 V are observed during impulsive auroral electron precipitation events. Stevens et al examined data from the Transient Event Counter on the CTS satellite. When discharges occurred, they were often recorded at the rate of a few per second, but no spacecraft anomalies appear directly related to the discharges. Purvis et al reported on active control of spacecraft charging using ATS-5 and ATS-6. Data from the ion engine neutralizer and an unbiased electron emitter were used. With the neutralizer on, the potential was -10 volts in eclipse and, when the neutralizer was turned off, the potential went to -1200 volts. The plasma bridge neutralizer is more effective than the emitter in maintaining vehicle potential near ground. Goldstein examined ATS-6 ion engine neutralizer data in conjunction with the UCSD particle detector. When the spacecraft potential was clamped to -10 volts, positive cesium ions flowed back to the spacecraft. He recommends mounting discharge devices away from the spacecraft on a boom in order to minimize contamination. Goldstein and Divine calculated spacecraft potential levels for Jupiter. Potentials of 10^3 to 10^4 volts are expected. Beattie and Goldstein described the selection process, including various trade-offs, for the active control system for the Jupiter Orbiter with Probe (JOP) spacecraft. Calculations by Pavel et al indicated that high altitude nuclear bursts can lead to processes which result in high charging levels on synchronous satellites. Juillerat and Philippon showed that proton fluxes in the South Atlantic Anomaly lead to currents which charge the proof mass of a low altitude "drag-free" satellite. Garrett combined measurements of ATS-6 eclipse data on particle fluxes and AE-C satellite data on UV radiation. He presented a nearly linear relationship between solar illumination/photoelectron flux and the logarithm of spacecraft potential. Grard described the many applications that an electron source such as a simple cathode may have to scientific and engineering satellite payloads.

SESSION II. MODELING

This summary will attempt to indicate the trends of research in the area of modeling with an emphasis on what is still needed. A detailed summary of the talks that were given will not be given. Some of the points to be discussed were brought out in the panel discussion which followed the main sessions of the conference.

The ultimate aim of the modeling efforts is to provide a theoretical scheme which can be used to describe the structure of the sheath around the spacecraft and to calculate the charging currents to the spacecraft. In order for the model to be useful, it should be readily applicable to real spacecraft, and the results should be capable of verification by comparison with data.

A full three-dimensional, self-consistent, time-dependent model for spacecraft charging is likely to be so complicated and time-consuming on a computer that its application to real problems would be quite limited. An important aspect of modeling research is finding out what approximations can be made. Any approximation which does not compromise the essential physics and which reduces the complexity of the computations should be very useful. A number of such approximations were discussed at the conference.

One obvious approximation is the neglect of time-dependence and the assumption of quasistatic conditions. There are probably many situations where this is a realistic assumption since the time constant for the plasma response is usually short compared to the time scale for changes in conditions. Occasions where this assumption is not valid may occur during discharge events and possibly during the charging of dielectrics which have large capacitances and hence long time constants for charging.

Another approximation is the utilization of a more restricted geometry than the full three-dimensions. Such models can give insight into the basic physical mechanisms and their relative importance with less cost. However, their application to realistic spacecraft configurations is probably restricted.

Neglect of space charge may be a valid approximation under some circumstances. In particular, it is probably quite realistic to neglect the contribution to the space charge from the ambient plasma in environments where the electron density in the magnetospheric plasma is small compared to the photoelectron density. Including only the space charge due to the photoelectrons is probably adequate in such circumstances.

An aim that all modelers should keep in mind is the possibility of representing their numerical results with analytic formulas. As insight is gained into the relative importance of the various physical processes, it is probable that many of these processes can be individually modeled with some sort of an analytic representation. Any such representation could be extremely useful in reducing computing time and costs.

Another important aspect of modeling is that of verification. This involves at least two things. First, a model must be built for an actual spacecraft which will be obtaining data. Second, data must be obtained with experiments on that spacecraft which can be used to compare with the predictions of the model.

Thought should be given now to the problem of developing a charging model for specific spacecraft. Two spacecraft which are obvious candidates are ATS-6 which is at present providing most of the currently available data on spacecraft charging in synchronous orbit, and the SCATHA spacecraft which will be launched in early 1979. Differential charging has been detected on ATS-6 but a full interpretation of the data requires a modeling effort. A charging model for SCATHA will be essential for the interpretation of data from that spacecraft.

One final comment on verification: the experiments on the ATS satellites and on SCATHA were developed without the insights that a charging model would provide. It is highly likely that as a charging model is developed and compared with spacecraft data, new experiments and better configurations of existing instruments will be devised for verification of charging processes. In this respect, the present modeling work must be regarded as an interim effort until there has been at least one iteration of the modeling – verification cycle.

SESSION III. MATERIALS CHARACTERIZATION

The materials characterization session of this conference was devoted to presentations on the experimental determination of the behavior of typical spacecraft materials when exposed to simulated geomagnetic substorm conditions. In addition, there were papers on facility related topics.

Papers by Stevens et al and Saylor presented results of survey tests on the response of various materials to electron bombardment. Results given by Stevens et al were based on measurements of leakage current and surface voltage, while those given by Saylor were based on measurements of leakage current. Surface voltages given by Saylor were calculated from the leakage current and sample capacity. The most striking difference in results was in the surface voltages reported. Saylor reports large positive surface voltages (2-3 kV) for teflon and kapton samples under bombardment by electron beams with beam energies up to 7 keV. In contrast, Stevens et al report only negative surface voltages for these materials under bombardment by electron beams with beam energies from 2 to 20 keV.

The test results for flexible solar array segments were given by Stevens et al and Bogus. The results were similar. The tests reported by Bogus were more complete and conclude ... at temperature can have an influence on discharging characteristics.

Edge voltage gradients were discussed by Robinson. This work complimented that presented by Stevens et al. However, in this work, discharges in the silver teflon samples were hard to obtain until the sample was cut. Discharges were obtained in the tests described by Balmain. Here the characteristics of surface micro-discharges in dielectric samples in a scanning electron microscope facility were described.

Sellen discussed the problems of sample hysteresis and its effect on the interpretation of the results. Facilities and possible electron sources were discussed by Berkopec et al and Nanevicz and Adamo.

In general, the papers given in this session presented more information than was available one year ago. However, there are sufficient differences noted in these results to warrant a critical evaluation of test methods and sample preparation.

SESSION IV. MATERIALS DEVELOPMENT

1. Overview

In principle, an attractive technique for controlling and minimizing spacecraft charging or at least for distributing the charge in an equipotential manner is through the use of electrically conductive surfaces for the materials exposed to the space environment. As discussed elsewhere during this symposium, the level of electrical conductivity required is relatively modest in most cases. Some promising advances have been made in this direction as summarized in some of the papers in this session. In other cases, further advances present a real challenge. Spacecraft surface materials are varied (for example, insulating blankets, solar cells, structural members, and optical components) and the task of developing electrically conductive analogues of all these materials while maintaining their primary functional features presents difficult technical issues. An example here would be electrically conductive thermal control coatings. Coatings, black in color (both visually and in the IR), can be produced readily based on the carbon black pigmented materials used widely in the aircraft industry. However, such coatings will clearly produce significant thermal loads in the substrates beneath them. While they will emit satisfactorily in the IR, they will have very high solar absorptance and thus not really perform the thermal control function at all. Obtaining acceptable thermal control features along with electrical conductivity in a practical coating is proving to be very difficult.

Even with conductive surfaces, practical methods of electrically interconnecting different surface regions may not be straightforward. An example here would be the interconnection of optical solar reflector mirrors which have been coated with electrically conductive surface material. The OSRs are, of course, quite small, thus the interconnections have to be numerous. The mirrors are also fragile and their coatings are delicate, thus introduction of conduction paths through the adhesion materials around and under the mirrors is a difficult design problem. An additional design requirement especially important for Department of Defense satellites is dependable long term performance. Assuring long lifetime, on the order of 5 to 10 years, for materials which must perform under a multiplicity of environmental stresses can be difficult. For example, one of the central issues at present is the interdependency of contamination and spacecraft charging. Questions such as the following arise: (1) does contamination change the electrical characteristics of conductive surfaces? (2) does significant contamination arise when electrical discharging occurs especially when the latter is low level, but chronic, over long periods of time? Several papers at this symposium address these questions.

As discussed at some length during the symposium, there are design alternatives to conductive materials for control of charging effects. Electromagnetic shielding of critical components would be one example, simply halting operation of the satellite during periods of high level solar activity would be another. Some methods of control, especially the so-called "active" techniques of dissipating charge, actually depend on the presence of interconnected electrically conductive surfaces to "funnel" the charge to the point of dissipation.

Once conductive materials become available, issues of spacecraft system design using these materials arise. From the material developer's view, this generally means that a substantial design information package must be developed including the response of the material in a number of combined-environment exposure situations. Again, as discussed frequently during this symposium, there are a number of unresolved questions as to exactly what tests are necessary and sufficient to produce the design package. Since the required materials characterizations seem to be complex and the effects in the materials subtle, questions arise as to intercomparisons of test results among different investigators and how standardization of the test methodology can be affected.

Even though the development of conductive materials represents high risk, probably long range technology, the effort should be undertaken because of the high payoff in spacecraft design flexibility and reliability. Without improved materials, alternative design fixes or change in modes of system operation present penalties in higher system weight, shorter lifetime, and lessened reliability.

The papers in this session can conveniently be divided into two categories. First is a group dealing specifically with new electrically conductive materials development: paper numbers IV-1, 3, 4, 5 and 6. Second is a group dealing with effects on materials of an electrically energetic environment and with the methods of materials characterization: paper numbers IV-2, 7, 8, 9, 10 and 11. As mentioned above, the effects/characterization issues are central to the effective use of these new materials in spacecraft design and for high confidence predictions of performance especially in long lifetime missions.

2. Materials Development Papers

The first paper in this group by W. L. Lehn (IV-1) presents an overview of the on-going and planned materials development efforts under a cooperative USAF/NASA program. A jointly planned USAF-NASA interagency cooperative research and technology program has been established and implemented to investigate spacecraft charging phenomena. The majority of the materials development task under this joint program is the responsibility of and is being directed by the USAF Materials Laboratory (AFML). This paper gives an overview of the materials development work, much of it just recently initiated, in four fundamentally different functional areas: (1) thermal control materials, (2) insulative materials, (3) transparent materials for OSR application and conductive materials for solar cell application, and (4) conductive low outgassing adhesives.

The current situation in the development of electrically conductive thermal control coatings (paints) is summarized by J.E. Gilligan (paper IV-3) of IIT Research Institute working under Air Force sponsorship and by C.M. Shai (paper IV-4) who discusses the in-house work at NASA Goddard.

A wide variety of approaches for the development of conductive paint type thermal control coatings have been investigated under the IITRI program. Materials which have been investigated and evaluated include both standard as well as electrically conductive organic and inorganic binders pigmented with conductive metallic and inorganic doped oxides. The paint systems formulated using commercially available conductive organic quarternary-ammonium salt-polyvinylcarbazole polymers are interesting but will require a substantial, long term development before space stable materials will be realized. A major concern is poor vacuum and radiation stability of the polymeric binders. Several promising coatings based on a conductive antimony-doped tin oxide pigment in silicone and silicate binders with resistivities in the desired range of 1×10^9 ohm-cm or lower were prepared but further development is required. From an overall point of view, the inorganic silicate coatings offer the greatest near term potential. The standard state-of-the-art Z-93 specification inorganic thermal control coating exhibits good electrical properties and is a very space stable system. This material does develop a low level surface charge but does not arc/discharge. Development of an inorganic coating with improved electrical conductivity properties could be completed in 1-2 years. The materials developed were evaluated based on electrical conductivity, goal of 1×10^9 ohm-cm or lower, physical properties and stability of the spectral reflectance under simulated space vacuum ultraviolet exposure.

The NASA coatings development program is in direct support of the International Sun Earth Explorer (ISEE) spacecraft. Materials which have been developed and evaluated include both organic and inorganic binders pigmented with standard dielectric as well as semiconductor pigments. The formulation, evaluation, and testing of these materials are presented. Conductive paints ranging in color from white and light yellow to green exhibiting solar absorptance values from 0.22 to 0.65 have been formulated from doped inorganic oxide pigments in inorganic mixed alkali silicate binders. Emittance values range from 0.87 to 0.90 and resistivities from 1×10^3 to 1×10^5 ohm-m^2. The green paint has been selected for application on the ISEE satellite. Results of the materials characterization studies have shown that conventional thermal control paints charge to a certain degree under simulated synchronous orbit radiation exposure, but they do not arc or discharge, the excess charge being lead/conducted to the conductive substrate or ground. The conductive paints do not charge but conduct the charge to ground.

An entirely different approach to thermal control is discussed by V.J. Belanger and A.E. Eagles (paper IV-6). Their concept, developed at General Electric under USAF sponsorship, involves the use of high purity silica fabric as an extremely space stable, low solar absorptance to emittance ratio (white paint type) coating. The application of these high purity silica fabrics and conductive fiber/silica fiber interweaves to control the effects of spacecraft charging is being investigated. Further, a number of satellite systems contractors are considering use of the material because of its extreme space stability, contamination resistance, long life characteristics, and its resistance to heat pulse loading. The materials prepared have been studied as part of the NASA responsibility for the engineering characterization of the materials developed under the broad USAF/NASA joint program. It has been found that under simulated synchronous orbit charging conditions the silica fabric coating material, either by itself or when used as the outer layer of multilayer insulation (MLI) blankets, does become charged but does not arc or discharge. All of the other typical MLI configurations using outer layers of dielectric polymeric materials charge and arc/discharge to an excessive degree. The basic fabric material is commercially available. Secondary emission conductivity, proposed as the mechanism for the observed behavior, is discussed in the paper. A program to develop a silica fabric with optimized thermal optical, weight, and other physical and engineering properties has been initiated.

The final paper in the materials development category (paper IV-5) by L. Amore, A.E. Eagles and E. Okress of General Electric describes the design, fabrication and testing of conductive coating materials in the form of low cost conductive transparent coatings for optical solar reflectors, solar cell cover glasses and conductive polymeric films for a variety of uses such as thermal insulation blankets.

Examples of the approaches discussed in the paper include the deposition of transparent metal oxide coatings (indium tin oxide) on Kapton and Teflon metallized polymeric films. Thus far, good adhesion has been obtained and there has been little degradation of the thermal control features of the films. Conductive grids, photoetched on polymeric film substrates, also perform well as described in the paper. OSR and solar cell cover glass modifications have shown to hold promise. Glass frits modified or doped with zinc, lead, lithium, and cerium are effective in producing conductive surfaces in these materials.

3. Materials Effects and Characterization Papers

The first paper in this group by J.A. Wall, E.A. Burke, A.R. Frederickson and J.C. Garth (paper IV-2) deals with electrical properties of insulating materials. A knowledge of the dielectric properties and electron interaction phenomena of the materials applied to the exterior surfaces of a spacecraft is required in order to determine the susceptibility of the spacecraft to the ambient as well as the disturbed synchronous environment. A comprehensive literature search was performed by Wall and coworkers at Rome Air Development Center on spacecraft insulating materials in the areas of electrical conductivity, basic mechanisms of energetic electron interactions, (for example, secondary emission, backscatter, range, etc.) charge storage and electrical breakdown. The search concentrated primarily on polymeric dielectrics. Although work has continued in these areas for a number of years, much of the information has been generated only in the past 5 to 10 years and new data and theoretical approaches are appearing more and more frequently. With the exception of dielectric breakdown, much of the data and theory needed to help solve the spacecraft charging problem except for certain specific materials should therefore be available soon in the open literature.

In the next paper (IV-7), R.C. Adamo and J.E. Nanevicz of Stanford Research Institute discuss photoconductivity effects in high voltage space insulating materials. The dark and photoconductivity of various external satellite dielectric materials is an important factor in any synchronous orbit charging/discharging situation. Recent investigations of several typical and potential spacecraft insulating materials have shown that the conductivity under simulated synchronous orbit conditions as well as the conditions required for electrical breakdown are a function of temperature, illumination intensity and wavelength, and electron beam energy and current.

These authors indicate that many of their samples showed an increase in conductivity of several orders of magnitude, particularly at higher temperatures while Kapton showed a change of five orders of magnitude under illumination. Adamo and Nanevicz conclude that further materials investigations in this area are warranted to help provide guidance and direction for future development efforts.

A technique for determining the conductance of thermal control coatings by a contactless method in vacuo is outlined by W. Viehmann, C. M. Shai and E. L. Sanford of NASA Goddard (paper IV-8). In order to simulate orbital conditions more closely, current-density-voltage (j-v) curves were obtained with the contactless method in which the paint on an aluminum substrate was the anode of a vacuum diode configuration with a tungsten filament cathode. Conductances per unit area which satisfy the ISEE requirement were observed on black paints containing carbon and in "white" and green paints filled with zinc oxide which had been "fired" in order to induce defect conductivity. Because of surface effects and the nonhomogeneous nature of paints, large discrepancies were found between measurements with the contactless method and measurements employing metallic contacts, particularly at low current densities. Therefore, measurements with metallic contacts were considered to be of questionable value in deciding the suitability of coatings for electrostatic charge control.

D. F. Hall of Aerospace Corporation describes the charging/contamination experiment on the SCATHA spacecraft (paper IV-9). The ML-12 experiment, a joint project of the AF Materials Laboratory and Aerospace Corp. is designed to determine if spacecraft charging contributes significantly to the rate of contamination arriving at exterior spacecraft surfaces, and some of the characteristics and effects of the contamination collected. The contamination transport mode under investigation involves the ionization of molecules outgassed or released by the vehicle within the vehicle plasma sheath and their subsequent electrostatic reattraction to the vehicle.

Two sensor types will be flown. One type is a combination retarding potential analyzer (RPA) and temperature controlled quartz crystal microbalance (TQCM). With it, distinction can be made between charged and uncharged arriving molecules, and information concerning the temperature dependence of contamination absorption and desorption rates obtained. The other sensor type exposes samples of different spacecraft surface materials to arriving contamination and continuously measures the solar absorptance (α_s) of these materials. Changes in α_s of space-stable samples will be entirely ascribed to contamination effects whereas changes in other samples will result from a combination of contamination, photochemical, and radiation effects. Upon ground command, some samples will go through a heating sequence designed to roughly determine the temperature at which contamination is desorbed.

In addition to describing the goals and techniques of ML-12 in more detail, the expected performance of the sensors and the need for coordination with other experiments on SCATHA are discussed in the paper.

Paper IV-10 by J.B. Reagan, W.L. Imhof and E.E. Gaines at Lockheed Palo Alto Research Laboratory deals with the effects of energetic particle radiation on spacecraft charging at geosynchronous orbit. In addition to the low energy, 5 to 50 keV electron environment at geosynchronous orbit which affects the external dielectric surfaces of the spacecraft there is also a very intense, dynamic and penetrating radiation environment, particularly at penetrating energies >1.5 MeV, which is responsible for a va[illegible]ty of adverse charging effects on spacecraft components. The most serious of these is the degradation and failure of the widely used complimentary-metal-oxide-semiconductor (CMOS) electronic components as a result of internal charge-buildup induced by the energetic electrons. The dose received by a CMOS device from energetic electrons and associated bremsstrahlung was predicted with two computational codes. The two models were found to be different by as much as a factor of six. Resolving these discrepancies with the High Energy Particle Spectrometer experiment (SC-3) on SCATHA is discussed by these authors along with a review of the present discrepancies in the radiation models and the corresponding influences on spacecraft materials and component lifetimes.

Finally, a paper entitled "Electrical Discharges Caused by Satellite Charging at Synchronous Orbit Altitudes" by Nanevicz, Adamo and Shaw of Stanford Research Institute was substituted for the paper originally scheduled (paper IV-11). This paper which complements the earlier CTS Transient Event paper by Stevens et al in Session I reports on some of the earlier, on-orbit measurements of satellite discharge events.

SESSION V. DESIGN AND TEST

The papers in this section cover several subjects pertinent to the satellite design engineer: environmental specifications, charge effect monitor devices and several approaches in vehicle design to limit, control or prevent spacecraft charging.

The paper by Bower provided an overview of the spacecraft charging problems encountered by satellite systems and what must be done to circumvent these problems. The charging phenomenon is very geometry-dependent and therefore varies immensely from satellite to satellite, but there are certain fundamentals which can be considered. The surfaces of current on-orbit systems are almost entirely dielectric, whether that dielectric is the 12 mils of cover glass over the solar cells, the 2 mils of kapton surface on multiple layer thermal blankets, or the 2 mils of cover glass backed by aluminum or silver used as second surface reflectors. These surfaces become capacitors when electrons are deposited on them, and in the environment described preliminarily by Stevens/Lovell/Purvis in the third paper, they charge to the breakdown voltage. The subsequent discharge and punch-through induces spurious signals in the cables between electronic boxes with the possibility of upsetting the electronics or burning them out. This burn-out must be a concern, but can be coped with by eliminating the charging and subsequent discharging, by preventing coupling into the cables through shielding, or by designing immunity into the electronics.

Conductive fabrics are currently being defined and conductive polymeric coatings for cover glasses are in the development stages, but they are expensive and they may attenuate x-ray hardening in the case of military satellites. Considering the weight penalty of increased shielding, current preference is to design immunity into the electronics. The lack of a data base around which to design, however, leads to some over-design; in fact, most systems being designed today utilize all three approaches to controlling charging and discharging. Fortunately, but again only in the case of military systems, the design approach to solve SGEMP and EMP problems may solve ESD problems, and this is discussed extensively in the papers by Smith and Holman and Ling. Lewis described the design approaches used on two experimental satellite systems. One, requiring survival upon entry into the Martian atmosphere, allowed operation with corona but prevented arcing, while the other will be subjected to energetic particle charging and subsequent arcing.

An approach to solving the problem after-the-fact (subsequent to design) is presented by Gore. The extensive grounding, shielding and strict adherence to EMI requirements proved successful on this Canadian/US venture.

The original problem of convincing satellite designers and operators that some anomalous occurrences were indeed caused by arc discharge-triggered transients was aggravated by the fact that no on-orbit record existed. In fact, charge effect monitor devices are not included on the majority of satellites scheduled for launch in the near future. Nanevicz and Stevens et al discussed the importance of establishing a one-to-one correlation between system electronic perturbations and the local environment, as well as how it can be done.

Rosen presented an approach to radiation susceptibility tests through pulse injection on an engineering model of the satellite electrical system, and concludes that the radiative part of the problem is controllable by means of reasonable EMC controls.

An entire spectrum of possibilities for limiting or preventing charging is thus presented, but the measures are expensive and much work remains in order to fully understand the problem.