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SPACECRAFT CHARGING MODELING DEVELOPMENT AND VALIDATION STUDY*

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SUMMARY

Prediction of the effects of spacecraft charging requires validated analytical models of the magnetospheric environment, the charging interaction between the spacecraft and the plasma sheath, the discharge phenomena, electromagnetic coupling from the discharge to spacecraft components, and of material damage. This paper reviews the analytical models now available and describes the use of SCATHA data and ground tests to validate the models.

INTRODUCTION

One of the objectives of the cooperative NASA/Air Force Spacecraft Charging Investigation is to ensure that validated analytical models are developed which are capable of predicting the interaction of spacecraft with the environment. Historically, modeling activity has been divided into four regions:

- The undisturbed environment
- The plasma sheath surrounding the spacecraft
- The spacecraft surface
- The spacecraft interior

Models must be capable of predicting the degradation of the spacecraft due to its interaction with the environment. This degradation can fall into two categories: (1) anomalies, which are interruptions in service due to electromagnetic coupling of static discharges into sensitive electronic circuits, and (2) materials degradation, such as changes in thermal absorption and emission coefficients. Anomalies can be temporary, such as the upset of a digital logic circuit, which is restorable by ground command, or permanent damage due to burnout of semiconductor elements.

Emphasis to date has been put on solving the anomaly problem, but with long mission life requirements expected for space systems, material degradation may become extremely important.

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ANALYTICAL MODELS

Environmental Models

The environmental model describes the magnetospheric substorm in terms of electron and ion concentrations, particle energies, and probability of occurrence. A comprehensive model should include

- Electric and magnetic fields
- Plasma particle identities and number densities
- Particle fluxes and current densities
- Particle energy spectra
- Particle angular distributions (isotropy, field alignment, etc.)
- Temporal variations of plasma parameters
- K_p, A_p dependence of plasma parameters
- Spatial dependences
- Probabilities of occurrence of various severities of substorm activity

Table 1 lists the environmental models available and in use today. The AFGL model, usually known as the Environmental Atlas (Ref. 1), when updated with data from the SCATHA satellite, will be issued in CY 1980 and will serve as the standard reference for magnetospheric environments. Haffner (Ref 5) has computed substorm conditions and probabilities of occurrence for subsynchronous orbits.

Sheath/Charging Models

The sheath/charging model determines the spacecraft charging condition, the electromagnetic fields in the plasma sheath surrounding the spacecraft and the particle trajectories and fluxes in the sheath region. For engineering purposes, it is sufficient to determine the charging condition: potential distributions on the spacecraft surface; but for scientific payloads, the sheath fields, particle trajectories, and particle fluxes may be of extreme importance.

Engineering models, such as those used by design organizations, usually are of the equivalent circuit type, described by Inouye (Ref 8) and Massaro (Ref. 9). More sophisticated treatments needed for scientific purposes require iterative solutions of the Poisson and Vlasov equations with the approach dependent upon the geometry involved. Table 2 lists the models used for sheath/charging analyses.

The most ambitious model to date is the NASCAP code developed by Systems, Science, and Software for NASA (Ref. 14).

Discharge Models

As the charge accumulates on a spacecraft dielectric surface, the probability increases that the surface will discharge to spacecraft ground or another surface of lower potential. Discharges fall into three categories:

- Punchthrough - dielectric breakdown from the front to back surfaces of a material
- Flashover - dielectric breakdown along a surface or between two adjacent surfaces
- Blowoff - the expulsion of charge to free space

It has been observed that all three types of discharges will result in charge expulsion, and it is the time dependence of the effluent charge that is the single most important parameter in modeling discharges.

The discharge models must describe the discharge current amplitude and pulse shape, the energy released ejecta material species and time history, the current paths, and the dependence of these upon the following variables:

- Surface area
- Dielectric properties (Teflon, Kapton, etc.)
- Material juxtaposition
- Environmental conditions (electron and ion spectra, photo illumination, etc.)

Discharge models fall into three categories: (1) phenomenological, which are simply aggregations of data tied together with empirical relationships; (2) qualitative models, which postulate a physical process but do not attempt mathematical formulations; and (3) physical models, which attempt to formulate a fundamental physics approach to explaining discharge phenomena. At present no suitable models of any category exist. Table 3 describes the models now existing and those in development.

Coupling/EMI Models

The Coupling/EMI models are used to predict the electromagnetic interference (EMI) at sensitive electronics packages due to the dielectric discharge. This can be done in one or two steps, depending upon the analyst.

In the one-step approach, as was used by Inouye, et. al, (Ref. 19) an EMI model of the spacecraft is devised and a standard EMI computer code such as IEMCAP or SEMCAP is used to predict interface transients. In the two-step approach, a time-domain electromagnetic analysis is performed to predict spacecraft structural currents and internal fields. Then, using a transient circuit analysis code such as SYSCAP, the transient interface and voltages and currents are predicted.

Table 4 lists the codes available for Coupling/EMI analyses.

Buried Component and Cable Models

High energy electrons (trapped radiation) will penetrate spacecraft surfaces and deposit charges at depth in the spacecraft. It has been shown by Beers (unpublished) and Wenaas (Ref. 20) that spacecraft cables can accumulate sufficient charge to approach breakdown conditions in the cable dielectric. It is expected that other buried dielectrics, such as capacitor dielectrics, printed circuit boards, etc., could also experience breakdown.

Of the buried components, only the cables have been treated analytically, and these analyses are not adequate to predict the spacecraft performance. It should be noted that in the event of an exoatmospheric nuclear explosion, trapping of fusion product beta radiation could lead to severe high energy electron environments, in which the buried component discharge phenomena could well dominate magnetospheric plasma effects.

Materials Damage Models

A materials damage model would relate important materials properties (emission, absorption, electrical and thermal conductivity, etc.) to sample charging and discharging history. Though some data exist, no attempt has been made to formulate even a phenomenological model.

MODEL VALIDATION ACTIVITIES

The previous section has shown that a variety of analytical models have been developed or are being developed for spacecraft charging analyses. This section describes the ground and space programs which will be used to validate the models.

SCATHA Model Validation

Table 5 lists the SCATHA experiments and describes how the data will be used for model validation. As this table is summary in nature, it will be useful to describe in detail the process by which SCATHA data will be used. Two examples will be given:

- SC1-1,2,3 validation of NASCAP
- SC1-8B validation of discharge, coupling, and EMI models

NASCAP Validation

The Satellite Surface Potential Monitors (SSPMs) are material samples specially instrumented to measure the sample potential relative to spacecraft ground, the leakage and displacement currents. A SCATHA version of NASCAP has already been developed by Systems, Science, and Software (S^3) and sample runs have been made. Once SCATHA is in orbit and data have been telemetered to ground, the environmental conditions at the spacecraft will be determined from other SCATHA experiments (SC2, SC3, SC5, SC6, SC7, SC8, SC9), and this environment will be used as NASCAP imput, which will predict SSPM parameters. The comparison of predicton with data provided by SC1, 1, 2, and 3, will validate NASCAP.

Further validation of NASCAP will come from monitoring the SSPM readings during SC4 (electron and ion gun) operation. Predictions will be made of the SSPM potential as a function of time during gun operation. If NASCAP is capable of predicting the potentials correctly, then the code is assumed to be valid.

Discharge, Coupling, and EMI Model Validation

Data from the Narrowband Pulse Analyzer can be used to validate coupling/EMI and discharge models as follows:

- From the NASCAP charging analysis, it will be possible to select likely discharge positions. Those positions will be the source locations for a time-domain coupling analysis. The driving function (current density vs time) will be provided by the discharge model.
- The coupling calculations will predict SCATHA structural currents and near fields as functions of time.

- The field excitation of the dipole antenna will be computed for each of the discharge sources. These results will be compared with SC1-8B measurements. The source terms will be iterated until agreement is satisfactory.
- Coupling calculations will also provide internal fields. Cable harness transients will be predicted using standard circuit analysis routines and the results compared with the internal monopole and loop antenna results.

The above process can be simplified considerably if the discharge location can be identified uniquely. For example, if the SSPM measurements indicated that one of the material samples discharged at time t_o, and the SC1-8B detailed a transient at the same time, then the SSPM single could be assumed to be the source of the discharge.

GROUND TEST PROGRAMS

As can be seen from Table 5, the primary purpose of SCATHA is to provide data for the environmental and sheath/charging models. Thus the bulk of the data for validation of discharge, coupling, EMI, and material damage models must be obtained via ground tests. Table 6 is a compilation of ground tests and other validation activities that are planned, in progress, or have recently been completed. Comments on selected efforts follow.

Validation of NASCAP will come primarily from material sample exposures at NASA LeRC, and a number of these tests have been conducted. A comparison of NASCAP with the Laframboise code will be initiated soon and should determine the effect of the corners in the NASCAP geometry. The Laframboise technique assumes an infinite cylindrical geometry; analysis of long cylinders should provide good comparisons for the purpose of code validation.

The discharge data of Balmain, at the University of Toronto, indicate strong functional dependence of discharge return current amplitude, charge, and energy upon sample area. Peak amplitude appears proportional to the half power of area, total charge is proportional to area, and energy is proportional to the three-halves power of area. The pulse duration, which data have more scatter, seem to vary roughly as area to the 0.55 power.

At present, the only program involving physical discharge modeling with experimental confirmation is a joint effort by SAI and SRI with SAMSO funding. This program should provide the first quantitative definition of the discharge source for use in coupling calculations.

A scale model of SCATHA has been constructed for coupling model validation and for EMI testing at IRT. Using this test vehicle, IRT has developed a set of preliminary test procedures that should serve as the basis for test standardization. Also, using a capacitive drive technique that best represents the discharge mechanism, IRT is developing empirical transfer functions that will simplify the interpretation of SCATHA data.

RECOMMENDATIONS

Most of the modeling activity to date has been concentrated in the areas of the free-field environments and the plasma-sheath region, and likewise, most of the SCATHA instrumentation is designed to validate these models. It is apparent that the cooperative NASA/Air Force Spacecraft Charging Investigation Program will provide at the minimum validated environment and sheath/charging models.

Coupling and EMI models can borrow from the technology developed for nuclear weapons effects phenomena. With only modest modifications, a number of computer codes developed for analysis of system-generated electromagnetic pulse (SGEMP) effects can be used for studies of electromagnetic coupling from discharges.

It is ironic that the earliest recognized electrical phenomenon, the electrostatic discharge, remains one of the most poorly understood. And it is important to realize that until the physics of the discharge phenomenon are understood, both qualitatively and quantitatively, there will be very little confidence in scaling laws or "worst-case" specifications that are imposed as design criteria.

What is needed is a thorough program to characterize discharges in physical terms. This program should have both analytical and experimental elements, interactive in the sense that analytical results are used to define experimental goals and experimental results are used to guide analytical directions.

Another program need is the development of a materials damage model. This model could be empirical, or semiempirical, but should make use of the data provided by the discharge model development.

To date, no one has extended the buried component and cable charging effects analyses past infancy. JAYCOR, with AFWL funding, is initiating a program that includes these effects, and these efforts should be included in an overall system assessment.

Finally, a system level combined effects test (simulating plasma, solar photons, and trapped radiation) should be planned. This test would validate (as well as possible in a ground test) the charging, discharge, coupling, and EMI analyses, as well as system level current injection (proof) tests.

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TABLE 1. - ENVIRONMENTAL REFERENCE SUMMARY

SOURCE	DESCRIPTION	THEORY, DATA BEHIND APPROACH
AFGL (Garrett) (Reference 1)	Elec. & mag. fields, particle distribution fcts., isotropy, maxwell vel. dist., K_p, A_p dependence, 3 hr. time resolution, local time variations incl.	Based on ATS-5, ATS-6 data. 4 plasma moments calculated for 10 days of data, 3 hour a_p dependence of predicted environment.
MAYA Dev. Corp. (LaQuey) (Reference 2)	24 hr. spectrograms, particle distribution fcts., 6 spectra output each 24 hour period, isotropy assumed.	Samples of ATS-5 and ATS-6 data for typical variety of conditions (6 days), 2.3 to 6.8 minute avgs., no theoretical treatment.
NASA/LeRC (Stevens, et.al.) (Reference 3)	Preliminary guide for environmental spec, isotropy assumed, estimates for particle energies, spectra current densities, estimates of S/C - environment encounter times.	3 months of ATS-5 and ATS-6 data, mild, moderate, severe substorms defined, probability of occurrence estimated.
TRW & UCSD (Vogl & DeForest) (Reference 4)	Provides estimates of importance of field-aligned components.	Based on ATS-5 and ATS-6 data (20 field aligned components in 6 months data)
Rockwell (Haffner) (Reference 5)	Provides some spatial and altitude dependence of environment.	Combination of theory and empirical information, reasonable treatments.
AFGL (Reference 6,7)	Statistical representation of substorm fluxes, rapid time variations of potentials.	Pre-1975 data.

TABLE 2. - SHEATH/CHARGING MODEL SUMMARY

SOURCE	DESCRIPTION	PURPOSE
Equivalent Circuit Models (Reference 8,9)	**Lumped element model of spacecraft with plasma currents as current sources.**	**Engineering estimates of spacecraft surface potentials.**
Beers and Pine (Reference 10)	**Monte Carlo calculation of electron transport in planar samples.**	**Charge distribution and internal fields as a function of time.**
Lee Parker (Reference 11)	**Numerical solution of Poisson and Vlasov equations. No azimuthal variations allowed. Uses "inside out" method of particle tracking.**	**Scientific studies of plasma sheath.**
Rothwell, et al (Reference 12)	**Monte Carlo simulation for spherically symmetric bodies.**	**Design studies; effect of material conductivity on spacecraft potential.**
Laframboise (Reference 13)	**Poisson-Vlasov iteration in infinite cylinder geometry.**	**Useful for studies of non-azimuthally symmetric bodies.**
System, Science, and Software NASCAP (Reference 14)	**Poisson-Vlasov iteration in three dimensions. Geometric building blocks are cubic grids and diagonal sections.**	**Particle trajectories, surface potentials, charging rates. Useful for engineering & scientific applications.**

TABLE 3. - DISCHARGE MODELING ACTIVITY

SOURCE	DESCRIPTION OF ACTIVITY AND KEY RESULTS
Bower (Reference 15)	Worst-case specification for spacecraft. Assumes pulse duration proportional to area.
Wilkenfeld, et al (Reference 16)	Input to coupling analyses. Assumes charge transferred dependency on Area of the form. $Q = \frac{dQ}{dA} A_o (1 - \exp). [-A/A_o])$
Muehlenberg (Reference 17)	Postulates blowoff charge is caused by surface bilayer.
Brushfire I & II Sellen (Reference 18)	Qualitative model of surface discharge propagation. Postulates that high field gradients near discharge point cause secondary electron acceleration and multiplication. Brushfire II extends model to depth in dielectric material.
Beers	Monte Carlo modeling of discharge propagation. Field gradients caused by bulk breakdown cause free charge acceleration in dielectric. Electron motion heats a material, increasing conductivity, allowing greater mobility and discharge spreads, causing "tree" effect.
Balmain	Empirical relationships between discharge current amplitude, charge removed, and pulse widths as functions of sample area.
Leadon	Mechanism similar to Beers. Postulates that magnetic fields caused by discharge current expel charge.

TABLE 4. - COUPLING/CMI CODE SUMMARY

CODE TYPE	APPLICATION	COMMENTS
Transient Circuit Analysis Codes (SYSCAP, ISPICE, SCEPTRE, etc.)	ISPICE used by Hughes for PIONEER charging, coupling, and EMI analyses. Can be used for black box analysis given internal fields.	Widely available and used. Lumped element model definition of spacecraft not unique. May have problems with multiwire effects.
Frequency Domain EMI Codes (SEMCAP, TEMCAP)	Used by JPL/TRW for Viking Coupling and EMI study.	Not designed for transient analyses. Accuracy can be improved by iterating test and analytical model results.
Three Dimensional Maxwell Equation Solvers (SABER, SEMP, FAT, etc.)	Time domain coupling given discharge current as driver. Computes structural currents fields. SABER used by IRT for SCATHA modeling.	Developed for SGEMP analyses. Well suited for spacecraft charging coupling analysis.
Transmission Line Analytical Models	Multiwire transmission line analyses. May be applicable to EMI analyses at spacecraft harnesses.	Developed for aircraft EMP studies. Development not complete.

TABLE 5. - SCATHA DATA UTILIZATION FOR MODEL VALIDATION

EXPERIMENTAL	DESCRIPTION	MEASURED QUANTITIES	DERIVED QUANTITIES	VALIDATION USE
SCI Engineering Experiments SC1-1	Satellite surface potential monitor (SSPM) 4 small samples, side mounted	Back surface E-field, leakage current, displacement current	Surface potential, material conductivity charging current, breakdown threshold, time of breakdown	NASCAP Discharge models (if samples discharge) Evaluate conductive coatings Materials properties
SC1-2	SSPM Large Kepton sample, side mounted reference band	Same as SC1-1	Same as SC1-1	Same as SC1-1
SC1-3	SSPM 4 small samples, end mounted	Same as SC1-1	Same as SC1-1	Same as SC1-1
SC1-4	External loop antenna External dipole antenna	Electromagnetic fields external to spacecraft	Discharge moments Spacecraft structural currents	Discharge models Coupling models
SC1-5	Internal loop antenna	Electromagnetic fields interior to spacecraft	Interior fields, structural currents	Same as SC1-4
SC1-7	RF analyzer	External EMI spectrum	EMI waveforms, discharge moments, structural currents	Discharge models Coupling model EMI model
SC1-8A	VLF narrowband analyzer			Not applicable for model validation
SC1-8B	Narrowband pulse analyzer with internal monopole antenna	Time domain waveforms detected by SC1-4,5 and internal monopole		Discharge models Coupling models EMI models

TABLE 5. - Continued.

EXPERIMENTAL	DESCRIPTION	MEASURED QUANTITIES	DERIVED QUANTITIES	VALIDATION USE
SC2 Sheath Electric Fields and Energetic Proton Detector				
SC2-1	Electrostatic analyzers (ESA)	Probe potential relative to S/C ground proton & electron energy spectra 1 eV - 20 KeV	Particle trajectories electron emission coefficients (correlate with SC-9)	NASCAP Materials properties Environmental atlas
SC2-2	Spherical probes 3 meters from spacecraft surface, commendable bias voltage			
SC2-3	Body mounted ESA and light sensor	Low energy proton & electron spectra (1 eV & 20 KeV)	Same as SC2-1,2	Same as SC2-1,2
SC2-3B	Ion background detector	Low energy low concentrations		Discharge model environmental atlas
SC2-6	Energetic proto telescope	Proton flux from 20-1000 KeV 20 Kev - 25 MeV		
SC3 High Energy Particle Spectrometer	Particle telescope with solid state radiation sensors	Electron spectra from 50 KeV to 10 MeV, proton spectra from 1 MeV to 100 MeV, alpha particle spectra from 6 MeV to 60 MeV	Absorbed dose as a function of shielding thickness	Environmental atlas

TABLE 5. - Continued.

EXPERIMENTAL	DESCRIPTION	MEASURED QUANTITIES	DERIVED QUANTITIES	VALIDATION USE
SC4 Particle Guns SC4-1	Electron emission gun 6 voltage steps from .05 to 3 Kv 6 current steps from .001 to 13 mA	Beam current, accelerating voltage	Beam particle trajectories, vehicle discharge rates spacecraft potentials	NASCAP discharge models Active potential control
SC4-2	Positive ion emitter can emit positive ions and/or electrons	Beam current, accelerating voltage	Same as SC4-1	Same as SC4-1
SC5 Rapid Scan Particle Detector	Electrostatic analyzers and solid state spectrometers. High time resolution capability	Differential energy analysis for electrons (50 eV to 1.2 MeV) and protons (50 eV to 35 MeV)	Sheath geometries particles trajectories spacecraft potential	Environmental atlas NASCAP
SC6 Thermal Electron Measurements	Body mounted and boom mounted gridded probes	Photoelectron, secondary electron and ion densities and energies from 1 to 100 eV	Emission rates	Materials data NASCAP Discharge model Environmental atlas
SC7 Light Ion Mass Spectrometer	Potential analyzer, mass spectrometer, and ion detector	Ion densities and species 1 - 100 eV		Environmental atlas Discharge model

TABLE 5. - Concluded.

EXPERIMENTAL	DESCRIPTION	MEASURED QUANTITIES	DERIVED QUANTITIES	VALIDATION USE
SC8 Lockheed Energetic Ion Spectrometer	Electrostatic analyzer and velocity filter	Ion energy spectra from 100 eV to 20 KeV		Environmental atlas
SC9 UCSD Particle Detectors	Electrostatic analyzers, electrostatic lens, and particle counter	Electron and proton fluxes from 1 eV to 80 KeV (63 energy groups)	Spacecraft potentials sheath geometries and particle trajectories	Environmental atlas NASCAP
SC10 Electric Field Detector	100 meter electric dipole	AC fields 3H$_z$ to 10 KH 1 - 100µV/M, DC fields from 0.1 to 20 mV/M	Spacecraft potential and near fields	NASCAP Discharge Coupling
SC11 Magnetic Field Monitor	3-axis magnetometer	Magnetic field density in the range ± 5 milligauss		Environmental atlas
ML12 Thermal Control & Contamination	Quartz crystal microbalance retarding potential analyzer thermal control coatings	Contamination mass flux temperature changes	Temperature dependence of contamination adsorption and desorption Ion gun return flux hemispherical absorptivity	Material damage NASCAP Discharge
Transient Pulse Monitor	Pulse detector and counter detector are low and high impedence cable bundle antennas, current probes on power reference ground and solar array input	Total transients, positive and negative peak amplitude, positive and negative pulse integrals	Cable bundle leak currents, internal fields, structural currents	Discharge models Coupling models EMI models

TABLE 6. - GROUND TESTS AND OTHER MODEL VALIDATION ACTIVITIES

MODELS	DESCRIPTION OF VALIDATION EFFORT	ORGANIZATION	COMMENTS
Sheath/ Charging	Exposure of material samples to monoenergetic electrons and monitoring surface potentials.	NASA LeRC	Good agreement with NASCAP for Teflon & Kapton; quartz and aluminum show disagreement.
	Analytical comparisons between Laframboise and NASCAP models for long cylinder.	York University, S^3	Scheduled to begin late CY1978.
	Experimental validation of calculations of pre-charging condition in planar Kapton sample.		Not yet awarded. Will be funded by Comsat Corp.
Discharge	Electron spraying of planar Teflon samples. Measuring discharge return current. Faraday cup measures effluent charge.	Colorado State University	Provides valuable scaling data & understanding of effluent. SEM photos indicate discharge paths.
	Electron spraying of planar mylar samples, measuring discharge return current.	University of Toronto	Provides area scaling data over several orders of magnitude. SEM photos of discharge tracks.
	Electromagnetic characterization of discharges in planar samples. Sprayed with electrons.	SRI International	Transient electromagnetic fields essential to coupling models.
	Electron spraying of planar Teflon samples, attempting to correlate electron beam voltage with discharge frequency, optical radiation amplitude, & radiated RF.	Communication Research Centre of Canada	Has seen discharges on floating samples.
	Dielectric breakdown studies of irradiated planar samples.	SRI International	Goal is to develop discharge-resistant materials.

TABLE 6. - Continued.

MODELS	DISCRIPTION OF VALIDATION EFFORT	ORGANIZATION	COMMENTS
Discharge (con't)	Electron spraying of planar Teflon samples, measuring discharge return current.	NASA LeRC	Capable of large (≈200 in^2) samples. Teflon tape used.
	Electron spraying of samples.	TRW	Provide scaling data.
	Electron spraying of samples.	Boeing	Also provide data for materials damage models.
	Conductivity measurements of irradiated planar samples. Characterization of secondary electrons and effluent.	IRT	Also provides data for use in charging models.
	Electron spraying of small & large planar samples, measuring return current and electromagnetic characteristics of discharge. Segmented backplate will localize discharge; uses rastered electron beam.	MRC	Also includes x-ray exposure to investigate SGEMP-charging synergisms. DNA program will start CY1978.
	Irradiation of planar samples & subsystem components with high and low energy electrons. Electromagnetic measurements & Faraday cup will characterize discharge phenomena. Attempt to measure punch thru current directly	JAYCOR	AFWL funding. Program will begin CY1978. Provides information for internal component discharge models.

TABLE 6. - Concluded.

MODELS	DESCRIPTION OF VALIDATION EFFORT	ORGANIZATION	COMMENTS
EMI/ Coupling	Capacitive and arc discharge drive of SCATHA scale model. Measures structural & cable currents. Comparisons made with SABER coupling code.	IRT	Defined EMI test procedures. Data will be used for SCATHA interpretation.
	Electron spraying of SKYNET satellite. Measured structural & power line currents induced by discharges.	MRC	Observed x-ray triggering of discharge.
	Voyager EMI tests.	TRW/JPL	Compared SEMCAP calculations with EMI measurements during arc discharges.
Material Damage	Electron spraying of small material samples & characterization of thermal property degradation.	GE	Also evaluating effectiveness of conductive coatings.