Comparison of Flight and Ground Tests of Environmental Degradation of MISSE-6 SUSpECS Materials

JR Dennison  
*Utah State University*

John Prebola

Amberly Evans

Danielle Fullmer

Joshua L. Hodges

Dustin H. Crider

*See next page for additional authors*

Follow this and additional works at: [http://digitalcommons.usu.edu/mp_conf](http://digitalcommons.usu.edu/mp_conf)

Part of the [Condensed Matter Physics Commons](http://digitalcommons.usu.edu/mp_conf)

Recommended Citation

Comparison of Flight and Ground Tests of Environmental Degradation of MISSE-6 SUSpECS Materials

JR Dennison, John L. Prebola Jr., Amberly Evans, Danielle Fullmer, Joshua L. Hodges, Dustin H. Crider and Daniel S. Crews

Abstract—The effects of prolonged exposure to the LEO space environment and charge-enhanced contamination on optical, thermal, and electron emission and transport properties of common spacecraft materials have been investigated by comparing pre- and post-flight characterization measurements. The State of Utah Space Environment and Contamination Study (SUSpECS) deployed in March 2008 on board the Materials International Space Station Experiment (MISSE-6) payload, was exposed for ~18 months on the exterior of the International Space Station (ISS), and was retrieved in September 2009. A total of 165 samples were mounted on three separate SUSpECS panels on the ram and wake sides on the ISS. Tests on a subset of the SUSpECS samples were conducted at the Arnold Engineering Development Center to simulate the effects of the LEO environment exposure.

I. INTRODUCTION

A cooperative, Utah-based project named SUSpECS (State of Utah Space Environment and Contamination Study) was developed as a flight experiment to study the effects of prolonged exposure to the space environment and charge-enhanced contamination on spacecraft materials. Utah researchers from the Utah State University (USU) Materials Physics Group, the USU Space Dynamics Laboratory (SDL) Contamination Control/Materials Chemistry Group, the ATK Space Systems Health Management Focus Group, and the USU Get-Away Special (GAS) Team built sample trays for flight on the MISSE-6 (Materials International Space Station Experiment) mission sponsored by Air Force Office of Scientific Research (AFOSR). The MISSE program objective is to “characterize the performance of new prospective spacecraft materials when subjected to the synergistic effects of the space environment” [1]. The SUSpECS sample panels include pertinent materials and coatings selected and characterized by each group member for a comprehensive study of the effects of the low Earth orbit (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 [2].

Sample material selections, conceptual design of the SUSpECS sample panels, and construction of the panels were completed during 2005, led by student researchers from the USU GAS Team. Design of the sample panels are described below, including a three tiered configuration intended to provide variable atomic oxygen and ultraviolet radiation exposure. The SUSpECS sample panels were delivered to Boeing in spring 2006 for integration with the panels contributed by other industry, university, and government investigators. The sample panels were installed into two standard MISSE “suitcase” pallets that were powered and instrumented to record relevant space environmental parameters during the on-orbit exposure. The integrated payload was delivered to NASA Langley Research Center in summer 2006. The Shuttle flight STS-123 (Fig. 1(a)) transported MISSE-6 to the ISS and deployed it on the ISS “back porch” in March 2008 (Fig. 1(b)). MISSE-6 was returned to Earth in September 2009 and the SUSpECS sample trays were de-integrated from the MISSE PECs at NASA Langley Research Center in November 2009 (Fig. 1(c)).

II. SUSpECS SAMPLE SETS

A. Sample Selection for Materials Studies

The samples for flight were 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.

Results reported here focus on the comparison of two specific sets of materials samples. The first comparison focuses on six sets of four identical samples [Au, Al, carbon-loaded polyimide (Dupont Black Kapton™ 100XC), and carbon-loaded polyester (Sheldahl Thick Film Black)]. Two sample sets were located on the top and bottom tiers of a three-tiered sample panel designed to provide variable atomic oxygen and UV exposure. The four other sample sets were located on the wake side sample panel, with three of the sets at constant bias for the duration of the flight. The biased sample configuration was designed to approximate typical conditions of materials subject to charge-enhanced contamination due to spacecraft charging by actively biasing samples to low positive and negative voltages. Positively charged components will typically charge to only a few volts positive. By contrast, negatively charged materials can charge to large voltages. Biases of -5 V and -15 V were chosen as representative of modest and more extreme negative charging.

The second comparison reported here focused on four materials [carbon-loaded polyimide, aluminized polyester (Dupont Mylar™), Al₂O₃ (sapphire), and SiO₂ (quartz)] that showed varying degrees of environmentally–induced changes in optical properties. Samples of each material on the wake and three-tiered sample panels were exposed to a complex environment during the flight. Identical witness samples were also exposed to a simulated subset of the environment in the Characterization of Combined Orbital Surface Effects (CCOSE) space environment test chamber at the USAF Arnold Engineering Development Center (AEDC) to mimic the space exposure profile. The primary optical characterization methods employed for the comparison were UV/VIS/NIR and FTIR transmission of the sapphire and quartz and UV/VIS/NIR reflectance of the polyimide and polyester. Comparison of pre-flight, post-flight, and simulated exposure samples served two primary purposes: (i) to investigate the validity of simulated environmental testing methods and (ii) to help distinguish the effects of specific components of the complex space environment that samples were simultaneously exposed to during the flight.

Four additional SUSpECS test programs with direct relevance to spacecraft charging issues are briefly outlined below. These are studies of electron emission and resistivity of typical spacecraft materials, CRRES materials charging and contamination, ISS materials charging and contamination, and the effects of contamination on FPMU materials.

Electron-, ion-, and photon-induced electron emission yield curves, crossover energies and emission spectra, resistivity, dielectric strength, optical and electron microscopy, UV/VIS/NIR reflection spectroscopy, and emissivity were tested for pre-flight SUSpECS samples in their pristine conditions. The majority of the test samples have already undergone pre-flight analysis during an ongoing seven year study of the electron emission [3-8] and resistivity properties [4], [9-11] 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 severe charging effects under certain circumstances [12,13]. A preliminary study of the effects of contamination on resistivity using the charge storage method 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.
Several types of samples were flown aboard the CRRES satellite [14] as part of a study of spacecraft charging induced arcing [15]. The samples were the subject of detailed resistivity tests using the charge storage method [16] and very successful modeling of their pulsed history during the CRRES flight [9,17]. The MISSE-6 tests will be valuable in trying to model the effects of prolonged space exposure during the CRRES flight. Relevant samples include Kapton (PI), Teflon (PTFE), Mylar (PET), FR4 PC board (PI composite) material, Alumina (Al₂O₃), and Silicon Dioxide (SiO₂).

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 [Au, Al, 316 SS, Anodized Al (Chromic acid etch), Anodized Al (Sulfuric acid etch), Kapton, Dupont Black Kapton, and UV AR-coated Ce-doped cover glass] and a study of two RTV materials (DC93-500 and CV-1147) thought to be key contaminants of the ISS solar arrays [8]. 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.

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 [18], [19] used to monitor spacecraft charging on the ISS [20-23] through plasma measurements. The sample set includes both basic materials used to construct the FPMU [Au, 316 SS, Aquadag] and two RTV materials (DC93-500 and CV-1147) thought to be potential key contaminants of the FPMU [4], [24]. 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.

Additional studies of critical thermal control and optical coating materials for the USU SDL Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) composites, mechanical and thermal properties of ATK Thermal Protection Systems and Lightweight Structure Systems materials, and NASA Solar Probe Mission composite and heat shield materials have been described elsewhere [2].

### Table I. SUSpECS samples.

<table>
<thead>
<tr>
<th>Material</th>
<th>Space</th>
<th>J Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kapton (PI) on Aluminum</td>
<td>Shielded</td>
<td>4</td>
</tr>
<tr>
<td>Teflon (PTFE) on Aluminum</td>
<td>Shielded</td>
<td>3</td>
</tr>
<tr>
<td>Mylar (PET) on Aluminum</td>
<td>Shielded</td>
<td>3</td>
</tr>
<tr>
<td>Mylar (PET) on Nitrogen Mask</td>
<td>Shielded</td>
<td>3</td>
</tr>
<tr>
<td>Nylon (6,6)</td>
<td>Shielded</td>
<td>1</td>
</tr>
<tr>
<td>SCC (Taped Quartz)</td>
<td>U/O2 Optics</td>
<td>3</td>
</tr>
<tr>
<td>A200 (Glassfibre)</td>
<td>U/O2 Optics</td>
<td>2</td>
</tr>
<tr>
<td>Gennianum on Kapton</td>
<td>Shielded</td>
<td>1</td>
</tr>
<tr>
<td>Anodized Aluminum (Chromic Acid Etch)</td>
<td>NASA / MEPF</td>
<td>1</td>
</tr>
<tr>
<td>Anodized Aluminum (Sulfuric Acid Etch)</td>
<td>NASA / MEPF</td>
<td>1</td>
</tr>
<tr>
<td>UV AR-coated Ce-doped Cover Glass</td>
<td>Tiled</td>
<td>3</td>
</tr>
<tr>
<td>FR4 Printed Circuit Board (PI Composites)</td>
<td>CRRES NASA USP</td>
<td>2</td>
</tr>
<tr>
<td>Cu 147 RTV on Copper</td>
<td>Nihon Ekon</td>
<td>2</td>
</tr>
<tr>
<td>DC93-500 RTV on Copper</td>
<td>Dow Corning Ekon</td>
<td>2</td>
</tr>
<tr>
<td>Zinc Oxide White Paint (GO-055)</td>
<td>Alum</td>
<td>3</td>
</tr>
<tr>
<td>Borosilicate B/C Glass</td>
<td>U/O2 Optics</td>
<td>1</td>
</tr>
<tr>
<td>Gold (88.9% Purity)</td>
<td>ESP</td>
<td>7</td>
</tr>
<tr>
<td>Aluminum (99.99% Purity)</td>
<td>ESP</td>
<td>7</td>
</tr>
<tr>
<td>316 Stainless Steel</td>
<td>McMaster-Carr</td>
<td>2</td>
</tr>
<tr>
<td>GPHC Copper (80.0% Purity)</td>
<td>McMaster-Carr</td>
<td>1</td>
</tr>
<tr>
<td>Silver (99.999% Purity)</td>
<td>United Materials</td>
<td>3</td>
</tr>
<tr>
<td>g/C (Graphite Amorphous Carbon) on Copper</td>
<td>Arizona Carbon foil</td>
<td>1</td>
</tr>
<tr>
<td>Aquadag (molybdenum disulfide) on Copper</td>
<td>LACD Research</td>
<td>2</td>
</tr>
<tr>
<td>100°C Black Kapton</td>
<td>Shielded</td>
<td>6</td>
</tr>
<tr>
<td>Thick Film Black</td>
<td>Shielded</td>
<td>6</td>
</tr>
<tr>
<td>Inconel on Silver on Teflon on ITO</td>
<td>Shielded</td>
<td>1</td>
</tr>
<tr>
<td>ITO on Teflon on Silver on Inconel</td>
<td>Shielded</td>
<td>1</td>
</tr>
<tr>
<td>Gold (2um/Al(2um) on 316 Stainless Steel</td>
<td>Gold Plating Services</td>
<td>3</td>
</tr>
<tr>
<td>Ni(2um) on 316 Stainless Steel</td>
<td>Gold Plating Services</td>
<td>3</td>
</tr>
<tr>
<td>Au(2um) on 316 Stainless Steel</td>
<td>Gold Plating Services</td>
<td>3</td>
</tr>
<tr>
<td>Au(2um) on Ni(2um)/Au(2um) on 316 Stainless Steel</td>
<td>Gold Plating Services</td>
<td>3</td>
</tr>
<tr>
<td>Reinforced Carbon Nano-fiber/RI 3 Cylindrical Emitter Composite</td>
<td>SDL GIFTS Satellite</td>
<td>2</td>
</tr>
<tr>
<td>AGM 720 Ceramic-Dielectric Composite Material</td>
<td>CO-fired Thckened</td>
<td>5</td>
</tr>
<tr>
<td>S129 Nonoxide Ceramic-Dielectric Composite</td>
<td>CO-fired thickened</td>
<td>5</td>
</tr>
<tr>
<td>Thiolcarboxylic Acid Epoxy Foul-No Hole</td>
<td>ATK Thckened</td>
<td>5</td>
</tr>
<tr>
<td>Thiolcarboxylic Acid Foul-7/16th Hole</td>
<td>ATK Thckened</td>
<td>5</td>
</tr>
<tr>
<td>Thiolcarboxylic Acid Carbon Composite</td>
<td>ATK Thckened</td>
<td>5</td>
</tr>
<tr>
<td>Thiolcarboxylic Acid Carbon Composite #2</td>
<td>ATK Thckened</td>
<td>5</td>
</tr>
<tr>
<td>Thiolcarboxylic Acid Carbon Composite #3</td>
<td>ATK Thckened</td>
<td>5</td>
</tr>
<tr>
<td>Thiolcarboxylic Acid Carbon-Francis Carbon Composite</td>
<td>ATK Thckened</td>
<td>5</td>
</tr>
<tr>
<td>90/10 Ceramic-Dielectric Composite</td>
<td>CO-fired Thckened</td>
<td>5</td>
</tr>
<tr>
<td>S129 Nonoxide Ceramic-Dielectric Composite</td>
<td>CO-fired Thckened</td>
<td>5</td>
</tr>
<tr>
<td>S129 Nonoxide Ceramic-Dielectric Composite Material</td>
<td>CO-fired Thckened</td>
<td>2</td>
</tr>
<tr>
<td>S129 Nonoxide Ceramic-Dielectric Composite Material</td>
<td>CO-fired Thckened</td>
<td>2</td>
</tr>
</tbody>
</table>

**B. Space Environment Exposure of Samples**

The SUSpECS study exposed three test panels of materials—SUSpECS I, II and III—to the LEO environment for ~18 months. Environmental monitoring on board the MISSE-6 suitcases included temperature monitoring at a number of points on each pallet. Atomic oxygen (AO) exposure was monitored by the degradation of Kapton strips placed on the pallet frames, with an estimated sensitivity of ~25% AO variation [25], [26], [27]. Solar ultraviolet (UV) exposure as a function of time was monitored with UV photodiodes at several locations. Absolute absorbed radiation dosage will be monitored with several thermoluminescent detectors (TLD). The Air Force MISSE-6 experiment also monitored the electron flux in the 0-200 eV regime. Specific details of space environment exposure for SUSpECS sample holders and space simulation tests are discussed in Section III.F.

### C. Ram Side Sample Panel Design and Configuration

One sample panel, SUSpECSI, was mounted on the ram side of the ISS, with enhanced exposure to atomic oxygen. These experiments were all passive LEO exposure experiments. This panel included 98 1.3 cm diameter (1 cm exposed diameter) conducting and insulating test samples held at ground potential, as shown in Figures 2(a-c). The specific samples are identified in Table I.

The ram-side sample holder was configured so that four stacked sample tiers were exposed to AO+UV, AO alone (2 sets), and no AO or UV. All these materials were tightly seated in a metal tray. The sample geometry was designed such that the sides of each tier were 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 outermost tier experienced the fullest exposure to all of the variables of LEO environment, most importantly atomic oxygen and ultraviolet radiation. The lower tiers, being shielded by the outermost layer, did not
have exposure to ultraviolet radiation. Due to a gap between the second and third tiers in the stacked configuration, the second and third tiers were exposed to reduced fluxes of atomic oxygen. The lowest tier was fully shielded from ultraviolet radiation and atomic oxygen by the third tier. In addition to the MISSE-6 onboard monitors of UV and AO flux, the cumulative fluence at various points on SUSpECS was also monitored. AO exposure was monitored [27] by the relative oxidation of high purity Ag strips [25], [26], [28] and the degradation of Kapton strips [25], [26] placed on the frame of each tier. UV exposure is monitored by the discoloration of 1.3 cm diameter, 1 cm thick borosilicate BK7 glass sample disks mounted on each tier as color centers are formed by the UV radiation.

D. Wake Side Sample Panels Design and Configuration

SUSpECS II and III sample panels faced the wake side of the ISS, with less exposure to atomic oxygen. SUSpECS III was fully passive with 25 mounted in a sample holder like the bottom tier of SUSpECS I. SUSpECS II had 13 1.3 cm diameter passive exposure test samples held at ground, as shown in the right hand side of Figures 2(c-d). Additional grounded samples are mounted underneath the exposed samples. The specific samples are identified in Table I.

SUSpECS II also had the sole active experiment. There were 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 on SUSpECS II, as
shown at left in Figures 2(c-d). These three sub-panels were held at +5 VDC, -5 VDC and -15 VDC, respectively, for the full duration of the flight. Voltages for the sub-panels are provided by the ISS through the MISSE-6 bus. Current was drawn from interaction of the biased plates with the space plasma environment. Based on a plasma current density of ~10 nA-cm⁻², the three biased plates collectively drew <1 μA. Resistors and fuses were mounted in series with each sub-panel to limit arcing currents. A grounded sample guard was positioned above the three sub-panels to minimize possible contact with biased sub-panels by astronauts during EVAs.

The beveled edges of the sample clamp and guard shield were designed to minimize fringing fields to provide nearly parallel voltage contours typical of larger biased samples.

The biased sample configuration was designed to approximate typical conditions of materials subject to spacecraft charging. The positive test bias was chosen as +5 V. Positively charged components will typically charge to only a few volts positive [29], since low energy emitted electrons will be re-attracted to a positively charged surface.
and the majority of emitted electrons have energies below ~5 eV [3]. By contrast, negatively charged materials can charge to large voltages, since emitted electrons are repelled from the charged surface and therefore do not self-limit charging, as is the case for positive biasing [3]. Biases of -5 V and -15 V were chosen as representative of modest and more extreme negative charging.

III. TESTING

A. 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 [30]), thermal tests (thermal expansion, thermal emissivity and absorptivity), and outgassing.

B. Electrical Properties of Spacecraft Materials

The electron emission properties and resistivity of many SUSpECS 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 [4,31]. Much of the pre-flight testing has already been done in conjunction with previous studies.

The electron emission and transport properties of materials are key parameters in determining the likelihood of deleterious spacecraft charging effects [4], [29], [32], [33] and are essential in modeling these effects with engineering tools such as the NASA NASCAP-2K [34], [35], [36] SPENVIS, and MUSCAT [37] codes. 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 [3-13], [16], [36], [38], [39].

Recent work [10], [40] 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 [41]. Under many typical conditions this can result in charge dissipation on the order of days to months rather than minutes to hours [9]. More appropriate methods to measure charge storage decay have been developed. Apparatus to measure the decay rate of charge deposited on the surface of thin film insulators have been designed and built at USU in conjunction with an on-going NASA research project with JPL [11] and the USU electron emission test chamber [42]. 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.

C. Pre- and Post-Flight Comparisons

Measurements of the optical microscopy and normal specular UV/VIS/NIR reflectance of selected pre- and post-flight samples that exhibited significant changes are presented in Figs. 3 and 5. These preliminary results can be compared to assess on–flight degradation.

Figure 3 shows results for five samples from SUSpECS II on the ram side with high AO exposure. The first three materials, (a) Black Kapton 100XC, (b) Aquadag colloidal graphite coating on Cu substrate, and (c) Kapton HN all exhibit significant material loss and changes in color evident in both the photographs and the reflection spectra. Presumably, these changes are due to strong AO oxidation of these carbon-based materials. The bulk Ag sample (d) also exhibits major oxidation. Work is underway to compare the results of the Kapton HN and Ag AO changes, to investigate whether the Ag represents a viable alternative as an AO fluence sensor. The changes observed in the vapor-deposited Al coated Mylar (PET) sample (e) are perhaps the most dramatic. It appears
that the AO oxidation has completely removed the VDA coating. There is also what appears to be a micrometeoroid impact site.

D. Charge-Induced Contamination Study

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 [36]. 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 [43]. Thin contaminant layers readily change the

Figure 5. Comparison of pre- and post-flight photographs and UV/VIS/NIR reflectance spectra of -5 V charge samples with wake exposure on SUSpECS I. (a) Au, (b) Al, (C) Carbon-filled polyimide or Black Kapton 100 XC, (d) Carbon-filled PET or Thin Film Black. (Left) Comparison of pre- and post-flight photographs of the full charge-induced contamination sample set on SUSpECS I.
optical [30,44] and electronic properties [12,13] 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 [38]. 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 [45]. 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 [30].

Studies at USU have shown that very thin layers of contamination—even a few monolayers—can potentially cause significant changes in electron emission properties that can dramatically affect the charging of satellites and can lead to catastrophic charging effects under certain circumstances [9, 46]. Figure 4 shows the threshold differential charging of clean Au and carbon-contaminated Au surfaces on a hypothetical satellite in GEO orbit [46]. 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.

The comparisons presented in Fig. 5 focus on six sets of four identical samples [Au, Al, carbon-loaded polyimide (Dupont Black Kapton 100XC), and carbon-loaded polyester (Sheldahl Thick Film Black)]. Two sample sets were located on the top and bottom tiers of a three-tiered sample panel designed to provide variable atomic oxygen and UV exposure. The four other sample sets were located on the wake side sample panel, with sets biased for the duration of the flight at 0 VDC, +5 VDC, -5 VDC, and -15 VDC, respectively. The biased sample configuration was designed to approximate typical conditions of materials subject to spacecraft charging. Positively charged components will typically charge to only a few volts positive. By contrast, negatively charged materials can charge to large voltages. Biases of -5 V and -15 V were chosen as representative of modest and more extreme negative charging. Further measurements and analysis are required to more fully determine the changes in materials properties that result from charge-enhance contamination.

E. Space Environment Simulation at ADEC

The initial idea for comparing MISSE-6 flight data to ground simulation data began in mid-2009, just prior to the return of the SUSpECS panels. Discussions between USU and AEDC researchers led to a cooperative research effort where Utah State supplied sample materials and AEDC furnished test time in the CCOSE chamber [47]. Sample selection was initiated following the MISSE-6 post retrieval inspection and return of samples to Utah in October 2009. Factors such as optical change (based on visual inspection) and sample availability was weighed against chamber test volume and exposure duration limits. Analysis of constraints limited the selection of samples to those on SUSpECS II wake panel, primarily due to a maintenance overhaul of the CCOSE atomic oxygen source [48]. In order to verify that all samples did not change in the same way, such as all darkening or all having no change, wake-side samples were selected which exhibited a variety of optical property changes on orbit. The final list was as follows: Mylar for having highly varying optical properties, Black Kapton for minor change, and quartz and sapphire for no change. These samples are shown in Fig. 6.

F. ADEC Test Planning

The first step in planning the test was to acquire the environmental profile of the MISSE-6 samples. The primary constituents of the ISS orbit are vacuum, solar, atomic oxygen,
protons and electrons. Of these, CCOSE could replicate all but the atomic oxygen as stated earlier. For the other components, the environment could be replicated if on-orbit data were available. Fortunately, the equivalent sun hour (ESH) estimates were provided in a timely manner by the Boeing ISS Thermal Analysis group. There were 2600 ESH for the ram and 1950 ESH for the wake side. These exposure durations are not possible in the short test window but ~350 ESH UV could be tested. Utah State provided the temperature/time history data that were given to them from NASA. In addition, NASA had Boeing-supplied Lithium Fluoride (LiF) thermoluminescent dosimeters (TLDs) radiation detectors located behind some of the samples on the MISSE-6 mission. These detectors output total radiation dose measurements. Preliminary radiation dose data from these TLDs were acquired from Dr. Sheila Ann Thibeault of NASA Langley Research Center. These data showed the total electron dose was much greater than the proton contribution and therefore protons were not included in further analysis. In order to properly set the CCOSE electron source, the following method was developed to derive the electron profile.

As the TLD measurements are bulk measurements, the energy distribution of the electrons had to be generated another way. The only available option was to use models since energy distribution data were not provided. Also, since the TLDs were behind the MISSE samples, electrons below a certain energy threshold would have been stopped in the sample material and not have been detected. This energy threshold had to be determined since significant numbers of lower energy particles may have contributed to the optical changes. A schematic of this is given in Fig. 7.

To begin the process, the TLD with the highest radiation dose of 14.93 Gy was selected. This TLD was behind sample 10 and had the minimum shield areal density of 0.0031 g/cm², thus it was the sample which stopped the least amount of electrons. The energy threshold was then determined using the NIST online program Electron STopping And Range (ESTAR). Aluminum shielding with an equivalent areal density to sample 10 has a stopping power threshold of 35 keV. Using this information, the electron spectrum from 40 keV to 6 MeV was taken from the AE-8 MIN model. The model was run for a 17 month ISS orbit beginning March 23, 2008. The AE-8 output was used to drive MUlti-LAyered Shielding Simulation Software (MULASSIS), an ESA radiation transport tool, to generate a total dose within lithium fluoride behind a 0.0031 g/cm² aluminum shield. The TLD was assumed to be 0.89 mm thick LiF, based on a TLD-100, which resulted in a total dose of 37.25 Gy. This indicated the AE8 spectrum had to be decreased in fluence by a factor of 0.4 to match the TLD reading. This is reasonable since the exact geometry was not available and additional support structure may have absorbed some of the incident radiation. The shifted AE8 spectrum was then supplemented with scaled data below 40 keV. This was taken from Dr. Mike Meshishnek’s earlier work on low-energy particle distributions in LEO, MEO, and GEO.

The final step to setting the CCOSE test profile was to divide up the electron spectrum and map it to the electron gun output. Due to the monoenergetic nature of the electron gun output, two different beam energies were selected to represent the full particle spectrum. The dividing point between the high energy and low energy grouping was set at 20 keV since the number of particles below this energy was roughly equivalent to those above this energy (see Fig. 8). A monoenergetic beam of 15 keV electrons was run to simulate the lower portion of the spectrum while a 60 keV beam was...
Figure 10. Comparison of optical properties of samples before and after ground simulation testing. (a) Quartz and (b) Sapphire transmission measurements. (c) Black Kapton™ and (d) Aluminized Mylar™ reflectance measurements.

used for the upper. This resulted in a run time of 129 hours of 15 keV and 39 hours of 60 keV. The time difference is due to increased beam current output at higher energies.

G. Testing and Results

To date, CCOSE samples have been tested individually due to the in-vacuum measurement system. The present test was different in that the SUSPeCS samples were measured prior to launch and upon return, therefore atmospheric exposure would be more “realistic”. Also, testing could be accomplished faster with simultaneous exposure of the four 1-cm diameter samples. A custom sample holder was fabricated to fit within the CCOSE exposure area and is shown in Fig. 9 with the samples both on the clean bench and installed in the chamber. Chamber pumpdown was initiated on July 15th, 2010 with sample exposure commencing on July 19th, 2010. Sample exposure was ended on July 28th, 2010. The samples were exposed to xenon and deuterium lamps for a total time of 147.6 hrs. At the measured intensity of each lamp, this resulted in 380 ESH of UV from 120 nm to 300 nm. Pre-test reflectance and transmittance measurements were performed at atmospheric conditions using both a Jasco UV-VIS-NIR spectrometer and a Bruker FTIR spectrometer. Post-test reflectance and transmittance measurements were also performed with these instruments.

The following results are based on initial assessment of the data and will be reviewed in greater detail in a future publication. With that said, the initial analysis follows the trend of the MISSE-6 SUSPeCS samples. As stated earlier, quartz and sapphire were selected for their resistance to any change. Figure 10(a) and Figure 10(b) show the transmission measurements made before and after testing. Minimal changes were observed in the UV region with these samples but appeared primarily unchanged.

Black Kapton had some small changes on the orbital samples but had little change in the ground test (Fig. 10(c)). This was likely due to interaction with atomic oxygen on orbit and lack of atomic oxygen in the ground test. Again some slight difference is observed in spectrum but these appear negligible. Also, the spike at 800 nm is due to detector changeover within the spectrometer.

The most noticeable change in both the flight and ground samples occurred on the aluminized Mylar (Fig. 10(d)). Most of the loss appears within the visible region from 300 to 700 nm. This change was likely due to vacuum ultraviolet radiation severing the polymer bonds [49,50] but may have been enhanced by the electron beam as other researchers have found degradation in Mylar under energetic electron bombardment [51]. A series of follow-on testing is
recommended to verify repeatability and isolate any electron contribution.

IV. FUTURE WORK

Work on analysis of the effects of space environment exposure on the 168 samples has only begun. Measurements of optical and electron microscopy, reflectivity, FTIR, emissivity, mass loss, electron-, ion- and photon-induced electron emission, photoyield, AES, photoemission, and variable angle UV/VIS/NIR reflectivity will continue. Work will also progress in collaboration with the AEDC space simulation facility to understand the origins of these effects and quantify their impacts.

ACKNOWLEDGMENT

Research on SUSpECS was supported by funding from USU Space Dynamics Laboratory, the NASA Solar Probe Mission Program through Johns Hopkins Applied Physics Laboratory, and a Utah State University Undergraduate Research and Creative Opportunities grant. A special thanks goes to the USU Get-Away-Special Team—especially Jeff Duce and Josh Hodges—for their critical role in the design and construction of SUSpECS. 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, Steve Hahn, and the team at Boeing provided invaluable support for the project and as did the team at NASA Langley Research Center who integrated and de-integrated the SUSpECS sample panels into the MISSE-6 Passive Experiment Containers (PECs). 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; Clint Thompson and Jim Burns at ATK Space Systems; and A. Robb Frederickson and Nelson W. Green at the Jet Propulsion Laboratory about CRRES materials. Andrew Auman performed the SimION electric field simulations. Sarah Barton, Jodie Corbridge Guthrie, Ryan Hoffmann and Jonathan Abbott of the USU Department helped with various characterization measurements and sample preparation. Jim Dyer at USU Space Dynamics Laboratory was instrumental in characterization measurements and sample preparation and assembly.

REFERENCES


