STATE OF UTAH SPACE ENVIRONMENT & CONTAMINATION STUDY (SUSpECS): A MISSE-6 PAYLOAD TO INVESTIGATE THEIR EFFECTS ON ELECTRON EMISSION AND RESISTIVITY OF SPACECRAFT MATERIALS

J.R. Dennison,[a] L. Pearson[b], L. Davis[b], J.W. Burns[b], R.S. Hyde[b], James S. Dyer[c], Tina Andrus[d], Andrew Auman[d], Jeff Duce[d], Tim Neilsen[d], Rob Leishman[d]

[a] Physics Department, Utah State University, SER 250 UMC 4415, Logan, UT, USA 84322-4415, Phone: 435.797.2936, Fax: 435.797.2492, JR.Dennison@usu.edu

[b] Health Management Focus Group, ATK Thiokol, P.O. Box 707, M/S 245C, Brigham City, UT, USA 84302-0707, Phone: 435.863.3562, Fax: 435.863.2443, Lee.Pearson@atk.com

[c] Contamination Control/Materials Chemistry Group, Space Dynamics Laboratory, 1695 North Research Park Way, North Logan, UT, USA 84341, Phone: 435.797.4386, Fax: 435.797.2492, Jim.Dyer@sdl.usu.edu

[d] Get-Away-Special Program, Physics Department, Utah State University, UMC 4415, Logan, UT, USA 84322-4415, Phone: 435.797.2857, Fax: 435.797.2492, Auman@cc.usu.edu

Abstract

A study of the effects of prolonged exposure to the space environment and of charge-enhanced contamination on the electron emission and resistivity of spacecraft materials, the *S*tate of *U*tah *Sp*ace *E*nvironment & *C*ontamination *S*tudy (***SUSpECS***), is planned for flight aboard the MISSE-6 payload. The *M*aterials *I*nternational *S*pace *S*tation *E*xperiment (***MISSE-6***) program is designed to characterize the performance of candidate new space materials over the course of ~9 months exposure periods on-orbit on the International Space Station, with a target flight date of mid-2006. Approximately 70 samples will be mounted on panels on both the ram and wake sides of the ISS. They have been carefully chosen to provide needed information for different ongoing studies and a broad cross-section of prototypical materials used on the exteriors of spacecrafts. Pre- and post-flight characterization measurements include optical and electron microscopy, reflection spectroscopy, resistivity and Auger electron spectroscopy. Studies of the service life of composite and ceramic materials of the ATK Thermal Protection Systems and Lightweight Structure Systems will evaluate chemical and mechanical properties as a function of depth from the AO and UV exposure surface. Most materials will be tested for resistivity and dielectric strength, and for electron-, ion-, and photon-induced electron emission yield curves and emission spectra. Electron emission and transport properties of materials are key in determining the likelihood of deleterious spacecraft charging effects and are essential parameters in modeling these effects with engineering tools like NASCAP-2K code. While preliminary ground-based studies have shown that contamination can lead to catastrophic charging effects under certain circumstances, little direct information is presently available on the effects of sample deterioration and contamination on emission properties for materials flown in space.

Project Description

A cooperative, Utah-based project named **SUSpECS (State of Utah Space Environment & Contamination Study**) is developing a flight experiment to study the effects of prolonged exposure to the space environment and of charge-enhanced contamination on spacecraft materials. Utah researchers from the Utah State University (USU) Materials Physics Group, the Space Dynamics Laboratory Contamination Control/Materials Chemistry Group, the Alliant Technosystems (ATK) Thiokol Health Management Focus Group, and the USU Get-Away-Special (GAS) Program are preparing a sample tray for flight on the **MISSE-6** (**M**aterials **I**nternational **S**pace **S**tation **E**xperiment) mission sponsored by Air Force Office of Scientific Research (AFOSR). The MISSE program objective is to "characterize the performance of new perspective spacecraft materials when subjected to the synergistic effects of the space environment."[1] The **SUSpECS** sample panel includes pertinent materials and coatings selected and characterized by each group member for a comprehensive study of the effects of the LEO space environment and contamination on electrical, mechanical and optical properties of materials related to several on-going projects of high relevance to manned space exploration and other long duration space missions.

Sample material selections and conceptual design of the **SUSpECS** sample panels have already been completed. The panels' design, fabrication and testing will be completed during Summer 2005, led by student researchers from the USU GAS program. The **SUSpECS** sample panels will be delivered to Boeing in Fall 2005 for integration with the panels contributed by other industry, university, and government investigators. The sample panels will be installed into two standard MISSE "suitcase" pallets that are powered and instrumented to record relevant space environmental parameters during the on-orbit ram and wake exposure. The integrated payload will be delivered to NASA Langley Research Center by December 2005. The Shuttle flight to transport MISSE-6 to the ISS is now scheduled for early to mid-2006, with return after ~9 months exposure in the LEO environment. After retrieval, sample panels will be returned for post-flight analyses.

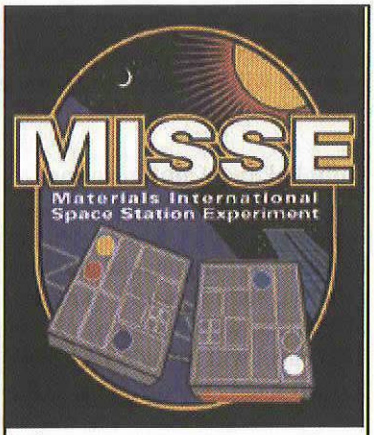

Figure 1. **The MISSE (Materials International Space Station Experiment) program is sponsored by the Air Force Office of Scientific Research (AFOSR). [Ref. 1]**

The overall project has four key objectives: (i) basic research will extend our understanding of the materials/space environment interactions, (ii) specific knowledge will be gained for critical materials in several on-going projects of the team members, (iii) valuable collaborations between team members will be fostered, and (iv) analysis capabilities and flight experience will be developed that will prove useful not only for follow-up for post-flight analysis of the **SUSpECS** sample set, but for other joint ventures involving reliability and aging of materials in the space environment.

Electrical Properties of Spacecraft Materials

A primary focus of **SUSpECS** is the study the effects of contamination on the accumulation, re-emission, and dissipation of charge from spacecraft surfaces and on the resulting changes in electron emission and resistivity of spacecraft materials. This project also investigates on the effects of charging on contamination rates. Synergistic phenomena in the space environment (e.g., charging, contamination, UV exposure, atomic oxygen) can cause dramatic changes in material surface properties and performance.[2] Thin contaminant layers readily change the optical[3] and electronic properties[4,5] of surfaces, and often result in long-term degradation of the optical, thermal control, or electronic performance of space based sensors and components. For example, plasma diagnostic instrumentation (such as Langmuir and plasma impedance probes) requires stable surface conductivity and charging properties, which is altered by contamination.[6] Further, at geosynchronous orbits, high spacecraft charging potentials (typically tens of kilovolts) and long Debye lengths can actually accelerate surface contamination rates by electrostatic re-attraction of ionized outgassed or vented molecules to the negatively charged satellite.[7] The accelerated contamination rates can affect the long-term performance of optical, thermal control, or solar panel surfaces. Also, at all altitudes, the performance of new high efficiency multijunction solar cells is more susceptible to current loss caused by contamination than conventional single junction cells.[8]

The electron emission and transport properties of materials are key parameters in determining the likelihood of deleterious spacecraft charging effects [9,10,11,12] and are essential in modeling these effects with engineering tools such as the NASA NASCAP-2K code.[13,14] The **SUSpECS** studies of electron emission and resistivity will extend more than a decade of research in the field by the USU Materials Physics Group.[4,5,6,12,15,16,17,18,19,20,21,22] Preliminary ground-based studies have shown that contamination can lead to catastrophic charging effects under certain circumstances.[4] However, little direct information is available on the effects of sample deterioration and contamination on the electron emission and resistivity of materials flown in space.

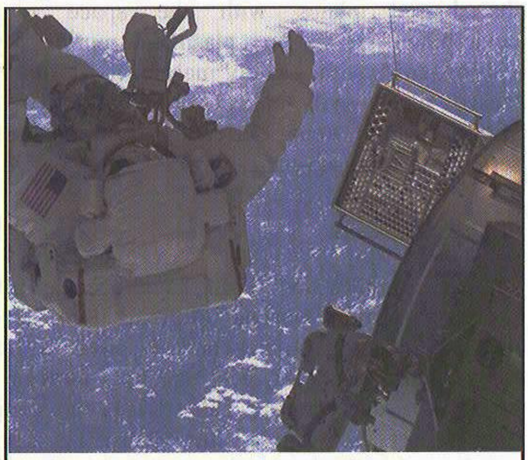

Figure 2. **Astronaut deploying MISSE-2 on the International Space Station. [Ref. 1]**

Recent work[18,23] has found that dissipation of charge accumulated on thin film insulating spacecraft surfaces during on-orbit conditions is substantially slower than predicted using resistivity values acquired by standard ASTM methods.[24] Under many typical conditions this can result in charge dissipation on the order of days to months rather than minutes to hours.[16] More appropriate methods to measure charge storage decay have been developed. An apparatus to measure the decay rate of charge deposited on the surface of thin film insulators has been designed and built at USU in conjunction with an on-going NASA research project with JPL.[20] Comparison of pre- and post-flight analysis of SUSpECS samples using these methods will provide a better understanding of modifications to these long decay times as a result of space exposure and contamination.

Sample Panel Configuration

The SUSpECS study will expose two test panels of materials to the Low Earth Orbit (LEO) environment for ~ 9 months. Environmental monitoring on board the MISSE-6 suitcases will include temperature plus atomic oxygen, electron, and ultraviolet exposure as a function of time. One SUSpECS sample panel will be mounted on the ram side of the ISS, with enhanced exposure to atomic oxygen. These experiments are all passive LEO exposure experiments. This panel will include 17 1.3 cm diameter conducting and insulating test samples held at ground potential, as shown in the left hand side of Figure 3(a). The specific samples are identified in Table I. Additional samples may be added if more panel space becomes available (see Table I).

The ram-side sample panel also includes a sub-panel of composite material components for tests of mechanical and chemical modifications, as shown on the right hand side of Figure 3(a). These ATK Thiokol experiments will test the space exposure of eight circular shaped specimens of materials, each of 1.3 cm diameters. For each of eight ATK materials (see Table I), three stacked sample layers will be exposed to AO+UV, AO alone, and no AO or UV. The outermost layer will experience the fullest exposure to all of the variables of LEO environment, most importantly atomic oxygen and ultraviolet radiation. The lower layers, being shielded by the outermost layer, will not have exposure to ultraviolet radiation. Due to a gap between the second and third layers in the stacked configuration, the second and third layers will have exposure to atomic oxygen. All these materials will be tightly seated in a metal tray. This sample geometry is designed such that the sides of each layer will be masked allowing only front face exposure and forcing any diffusion into a one-dimensional regime. This will permit one-dimensional depth profiling of the materials to evaluate the effects of environmental exposure.

The second SUSpECS sample panel will be mounted on the wake side of the ISS, with less exposure to atomic oxygen. The experiments are both passive and active LEO exposure experiments. This panel will include 13 1.3 cm diameter test samples held at ground, as shown in the right hand side of Figure 3(b). The specific samples are identified in Table I. Additional samples may be added if more panel space becomes available (see Table I). There will also be three separate test sub-panels of ~13 cm^2, each with four conducting samples (Au, Al, Dupont Black Kapton, and Sheldahl Thick Film Black) mounted, as shown at left in Figure 3(b). The three sub-panels will be held at + 5 VDC, -5 VDC and –100 VDC, respectively. Voltages for the ±5 VDC sub-panels are provided by the ISS through the MISSE-6 bus. The –100 VDC bias is provided by a standard DC-DC converter. Current is drawn from interaction of the biased plates with the space plasma environment. Based on a plasma current density of ~10 nA-cm^{-2}, with a safety margin of 10, the three biased plates will collectively draw <10 μA. Diodes to limit arcing currents will be mounted in series with each sub-panel.

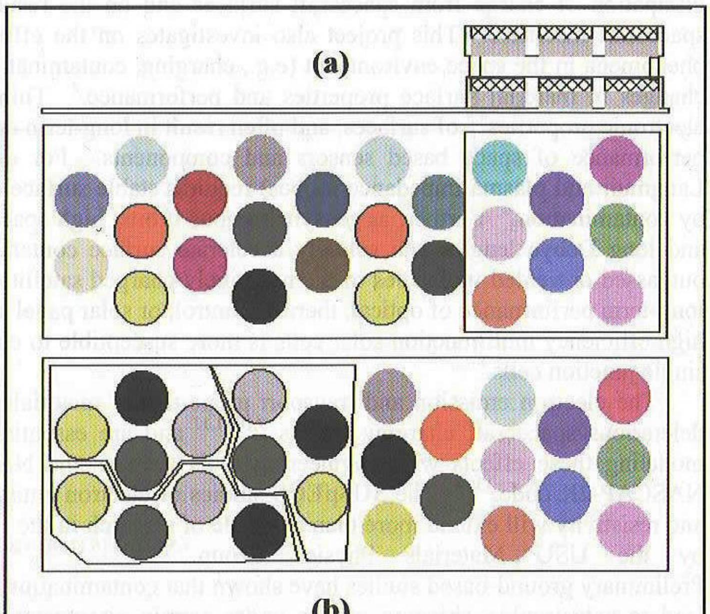

Figure 3. Configuration of two 15 cm x 30 cm, 78 cm^2 SUSpECS sample panels to be mounted on MISSE-6. **(a)** Ram side sample panel. Seventeen USU and SDL samples at left are passive experiments held at ground potential. There are eight ATK sample in each of three tiers on the right hand side of the ram panel. **(b)** Wake side sample panel. Thirteen USU and SDL samples at right are passive experiments held at ground potential. The three sub-panels at left each contain four identical samples held at + 5 VDC, -5 VDC and –100 VDC, respectively.

Sample Selection

The samples for flight have been carefully chosen to provide needed information for several different ongoing studies and to cover a broad cross-section of prototypical materials used on the exteriors of spacecrafts. Table I lists the samples selected for inclusion on the SUSpECS sample panels, and indicates which samples are relevant to the various studies outlined below.

1. The majority of the test samples have already undergone pre-flight analysis during an ongoing seven year study of the electron emission [12,15,17,21,22] and resistivity properties[12,16,18,20,25] of spacecraft materials sponsored by the NASA Space Environments and Effects Program. Preliminary ground-based studies at USU have shown that contamination can produce dramatic changes in electron emission that can lead to catastrophic charging effects under certain circumstances.[4] A preliminary study of the effects of contamination of resistivity is underway at USU. Comparison with post-flight analysis will provide the first extensive tests of space environment exposure and contamination on electron emission properties and resistivity measured with the charge storage method.
2. Several types of samples were flown aboard the CRESS satellite,[25] as part of a study of spacecraft charging induced arcing.[26] The samples have recently been subjected to detailed resistivty tests using the charge storage method[19] and very successful modeling of their pulsing history during the CRESS flight;[16,27] the MISSE-6 tests will be valuable in trying to model the effects of prolonged space exposure during the CRESS flight.
3. A study of the electron emission and resistivity properties of a set of materials used to construct the ISS has been performed. This includes both basic materials,[12] and a study of two RTV materials thought to be key contaminants of the ISS solar arrays.[22] Comparison of analysis of these MISSE-6 samples with pre-flight testing will provide valuable information for modeling the ISS spacecraft charging as the station ages.
4. A study of the electron emission and resistivity properties of a set of materials that were used to construct the Floating Potential Measurement Unit (FPMU) is currently underway. The FPMU is an instrument designed and built at SDL for use on the ISS[28,29] intended to study a critical spacecraft charging problem on the ISS[30,31,32,33] through plasma measurements. The sample set includes both basic materials used to construct the FPMU and two RTV materials thought to be potential key contaminants of the FPMU.[12,6] The electron emission properties and resistivity of the materials, and how these properties change with exposure to the space environment and the accumulation of contamination, are critical to the precise determination of the surface potentials. Comparison of analysis of these MISSE-6 samples with pre-flight testing will provide valuable information for modeling the FPMU electron emission and the instrument effectiveness in monitoring the ISS potential as the station ages.

Table I. SUSpECTS Samples

USU Electron Emission/Resistivity Samples

Au [R,WB], Al [R,WB]
316 SS [R,W*], Au/Ni on Cu [R,W*]
Dupont Black Kapton [R,WB]
Sheldahl Thick Film Black [R,WBI, Aquadag [R,W*]
PI-Kapton [R,W], PET-Mylar [R,W], PTFE-Teflon [R,W]
FR4 [R,W], DC93-900 RTV on Cu [R,W]
CeO_2-doped glass solar cell cover slips [R,W]
Al_2O_3-Alumina [R,W]

Anodized Al (Cr) [R*,W], Anodized Al (S) [R*,W]
Cu [R*,W*], Graphitic amorphous carbon [R*,W*]
Nylon [R*,W*], Kevlar [R*,W*1
ITO on Kapton [R*,W*], SiO_2 [R*,W*]
UV-coated CeO_2-doped solar cell cover slips [R*,W*]
CV-1147 RTV on Cu [R*,W*]

Charge-enhanced Contamination Samples

Au [R,WB], Al [R,WB], Dupont Black Kapton [R,WB]
Sheldahl Thick Film Black [R,WB]

CRRES Samples

PI-Kapton [R,W], PET-Mylar [RW], PTFE-Teflon [R,W]
FR4 [R,W], Al_2O_3-Alumina [R,W], SiO_2 [R*,W*]

ISS Sample

Au [R,WB], Al [R,WB], 316 SS [R,W*]
Dupont Black Kapton [R,WB], PI-Kapton [R,W]
DC93-900 RTV on Cu [R,Wl, Al_2O_3-Alumina [R,W]
CeO_2-doped glass solar cell cover slips [R,W]
Anodized Al (Cr), [R*,W], Anodized Al (S), [R*,W]

UV-coated CeO_2-doped solar cell cover slips [R*,W*]
CV-1147 RTV on Cu [R*,W*1

FPMU Samples

Au [R,WB], 316 SS [R,W*], Au/Ni on Al [R,W*]
Aquadag [R,W*], DC93-900 RTV on Cu [R,W]

Rh [R*,W*], CV-1147 RTV on Cu [R*,W*], Si02 [R*,W*]

SDL Optics Applications Samples

Pilkington CMG CeO2-doped glass solar cell cover slips [R,W]
White inorganic coating for GIFTS composites [R,W*]
Black polymeric coating for GIFTS composites [R,W*]
MgF_2-coated polished aluminum reflectors for sun-facing SOFIE optics [R,W*]

Aluminum with anodize or chromate conversion coating (iridite or alodine) [R*,W*]

ATK Thiokol Samples

Kevlar or graphite fiber-filled composite material [Rx3]
Neat epoxy resin of above composite [Rx3]
Carbon-carbon resin impregnated graphite composite [Rx3]
Neat epoxy resin of above composite [Rx3]
Carbon-phenolic [Rx3]
Oxide ceramic matrix composite [Rx3]
Polymer-dervied non-oxide ceramic matrix composite [Rx3]
Anodized aluminum [Rx3]

Legend	R-Ram panel	W-Wake panel
*Optional sample	B-4 Biased voltages	x3-3 Tier

5. Tests will be performed to study aging and degradation phenomenology of critical thermal control and optical materials currently in use or under development for SDL payloads. These include the inorganic white and black polymeric coatings developed for GIFTS composites and the MgF_2 reflective coatings used on sun-facing SOFIE optics and polished aluminum used for UV. Substrate materials of interest include Pilkington CMG CeO_2–doped glass solar cell cover slips used to protect solar cells and solar reflectors from radiation-induced degradation; aluminum with anodize or chromate conversion standard protective coatings (iridite or alodine) routinely used to stabilize aluminum surfaces and inhibit corrosion on spacecraft structures and electronic subassemblies such as housings, antennas, plasma impedance probes; and Protected Denton Silver, (FSS99 or X-1 coatings), typically used on infrared and uv-visible optics.
6. For the past half century, a perennial problem in the solid rocket industry has been the accurate assessment of cumulative damage in motor components. Solid rocket motor materials are highly complex, and they are exposed to a variety of harsh loading environments. These two facts make the prediction of a motor's structural integrity much too uncertain, and that occasionally leads to serious consequences.

   The Health Management Focus Group (HMFG) of ATK Thiokol, as the title of the group indicates, "manages" the "health" of ATK materials and products for any time period in any environment. This material characterization as a function of time and/or environment is accomplished using the proven ATK HMFG microspecimen technology tools for chemical and mechanical property analysis. ATK Thiokol has worked on a series of programs during the past few years that dramatically improved our ability to assess the effects of aging based on fundamental science rather than the empirical approaches that have dominated the past. Significant progress has been made in the union of high fidelity data sources and high fidelity structural, damage, and failure models. The results of SUSpECS will provide much needed input data for these models as the ATK HMFG assesses the effects of exposure to the environment of LEO on these materials.

   Composite and ceramic materials of the ATK Thermal Protection Systems (TPS) and the ATK Lightweight Structure Systems (LSS) are used on LEO bound and beyond ATK assets. These include materials for an ATK Thiokol project on snap-together structural components and solid rocket motor materials. A set of these composite materials will be evaluated for deleterious effects of AO, UV and other space environment exposure. Some ATK composite rocket motor cases include epoxy resin. Two of these epoxy resin types will be included in this LEO exposure experiment. Composite materials to be tested include a Kevlar or graphite fiber-filled composite, a carbon-carbon resin-impregnated graphite composite, a carbon-phenolic composite, and an anodized aluminum metal-coated composite. The proprietary ATK COI ceramic matrix composite (CMC) materials will be tested in an oxide form and a polymer derived non-oxide form.

Materials Testing

Comparison of post-flight analysis of these MISSE-6 samples with pre-flight testing will be valuable in trying to identify and model materials degradation and aging and the effects of prolonged space exposure on the samples. All samples will undergo an extensive series of pre-flight and post-flight tests to characterize the materials including surface morphology tests [optical microscopy, scanning electron microscopy (SEM), scanning tunneling microscopy (STM)], chemical compositions tests, [standard suite of chemical analysis tests such as HPLC, Auger Electron Spectroscopy (AES), Secondary Ionization Mass Spectroscopy (SIMS) and X-Ray Photoelectron Spectroscopy (XPS)], optical tests (IR-VIS-UV attenuated total (ATR), specular and/or diffuse reflection spectroscopy), thermal tests (thermal expansion, thermal emissivity and absorptivity), and outgassing. Outgassing tests and some optical and morphology tests will be performed at SDL; other characterization will be done at Thiokol.

The electron emission properties and resistivity of most USU/SDL materials will be tested. Specifically, the materials will be tested for resistivity and dielectric strength, and for electron-, ion- and photon-induced electron emission yield curves and emission spectra. Details of the testing procedures are described in Ref. 12. Much of the pre-flight testing has already been done in conjunction with previous studies.

Studies of the service life of composite and ceramic materials of the ATK Thermal Protection Systems and Lightweight Structure Systems will evaluate chemical and mechanical properties of the ATK MISSE samples. Triplicate samples will be evaluated for each material: one for zero-time properties, one for ground-based aged properties, and one for space exposure. Thiokol samples will be subjected to mechanical tests, including a destructive mechanical tests and ultrasonic measurements. In addition, a series of microtome slices of the pertinent composite samples will be made to evaluate chemical and mechanical properties as a function of depth from the AO and UV exposure surface. Chemical analysis, including ATR and/or diffusive reflection spectroscopy, Auger, SIMS, XPS spectroscopies, and standard chemical suite of tests as applicable will also be performed on all microtome samples.

Acknowledgements

We gratefully acknowledge the Air Force Office of Scientific Research (AFOSR) that sponsors the MISSE program and NASA that provides transportation to and from the ISS aboard the Space Shuttle. Gary Pippin and the team at Boeing have provided invaluable support for the project and will work with the NASA Langley Research Center to integrate the SUSpECS sample panels into the MISSE-6 Passive Experiment Containers (PECs) for transport to the ISS. Support for the design, assembly and test of the SUSpECS sample panels has been provided by the USU Space Dynamics Laboratory Enabling Technologies Program, ATK Thiokol Internal Research and Development funds, the USU Research Office and the NASA Rocky Mountain Space Grant Consortium. We also have profited from useful discussion with M.R. Carruth, Jr. and T. Schneider at NASA Marshal Space Flight Center and John Alred at Boeing about ISS materials; Charles Swenson in the Electrical and Computer Engineering Department at USU about FPMU materials; and A. Robb Frederickson and Nelson W. Green at the Jet Propulsion Laboratory about CRRES materials.

References

[1] "Material International Space Station Experiment (MISSE)," http://missel.larc.nasa.gov/ ,March 24, 2005.

[2] D.C. Marvin, T.B. Stewart, G.S. Arnold, D.F. Hall, R.C. Young Owl, W.C. Hwang, and H.D. Marten, , "Photochemical Spacecraft Self-Contamination: Laboratory Results and Systems Impacts," *J. Spacecraft and Rockets,* Vol. 26, p. 358-367 (1989).

[3] B. E. Wood, W. T. Bertrand, R. J. Bryson, B. L. Seiber, P. M. Balco, and R. A. Cull, "Surface Effects of Satellite Material Outgassing Products," *Journal of Thermophysics and Heat Transfer*, **2** (4), pp. 289-295, 1988.

[4] R.E. Davies and J.R. Dennison, "Evolution of Secondary Electron Emission Characteristics of Spacecraft Surfaces," *J. Spacecraft and Rockets*, **34**, 571-574 (1997).

[5] W.Y. Chang, J.R. Dennison, Jason Kite and R.E. Davies, "Effects of Evolving Surface Contamination on Spacecraft Charging," *Proceedings of the 38th American Institute of Aeronautics and Astronomics Meeting on Aerospace Sciences*, (Reno, NV, 2000).

[6] L. Gamble, J. R. Dennison, B. Wood, J. Herrick, and J. S. Dyer; "Calculation of Spectral Degradation due to Contaminant Films on Infrared and Optical Sensors," *Proc. SPIE—The International Society of Optical Engineering*, Vol. 4774, p. 111-118, Optical System Contamination: Effects, Measurements, and Control VII, Philip T. Chen; O. Manuel Uy; Eds. (2002).

[7] P.D. Thomas, Michael C. Fong, and K.L. Neir, "Return Flux of Neutral and Charged Particles in Geosynchronous Orbit", *Proc. SPIE—The International Society of Optical Engineering*, Vol. 3427, p. 290-301, Optical System Contamination: Effects, Measurements, and Control, Philip T. Chen; William E. McClintock, Gary J. Rottman; Eds. (1998).

[8] D.F. Hall and D.C. Marvin, "Effects of Molecular Contamination on Triple Junction Solar Cells," *Proc. SPIE—The International Society of Optical Engineering*, Vol. 4774, p. 129-134, Optical System Contamination: Effects, Measurements, and Control VII, Philip T. Chen; O. Manuel Uy; Eds. (2002).

[9] D. Hastings, and H. Garrett, Spacecraft-environment Interactions, Cambridge University Press, 1996.

[10] K.L. Bedingfield, R.D. Leach and M.B. Alexander,: "Spacecraft System Failures and Anomalies Attributed to the Natural Space Environment." NASA Reference Publication 1390, NASA MSFC, 1996.

[11] R.D. Leach, and M.B. Alexander: "Failures and Anomalies Attributed to Spacecraft Charging," NASA Reference Publication 1354, NASA Marshall Space Flight Center, November 1994.

[12] J.R. Dennison, C.D. Thomson, J. Kite, V. Zavyalov and, Jodie Corbridge, "Materials Characterization at Utah State University: Facilities and Knowledgebase of Electronic Properties of Materials Applicable to Spacecraft Charging," *Proceedings of the 8th Spacecraft Charging Technology Conference,* (NASA Marshall Space Flight Center, Huntsville, Al, October 2003).

[13] M.J. Mandell, P.R. Stannard and I. Katz, "NASCAP Programmer's Reference Manual," NASA LRC, 1993.

[14] Myron Mandell, "NASCAP-2K – An Overview"," *Proceedings of the 8th Spacecraft Charging Technology Conference,* (NASA Marshall Space Flight Center, Huntsville, Al, October 2003).

[15] JR Dennison, W.-Y. Chang, Neal Nickles, Jason Kite, C.D. Thomson, Jodie Corbridge and Carl Ellsworth, *Final Report Part III: Materials Reports*, NASA Space Environments and Effects Program Grant, "Electronic Properties of Materials with Application to Spacecraft Charging," September 2002. Published by NASA electronically at http://see.msfc.nasa.gov/scck/ , the work is comprised of 16 individual *Materials Reports*.

[16] J.R. Dennison, A.R. Frederickson and Prasanna Swaminathan, "Charge Storage, Conductivity and Charge Profiles of Insulators As Related to Spacecraft Charging," *Proceedings of the 8th Spacecraft Charging Technology Conference,* (NASA Marshall Space Flight Center, Huntsville, Al, October 2003).

[17] JR Dennison, C. D. Thomson, and Alec Sim, "The effect of low energy electron and UV/VIS radiation aging on the electron emission properties and breakdown of thin-film dielectrics," *Proceedings of the 8th IEEE Dielectrics and*

Electrical Insulation Society (DEIS) International Conference on Solid Dielectrics (ICSD), 967-971, (IEEE, Piscataway, NJ, 2004.

[18] A.R. Frederickson and J.R. Dennison, "Measurement of Conductivity and Charge Storage in Insulators Related to Spacecraft Charging," *IEEE Transaction on Nuclear Science*, **50**(6), 2284-2291 (December 2003).

[19] Nelson W. Green, A. Robb Frederickson and J.R. Dennison, "Charge Storage Measurements of Resistivity for Dielectric Samples from the CRRES Internal Discharge Monitor," *Proceedings of the 9th Spacecraft Charging Technology Conference,* (EPOCHAL TSUKUBA, TSUKUBA, April 4-8, 2005).

[20] Prasanna Swaminathan, A.R. Frederickson, J.R. Dennison, Alec Sim, Jerilyn Brunson and Eric Crapo, "Comparison of Classical and Charge Storage Methods for Determining Conductivity of Thin Film Insulators," *Proceedings of the 8th Spacecraft Charging Technology Conference,* (NASA Marshall Space Flight Center, Huntsville, Al, October 2003).

[21] C.D. Thomson, V. Zavyalov, and J.R. Dennison, "Instrumentation for Studies of Electron Emission and Charging from Insulators," *Proceedings of the 8th Spacecraft Charging Technology Conference,* (NASA Marshall Space Flight Center, Huntsville, Al, October 2003).

[22] C.D. Thomson, V. Zavyalov, J.R. Dennison and Jodie Corbridge, "Electron Emission Properties of Insulator Materials Pertinent to the International Space Station," *Proceedings of the 8th Spacecraft Charging Technology Conference,* (NASA Marshall Space Flight Center, Huntsville, Al, October 2003).

[23] A.R. Frederickson, C. E. Benson and J. F. Bockman, "Measurement of Charge Storage and Leakage in Polyimides," Nuclear Instruments and Methods in Physics Research B, 454-60, 2003.

[24] ASTM D 257-99, "Standard Test Methods for DC Resistance or Conductance of Insulating Materials," (1999).

[25] E. Mullen and M. Gussenhoven, "Results of Space Experiments: CRRES," in R.N. DeWitt, D. Duston, and A.K. Hyder (eds.) The Behavior of Systems in the Space Environment, pp. 605-654, (Kluwer Academic Publishers, 1993).

[26] A.R. Frederickson, E.G. Mullen, K.J. Kerns and P.A. Robinson, "The CRRES IDM Spacecraft Experiment for Insulator Discharge Pulses," IEEE Trans. Nuc. Phys. 40(2), 233-241 (1993).

[27] A. Robb Frederickson and Donald H. Brautigam, "Mining CRRES IDM Pulse Data and CRRES Environmental Data to Improve Spacecraft Charging/Discharging Models and Guidelines," Final Report: NASA SEE Program Contract No. NAS7-1407, Task Order 10676, 2003(b); to be published.

[28] Charles M, Swenson, Barjatya, A., Thompson, D., Fish, C, "Calibrating the Floating Potential Measurement Unit," *Proceedings of the 8th Spacecraft Charging Technology Conference,* (NASA Marshall Space Flight Center, Huntsville, Al, October 2003).

[29] C. Swenson, D. Thompson , C. Fish, *The Floating Potential Measurement Unit,* number AIAA-2003-1081 in 41st aerospace Sciences Meeting and Exhibit, January 2003.

[30] Dale C. Ferguson, David B. Snyder, Ralph Carruth, Report of the Joint Workshop of the Space Station Freedom Plasma Interactions and Effects Working Group, the Space Station Freedom Plasma Working Group, and the Space Station Freedom EMI/EMC and Electromagnetic Effects Working Group, 1990.

[31] Steve Koontz, Marybeth Edeen, William Spetch, Thomas Keeping, Penni Dalton, *Assessment and Control of Spacecraft Charging Risks on the International Space Station, Proceedings of the 8th Spacecraft Charging Technology Conference,* (NASA Marshall Space Flight Center, Huntsville, Al, October 2003).

[32] M.R. Carruth Jr., T. Schneider, M. McCollum, M. Finckenor, R. Suggs, D. Ferguson, I. Katz, R. Mikatarian, J. Alred, and C. Pankop, "ISS and space environment interactions without operating plasma contactor," AIAA Paper #2001-0401, Proc. of the 39th AIAA Aerospace Sci. Meeting, Reno, Nevada, Jan. 8-11, 2001.

[33] M.R. Carruth, Todd Schneider, Matt McCollum, Miria Finckenor, Rob Suggs, Dale Ferguson, Ira Katz, R. Mikatarian, John Alred, H. Barsamian, J. Kern, S. Koontz , and J.F. Roussel, *Plasma Charging of the International Space Station.* IAS paper IAC-02-T.2.05, 2002.