NASA GLENN RESEARCH CENTER'S MATERIALS INTERNATIONAL SPACE STATION EXPERIMENTS (MISSE 1-7)

Kim K. DE GROH [1], Bruce A. BANKS [2], Joyce A. DEVER [3], Donald A. JAWORSKE [1], Sharon K. MILLER [1],
Edward A. SECHKAR [4] and Scott R. PANKO [4]

[1] *Space Environment and Experiments Branch, NASA Glenn Research Center*
[2] *Consultant to Alphaport, Inc. at NASA Glenn Research Center*
[3] *Durability and Protective Coatings Branch, NASA Glenn Research Center*
[4] *ASRC Aerospace Corp. at NASA Glenn Research Center*
21000 Brookpark Rd., Cleveland, OH 44135, USA

NASA Glenn Research Center (Glenn) has 39 individual materials flight experiments (>540 samples) flown as part of the Materials International Space Station Experiment (MISSE) to address long duration environmental durability of spacecraft materials in low Earth orbit (LEO). MISSE is a series of materials flight experiments consisting of trays, called Passive Experiment Carriers (PECs) that are exposed to the space environment on the exterior of the International Space Station (ISS). MISSE 1-5 have been successfully flown and retrieved and were exposed to the space environment from one to four years. MISSE 6A & 6B were deployed during the STS-123 shuttle mission in March 2008, and MISSE 7A & 7B are being prepared for launch in 2009. The Glenn MISSE experiments address atomic oxygen (AO) effects such as erosion and undercutting of polymers, AO scattering, stress effects on AO erosion, and in-situ AO fluence monitoring. Experiments also address solar radiation effects such as radiation induced polymer shrinkage, stress effects on radiation degradation of polymers, and radiation degradation of indium tin oxide (ITO) coatings and spacesuit fabrics. Additional experiments address combined AO and solar radiation effects on thermal control films, paints and cermet coatings. Experiments with Orion Crew Exploration Vehicle (CEV) seals and UltraFlex solar array materials are also being flown. Several experiments were designed to provide ground-facility to in-space calibration data thus enabling more accurate in-space performance predictions based on ground-laboratory testing. This paper provides an overview of Glenn’s MISSE 1-7 flight experiments along with a summary of results from Glenn’s MISSE 1 & 2 experiments.

Keywords: Materials International Space Station Experiment, International Space Station, low Earth orbit, flight experiments, atomic oxygen, radiation, degradation

1. Introduction

Functional materials used on the exterior of spacecraft are subjected to many environmental threats that can cause degradation in materials properties, possibly threatening spacecraft mission success. In LEO these threats include AO, photon radiation, charged particle radiation, temperature effects and thermal cycling, impacts from micrometeoroids and debris, and contamination. Atomic oxygen is the most predominant species in LEO and is present in other planetary orbital environments. At spacecraft velocities, LEO AO is energetic enough (≈4.5 eV) to cause bond breakage and subsequent oxidation. The oxidation products of most polymers are gas species, therefore material erosion occurs. Atomic oxygen can produce serious structural, thermal or optical degradation of spacecraft components. Figure 1 shows AO erosion of Teflon® fluorinated ethylene propylene (FEP) around a small protective particle. To assess the AO durability of a material for mission applicability, the erosion yield (volume loss in cm^3 per incident oxygen atom) needs to be characterized using actual space flight data, as ground AO facilities do not perfectly simulate the space environment.

The most common approach to protecting susceptible spacecraft materials from AO erosion is to coat the material with a thin AO protective film, such as SiO_X. Unfortunately, microscopic scratches, dust particles or other imperfections in the substrate surface can result in defects in the protective coating. These coating defects can provide pathways for AO attack and undercutting erosion of the substrate can occur. Undercutting erosion can be a serious threat to component survivability. An example is shown in Figure 2, where AO undercutting erosion has severely degraded the P6 Truss port solar array wing two-surface aluminized-Kapton® blanket box cover on the ISS.[1]

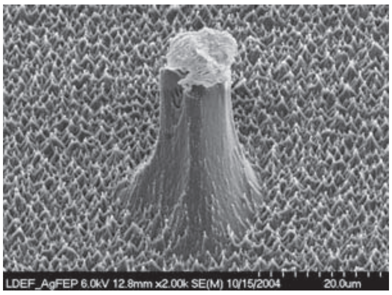


Fig. 1 Atomic oxygen erosion of Teflon FEP in space.

An example of radiation induced polymer degradation is found through extensive embrittlement of thermal control insulation on the Hubble Space Telescope (HST). During the second servicing mission (SM2), after 6.8 years in space, severe cracking was observed in the aluminized-Teflon fluorinated ethylene propylene (Al-FEP) outer layer of the multilayer insulation (MLI) covering the HST Light Shield. Astronaut observations combined with photographic documentation revealed extensive cracking of the MLI in many locations, with the solar facing surfaces being heavily damaged.[2] Figure 3 shows two large cracked areas. Extensive testing was conducted on retrieved HST insulation, combined with ground-based testing, which revealed that embrittlement of FEP on HST is caused by radiation exposure (electron and proton radiation, with contributions from solar flare x-rays and ultraviolet (UV) radiation) combined with thermal effects.[2]

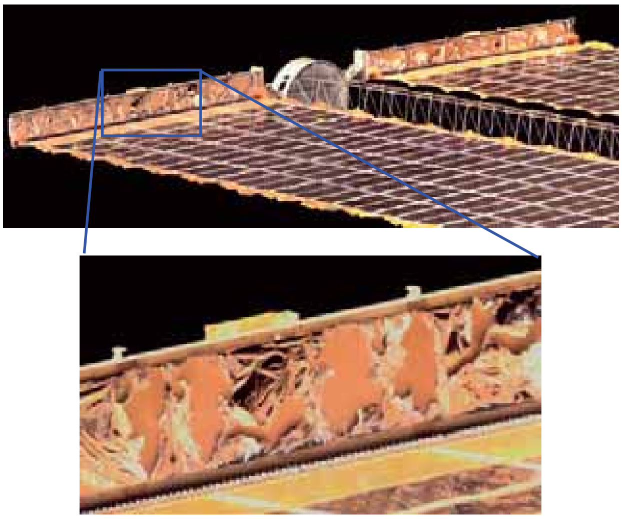


Fig. 2 Atomic oxygen undercutting degradation of the solar array wing blanket box cover on ISS.

Fig. 3 Large cracks in HST MLI after 6.8 years in space.

Unfortunately, accelerated laboratory testing often does not accurately simulate degradation caused by combined on-orbit environmental exposures. One example was the inability to reproduce the extent of embrittlement of Al-FEP insulation on the HST based on mission fluence requirements.[3] The fact that highly accelerated ground-laboratory testing did not replicate the on-orbit degradation highlights the necessity of actual long-duration space flight data.

NASA Glenn Research Center has 39 individual materials flight experiments, with over 540 samples, being flown as part of the MISSE series to address long duration environmental durability issues for spacecraft materials in the LEO space environment. The Glenn MISSE experiments address AO effects such as erosion and undercutting of polymers, AO scattering, stress effects on AO erosion, and in-situ AO fluence monitoring. Experiments were also designed to address solar radiation effects such as radiation induced polymer shrinkage, stress effects on radiation degradation of thin film polymers, and radiation degradation of ITO coatings and spacesuit fabrics. Several NASA Glenn experiments also address combined AO and solar radiation affects on thermal control films, paints and cermet coatings. Experiments with Orion CEV Low Impact Docking System (LIDS) seals materials and UltraFlex solar array materials are also being flown. Several of the experiments were designed to provide ground-facility to in-space calibration data, thus enabling more accurate in-space performance predictions based on ground-laboratory testing. NASA Glenn's participation on MISSE 5 also included a substantial contribution to MISSE 5's primary experiment, the Forward Technology Solar Cell Experiment (FTSCE). The Glenn MISSE 1 & 2 materials experiments have already had a direct impact on the Exploration space program, the space industry, the military and education. This paper provides an overview of Glenn's MISSE 1-7 flight experiments and their relevance to various NASA missions. A summary of the results from NASA Glenn's MISSE 1 & 2 experiments are provided, along with the use of the data for ground-facility calibration and improved LEO environmental durability prediction.

2. Materials International Space Station Experiment (MISSE) Overview

MISSE is a series of materials flight experiments consisting of trays, called PECs, which are exposed to the space environment on the exterior of the ISS providing long-duration space exposure. Each PEC consists of two trays, hinged like a suitcase, as shown in Figure 4. The PECs are closed with the samples facing each other and protected for launch on the shuttle and then are attached to the outside of ISS during an extravehicular activity (EVA) and opened back-to-back, exposing the samples to space. The trays are typically positioned with one surface facing the ram direction thus receiving AO and solar radiation (Tray 1), and the back surface facing the wake direction thus receiving solar radiation with minimal AO exposure (Tray 2). The overall objective of MISSE is to test the stability and durability of materials and devices in the space environment in order to gain valuable knowledge on the performance of materials in space as well as to enable lifetime prediction of new materials and components that may be used in future space flight. Figure 5 shows MISSE PEC 1 during an EVA in January 2003 after 17 months of space exposure. Five MISSE PECs (MISSE 1-5) have been successfully flown and retrieved to date. Table 1 provides a summary of the MISSE 1-5 launch and retrieval missions, and the space exposure durations. MISSE 6A & 6B were deployed during the STS-123 shuttle mission in March 2008 and were planned as a one-year mission. At the time of writing this paper, MISSE 7A & 7B are being prepared for a 2009 launch.

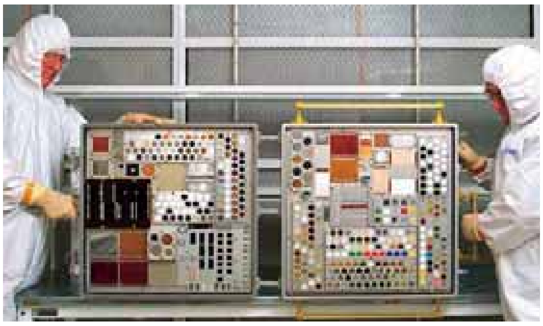


Fig. 4 Pre-flight photo of MISSE 2.

Fig. 5 MISSE 1 being examined during a spacewalk in January 2003.

3. Glenn’s MISSE 1-7 Experiments

Researchers at Glenn are principal investigators (PI) for seven materials experiments, with a total of 80 samples, flown for nearly 4 years on the exterior of the ISS as part of MISSE 1 & 2. These Glenn experiments investigated AO erosion of unprotected polymers, AO scattering characteristics, and effects of the overall LEO environment on optical and mechanical properties of polymer films. Experiments were also flown to provide data to calibrate ground-based facilities for simulating LEO AO effects on polymers with protective coatings. Results of these experiments are provided, along with an example of how the data are being used to improve LEO environmental durability prediction. The use of MISSE 1 & 2 data for durability prediction for specific missions is also provided.

Glenn has eight spacecraft materials durability experiments (with a total of 71 samples) that were flown as part of MISSE 3 & 4, and four experiments (with 105 samples) flown as part of MISSE 5. Glenn was also actively involved in the MISSE 5 FTSCE experiment. The MISSE 5 mission, which received 13 months of space exposure, flew directly after retrieval of MISSE 1 & 2. MISSE 3 & 4, which was deployed before retrieval of MISSE 5, received 1 year of space exposure. Post-flight sample documentation and analyses have begun on these experiments.

MISSE 6 and 7 differ from the prior trays in that many of the experiments are active experiments. The MISSE 6 active experiments are powered by ISS and the data are being stored on data loggers and will be available when the experiments are retrieved. NASA Glenn has six active experiments and six passive experiments on MISSE 6, with a total of 168 samples that are integrated into the two MISSE 6 PECs (6A & 6B). MISSE 6 was delivered to ISS during the STS-123 mission, and both 6A and 6B were placed outside of the Columbus Module on March 22, 2008. MISSE 7 will be powered by, and will have communication links through ISS. Hence, the active data will be retrieved daily via telemetry. Glenn has a total of nine experiments (three active and six passive), with a total of 120 samples that are being developed for integration into the MISSE 7 PECs, with a planned launch in 2009. MISSE 7A will be placed in a zenith/nadir orientation and MISSE 7B will be placed in a ram/wake orientation. The Glenn MISSE 6 & 7 experiments include Exploration Mission relevant materials such as spacesuit fabrics, thermal control blanket polymers and paints, solar array blanket materials, o-ring seals, and dust mitigation materials.

4. MISSE 1 & 2 Experiments and Flight Results

Table 2 provides a list of Glenn’s MISSE 1 & 2 materials experiments along with the on-orbit orientation, the individual experiment objective and the number of samples.

Estimated environmental conditions of AO, solar exposure, tray temperatures, and ionizing radiation doses on MISSE 1 & 2 are described in detail by Pippin.[4] Black light inspection of the trays showed minimal to no contamination on the MISSE surfaces.[4] Results of x-ray photoelectron spectroscopy (XPS) contamination analysis of two MISSE 2 sapphire witness samples in MISSE 2 ram sample tray E6 indicated an extremely thin silica contaminant layer (1.3 and 1.4 nm on each slide, respectively).[5] A small amount of fluorine was also detected.[5] The MISSE 2 environment was found to be an unusually clean environment with very low spacecraft induced molecular contamination. This is due to low outgassing of other MISSE 2 Tray 1 materials and also due to the position of MISSE 2 on ISS. Therefore, the flight data was not affected by contamination. This further increases the importance of this long duration flight data.

4.1. Polymer Erosion and Contamination Experiment (PEACE) Polymers Experiment (MISSE 2)

The PEACE Polymers experiment included 41 – 1” (2.54 cm) diameter samples (39 polymer samples and 2 Kapton H AO fluence witness samples). The experiment (sample tray E5) was flown on the ram side of MISSE 2 and was exposed to AO along with solar and charged particle radiation (see Figure 6). The objective of the MISSE 2 PEACE Polymers experiment was to accurately determine the AO erosion yield (Ey) of a wide variety of polymeric materials exposed for an extended period of time to the LEO space environment. The polymers range from those commonly used for spacecraft applications, such as Teflon FEP, to more recently developed polymers, such as high temperature polyimide PMR (polymerization of monomer reactants). Additional polymers were included to explore erosion yield dependence upon chemical composition so that an AO erosion yield predictive tool could be developed. The majority of samples were comprised of thin film polymers, with numerous layers stacked together to last a minimum of 3 years in LEO. The MISSE 2 PEACE Polymers experiment is unique because it contains the widest variety of well-documented polymers exposed to identical long duration LEO AO conditions.

Table 1. MISSE 1-6 Mission and Space Exposure Summary

MISSE PEC	Launch Mission	Date Placed Outside ISS	Location on ISS	Orientation	Retrieval Mission	Date Retrieved from ISS	LEO Exposure Duration
1 & 2	STS-105	8/16/2001	PEC 1: High Pressure Gas Tank PEC 2:Quest Airlock	Ram & Wake	STS-114	7/30/2005	3.95 years
3 & 4	STS-121	8/3/2006	PEC 3: High Pressure Gas Tank PEC 4:Quest Airlock	Ram & Wake	STS-118	8/18/2007	1 year
5	STS-114	8/3/2005	Aft P6 Trunion Pin Handrail	Solar & Anti-Solar	STS-115	9/15/2006	13 months
6A & 6B	STS-123	3/22/2008	Columbus Module	Ram & Wake	-	-	-

Table 2. Glenn's MISSE 1 & 2 Materials Experiments (80 Samples)

Glenn Experiment	Orientation	# Samples	Experiment Objective
PEACE Polymers	Ram	41	To determine the AO erosion yield of a wide variety of polymers with and without solar radiation
Spacecraft Silicones	Ram	4	To determine changes in optical properties and nanomechanical hardness for ground-testing
AO Scattering Chamber	Ram	1	To determine scattered AO erosion characteristics for undercutting modeling
Double SiO_x-Coated Kapton (Mass Loss)	Ram	2	To determine AO undercutting rate dependence in space as compared to ground-facility (mass loss)
AO Undercutting Erosion (Undercut Cavities)	Ram	2	To determine AO undercutting rate dependence in space as compared to ground-facility (undercut cavities)
Polymer Film Thermal Control (PFTC)	Ram & Wake	20	To assess radiation and temperature effects on a variety of currently used and candidate thermal control materials
Gossamer Materials	Ram & Wake	10	To assess solar exposure, radiation, and temperature effects on candidate materials for gossamer structures

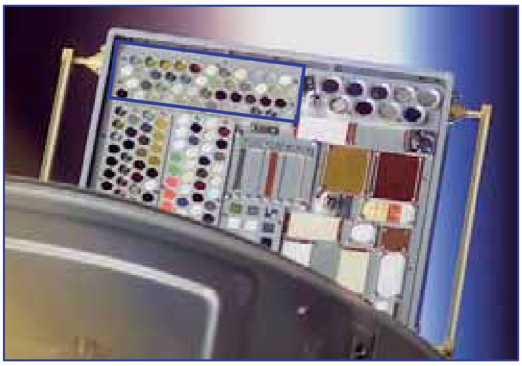


Fig. 6 MISSE 2 on the ISS Quest Airlock (the PEACE Polymers experiment is outlined).

Figure 7 provides photos of the MISSE 2 PEACE Polymers experiment prior to, and after, LEO space exposure. Although MISSE 2 was supposed to be a 1.5 year mission, planning for a three-year mission exposure was crucial in the success of this experiment, as it was exposed to LEO AO for four years. The AO fluence for the experiment was determined to be 8.43 x 10^{21} atoms/cm^2 based on mass loss of the two polyimide Kapton H witness samples. Atomic oxygen erosion yield values have been determined for each of the MISSE 2 PEACE polymers based on mass loss obtained from pre-flight and post-flight vacuum dehydrated samples. Table 3 provides a list of each of the MISSE 2 PEACE Polymer samples, the MISSE 2 mass loss, the sample density, the exposure area and the MISSE 2 erosion yield data.[6] Details on the specific polymers flown, flight sample fabrication, pre-flight and post-flight characterization techniques, AO fluence calculations and AO erosion yield results are reported by de Groh et al.[6,7]

a.

b.

Fig. 7 MISSE 2 PEACE Polymers experiment (Sample Tray E5), a). Prior to flight, and b). After space flight.

Table 3. MISSE 2 PEACE Polymers Erosion Yield Data [6]

MISSE Serial #	**Material**	**Polymer Abbrev.**	**MISSE 2 Mass Loss (g)**	**Density (g/cm^3)**	**Area (cm^2)**	**MISSE 2 Erosion Yield (cm^3/atom)**
2-E5-6	Acrylonitrile butadiene styrene	ABS	0.033861	1.05	3.4944	1.09E-24
2-E5-7	Cellulose acetate	CA	0.191482	1.2911	3.4831	5.05E-24
2-E5-8	Poly-(p-phenylene terephthalamide)	PPD-T (Kevlar)	0.026790	1.4422	3.5099	6.28E-25
2-E5-9	Polyethylene	PE	0.102760	0.918	3.5489	>3.74E-24
2-E5-10	Polyvinyl fluoride	PVF (Tedlar)	0.132537	1.3792	3.5737	3.19E-24
2-E5-11	Crystalline polyvinylfluoride w/white pigment	PVF (White Tedlar)	0.004714	1.6241	3.4176	1.01E-25
2-E5-12	Polyoxymethylene; acetal; polyformaldehyde	POM (Delrin)	0.378378	1.3984	3.5119	9.14E-24
2-E5-13	Polyacrylonitrile	PAN	0.047281	1.1435	3.4768	1.41E-24
2-E5-14	Allyl diglycol carbonate	ADC (CR-39)	0.267295	1.3173	3.5392	>6.80E-24
2-E5-15	Polystyrene	PS	0.115947	1.0503	3.5043	3.74E-24
2-E5-16	Polymethyl methacrylate	PMMA	0.194588	1.1628	3.5456	>5.60E-24
2-E5-17	Polyethylene oxide	PEO	0.066395	1.1470	3.5591	1.93E-24
2-E5-18	Poly(p-phenylene-2 6-benzobisoxazole)	PBO (Zylon)	0.056778	1.3976	3.5526	1.36E-24
2-E5-19	Epoxide or epoxy	EP	0.140720	1.1150	3.5576	4.21E-24
2-E5-20	Polypropylene	PP	0.072357	0.907	3.5336	2.68E-24
2-E5-21	Polybutylene terephthalate	PBT	0.036429	1.3318	3.5619	9.11E-25
2-E5-22	Polysulphone	PSU	0.105948	1.2199	3.5010	2.94E-24
2-E5-23	Polyeurethane	PU	0.057227	1.2345	3.5182	1.56E-24
2-E5-24	Polyphenylene isophthalate	PPPA (Nomex)	0.030549	0.72	3.5626	1.41E-24
2-E5-25	Pyrolytic graphite	PG	0.02773	2.22	3.5703	4.15E-25
2-E5-26	Polyetherimide	PEI	0.126853	1.2873	3.5352	>3.31E-24
2-E5-27	Polyamide 6 or nylon 6	PA 6	0.118376	1.1233	3.5646	3.51E-24
2-E5-28	Polyamide 66 or nylon 66	PA 66	0.065562	1.2252	3.5249	1.80E-24
2-E5-29	Polyimide	PI (CP1)	0.080648	1.4193	3.5316	1.91E-24
2-E5-30	Polyimide (PMDA)	PI (Kapton H)	0.124780	1.4273	3.4590	3.00E-24
2-E5-31	Polyimide (PMDA)	PI (Kapton HN)	0.121315	1.4346	3.5676	2.81E-24
2-E5-32	Polyimide (BPDA)	PI (Upilex-S)	0.038127	1.3866	3.5382	9.22E-25
2-E5-33	Polyimide (PMDA)	PI (Kapton H)	0.129250	1.4273	3.5773	3.00E-24
2-E5-34	High temperature polyimide resin	PI (PMR-15)	0.118887	1.3232	3.5256	>3.02E-24
2-E5-35	Polybenzimidazole	PBI	0.082708	1.2758	3.4762	>2.21E-24
2-E5-36	Polycarbonate	PC	0.142287	1.1231	3.5010	4.29E-24
2-E5-37	Polyetheretherkeytone	PEEK	0.107764	1.2259	3.4821	2.99E-24
2-E5-38	Polyethylene terephthalate	PET (Mylar)	0.125187	1.3925	3.5432	3.01E-24
2-E5-39	Chlorotrifluoroethylene	CTFE (Kel-f)	0.052949	2.1327	3.5452	8.31E-25
2-E5-40	Ethylene-chlorotrifluoroethylene	ECTFE (Halar)	0.088869	1.6761	3.5103	1.79E-24
2-E5-41	Tetrafluorethylene-ethylene copolymer	ETFE (Tefzel)	0.049108	1.7397	3.4854	9.61E-25
2-E5-42	Fluorinated ethylene propylene	FEP	0.012479	2.1443	3.4468	2.00E-25
2-E5-43	Polytetrafluoroethylene	PTFE	0.008938	2.1503	3.4841	1.42E-25
2-E5-44	Perfluoroalkoxy copolymer resin	PFA	0.010785	2.1383	3.4570	1.73E-25
2-E5-45	Amorphous Fluoropolymer	AF	0.012352	2.1463	3.4544	1.98E-25
2-E5-46	Polyvinylidene fluoride	PVDF (Kynar)	0.066860	1.7623	3.4993	1.29E-24

Note: Erosion yields listed with a > symbol indicate polymers that were eroded partially or completely through all layers.

An extensive error analysis was conducted to determine the error in the erosion yield values for each of the MISSE 2 PEACE Polymers flight samples. Three different equations were needed for determining mass loss of the flight samples, which is a factor in determining erosion yield. Therefore, it was necessary to develop three different equations for determining the fractional uncertainty in the erosion yield. Six of the 41 samples were partially or completely eroded through all layers, hence the erosion yield values for these samples are greater than those computed. These six polymers are being re-flown in the MISSE 6 Stressed PEACE Polymers experiment (see Section 7.1 below).

4.1.1. Atomic Oxygen Erosion Yield Predictive Tool

The MISSE 2 PEACE Polymers experiment consisted of 40 structurally different polymers (including the Kapton H witness samples) not only to allow accurate measurement of the AO erosion yields of commonly used polymers, but also to allow the development of a space validated AO erosion yield predictive tool that can approximate the LEO erosion yields of polymers based on structural chemistry and physical properties. The value of such a predictive tool is that as new polymers emerge, one would not have to wait for several years for flight experiment results to obtain AO durability information. A Glenn Atomic Oxygen Erosion Yield Predictive Tool has been developed based on best fit criteria for the MISSE 2 PEACE Polymers erosion yield data. The predictive tool utilizes polymer structural and physical properties, such as number and types of chemical bonds, density and ash content. The Atomic Oxygen Erosion Yield Predictive Tool is described in detail by Banks et al.[8]

4.1.2. Ground-Laboratory to In-Space Correlation

Although space flight experiments, such as the MISSE 2 PEACE experiment, are ideal for determining LEO environmental durability of spacecraft materials, ground-laboratory testing is most often relied upon for durability evaluation and prediction. Unfortunately, significant differences exist between LEO AO and AO in test facilities. These differences include variations in species, energies, thermal exposures and radiation exposures, all of which can result in different reactions and erosion rates. In an effort to improve the accuracy of ground-based durability testing, ground-laboratory to in-space AO correlation experiments have been conducted based on the MISSE 2 PEACE polymers flight data. In these tests, the AO erosion yields of the 39 PEACE polymers were determined relative to Kapton H using a radio-frequency (RF) plasma asher operated on air with the samples in metal holders. The asher erosion yields were compared to the MISSE 2 erosion yields for the PEACE polymers to determine the correlation between erosion rates in the two environments. The asher erosion yield of every polymer was higher than that of its in-space counterpart, and the asher to in-space erosion yield ratios ranged from 1.0 (1.02) to 37.1. The fluoropolymers in particular had higher ratios, ranging from 6.1 to 8.0. Kevlar, a woven fabric, had a ratio of 24.0, and White Tedlar, a material containing AO durable filler particles, had a ratio of 37.1. Details of this research, along with the asher-to-space Ey ratios, are provided by Stambler et al.[8]

4.1.3. Application to the Commercial Orbital Transportation System (COTS)

As one example of the use of MISSE data for Exploration Mission applications, the MISSE 2 PEACE Polymers Ey data has been used to evaluate the effects of AO texturing of a potential solar cell polymer cover being considered for the COTS mission solar array. The candidate polymer, polyvinyl fluoride (PVF, Tedlar), was subjected to end Hall AO (~70 eV O_2^+ ions) and then vacuum ultraviolet (VUV) radiation to determine the effects of the combined AO and VUV radiation (from deuterium lamps) on solar cell performance. The erosion yield of PVF from the MISSE 2 PEACE Polymers experiment was used along with the mission fluence requirement to determine the expected mass loss per area. This mass loss per area was then replicated in the end Hall AO facility to properly simulate the LEO erosion expected. The directed AO produced cones which slightly darkened the surface upon VUV exposure causing a slight loss in solar transmittance.

4.1.4. PEACE Team Collaboration

Glenn has numerous collaborative MISSE experiments with Hathaway Brown School in Shaker Heights, Ohio. These experiments include the MISSE 2 and MISSE 5 PEACE Polymers experiments, the MISSE 6A Stressed PEACE Polymers Experiment, and the MISSE 7B Polymers Experiment. Hathaway Brown School is Ohio’s oldest independent day school for girls. Through Hathaway Brown’s Science Research & Engineering Program (SERP) students join the Glenn/HB “PEACE” team, where they can work on MISSE research at NASA Glenn throughout their entire high school career. Over the past 10 years, 20 students have been part of the Glenn/HB PEACE team. To date the student involvement has included: MISSE pre-flight research, MISSE 2, 5, 6A and 7B flight sample fabrication, pre-flight characterization, and MISSE 2 post-flight characterization and error analyses. The students have authored research papers, presented their work at an international conference, and entered their research in science fairs, winning over $80,000 in scholarships and awards through this collaboration.

4.1.5. The Handbook of Atomic Oxygen Erosion

Glenn plans to write a Handbook of Atomic Oxygen Erosion, as a NASA Special Publication or NASA Standard, which will document the MISSE 2 PEACE Polymers AO erosion yield data, allowing proper selection of materials and thickness for future long-duration space flight missions. The Handbook will include an extensive background on LEO AO and will document the AO erosion yield of the MISSE 2 PEACE Polymers. Details on the specific polymers flown, flight sample fabrication techniques, pre-flight and post-flight characterization, and mission AO fluence calculations will be documented along with a summary of the AO erosion yield results. Details of the corresponding erosion yield error analyses will also be included along with the Glenn Atomic Oxygen Erosion Yield Predictive Tool. The handbook will inform users on how to use the predictive tool and how to use the erosion yield data for spacecraft durability prediction.

4.2. Spacecraft Silicones Experiment (MISSE 2 & 4)

The objective of the Spacecraft Silicones Experiment was to determine changes in optical properties and nanomechanical surface hardness of silicones exposed to various LEO AO and UV radiation fluence levels. Silicones are widely used on spacecraft, such as the use of DC 93-500 to bond cover glasses to solar cells for the ISS photovoltaic array blankets or as protective coatings on the back of solar arrays. Silicones have previously been thought of as being AO durable because they typically do not lose weight in an AO environment and the surface converts to a glassy SiO_x layer.[10] Unfortunately, the oxidized glassy layer eventually shrinks as it densifies and cracks form, exposing the underlying silicone or coated substrate to AO.[10] Surface hardness measurements for silicones exposed to various AO fluences are desired so that comparisons of equivalent fluences can be made with AO ground-laboratory exposed samples. These comparisons will allow ground-facility to in-space AO equivalent fluences to be determined, such as those reported by de Groh, Banks & Ma.[11] It is important to find a technique which enables effective fluences in ground facilities to be determined based on space data because traditional mass loss techniques do not work for silicones. Obtaining microhardness data on MISSE flown silicone samples will allow this correlation to be made for high fluence exposures. Therefore, the MISSE 2 and MISSE 4 Spacecraft Silicones Experiments each included four DC 93-500 silicone samples. Three of the four samples were covered with different thickness layers of Kapton H (0.3 mil, 0.5 mil and 0.8 mil) in order for each of the samples in the same experiment to receive different AO fluences, as the AO needs to erode through the over-laying Kapton before attacking the underlying silicone. Because the 10 mil thick silicone samples are rubbery and can stick to smooth surfaces, they were placed on 1/16" (0.16 cm) thick fused silica slides to allow post-flight optical properties to be made without the samples bending and hence inducing cracking in the glassy oxidized layer. Silicones can darken with AO and UV radiation exposure increasing the solar absorptance of the material, and hence knowledge of the degree of darkening on-orbit is desired. The MISSE 2 Spacecraft Silicones Experiment samples were flown in PEC 2 sample tray E5 (samples 2-E5-1 to 2-E5-4), along with the MISSE 2 PEACE Polymers experiment, and were exposed to ram exposure for 4 years. The MISSE 4 Spacecraft Silicones Experiment samples were exposed to ram exposure for 1 year in MISSE 4 sample tray E22 (samples 2-E22-2 to 2-E22-5).

The MISSE 2 samples all crazed due to AO exposure, which cause surface shrinking. Figure 8 shows the "mud-tile" surface that developed due to conversion of the silicone surface to a silicate glassy layer. Pre-flight and post-flight optical properties were obtained for each of the MISSE 2 samples with the fused silica base. Two of the back-up samples were also measured post-flight as control samples, with little change from the pre-flight measurements eight years earlier. The AO fluence for the MISSE 2 samples ranged from 8.43 x 10^{21} atoms/cm^2 (no cover) to 7.08 x 10^{21} atoms/cm^2 (0.8 mil thick Kapton cover). The fluence values are provided in Table 4 along with the pre-flight and control sample optical properties. Figure 9 is a graph of the total transmittance spectral data for flight sample 2-E5-1 (no Kapton H cover) and for a control sample. Although the reflectance did not change significantly, the diffuse transmittance increased, the specular transmittance decreased, the total transmittance decreased, and the solar absorptance increased significantly from 0.005 to 0.033-0.037.

Fig. 8 Post-flight photograph of MISSE 2 DC 93-500 sample 2-E5-1 showing the crazed surface.

4.3. Scattered Atomic Oxygen Characterization Experiments (MISSE 2 & 4)

When AO impinges upon a typical spacecraft surface (such as anodized aluminum) it can scatter with a lower flux and lower energy than the incoming AO. Yet scattered AO can react with, and hence, erode spacecraft components not in AO direct line of site. Therefore, it is desirable to characterize scattered AO with respect to its scattering distribution and effective erosion yield. Small (1" (2.54 cm) diameter) passive Scattered Atomic Oxygen Characterization Experiments have been designed to allow measurement of the distribution and effective erosion yield of scattered AO (see Figure 10a).

In these simple scattering chambers, ram AO passes through an aperture (0.12" (3 mm) diameter) in a SiO_2-coated polyimide Kapton H orifice plate. The AO impinges upon an aluminum disk at the bottom of the chamber and the ejected, scattered, AO can oxidize the bottom side of the Kapton H orifice plate (see Figure 10b). Sodium chloride salt particles have been dusted onto the bottom surface of the orifice plate to provide isolated protected areas. Post-flight the salt particles are washed off and profilometry is used to accurately measure the erosion as a function of ejection angle. The results of the MISSE 2 Scattered Atomic Oxygen Characterization Experiment were rather surprising in that the AO scattered almost exclusively, from the bottom aluminum plate at a 45 degree angle rather than being a cosine (Lambertian) distribution (see Figure 10c).

Table 4. MISSE 2 DC 93-500 Flight Sample Optical Property Summary Table

	DC 93-500 Flight Samples				DC93-500 Control (Back-ups)		
	2-E5-1	2-E5-2	2-E5-3	2-E5-4	Control 1	Control 2	Average
AO Fluence (atoms/cm^2)	*8.43 E+21*	*8.18 E+21*	*7.75 E+21*	*7.08 E+21*	0	0	
Total Reflectance, TR	0.074	0.072	0.070	0.071	0.071	0.071	0.071
Diffuse Reflectance, DR	0.039	0.038	0.035	0.036	0.011	0.013	0.012
Specular Reflectance, SR	0.036	0.034	0.035	0.035	0.061	0.058	0.059
Total Transmittance, TT	0.893	0.892	0.894	0.894	0.924	0.924	0.924
Diffuse Transmittance, DT	0.249	0.237	0.228	0.230	0.013	0.013	0.013
Specular Transmittance, ST	0.644	0.655	0.666	0.664	0.912	0.911	0.911
Solar Absorptance, A	0.033	0.037	0.037	0.035	0.005	0.005	0.005

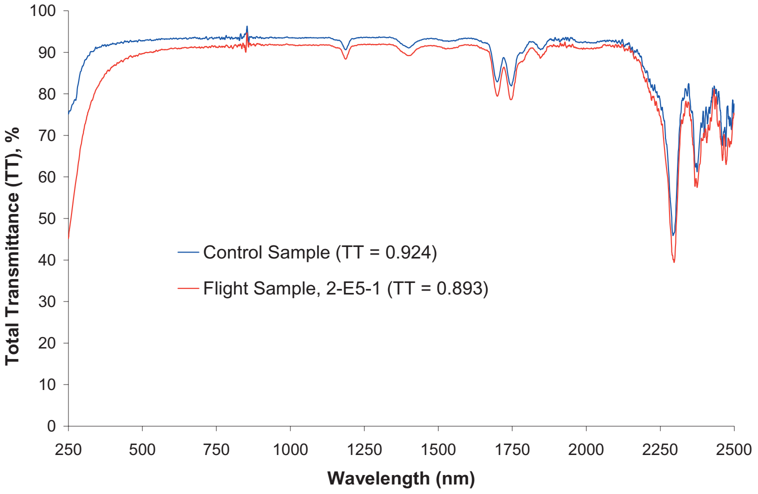
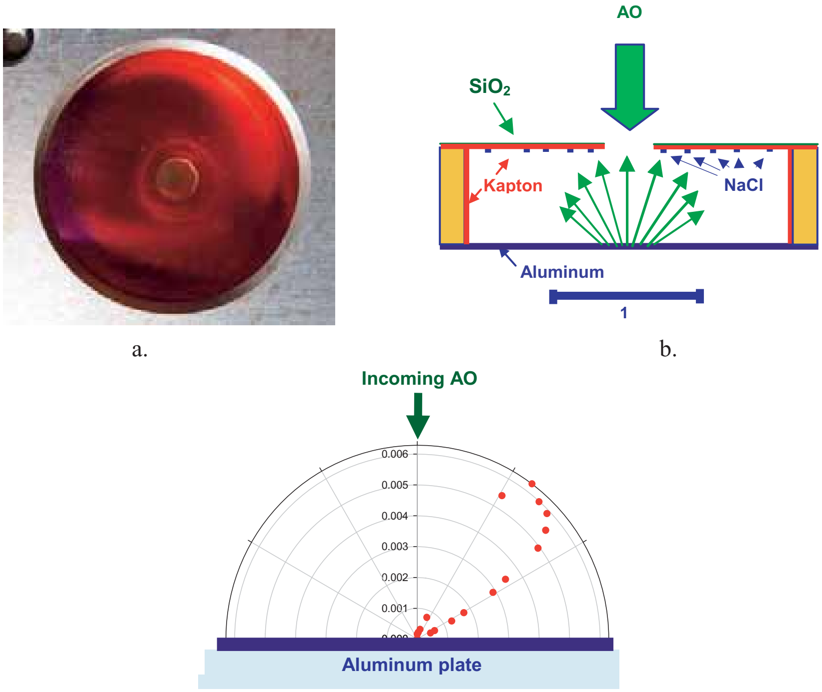


Fig. 9 Total transmittance spectral data for flight sample 2-E5-1 (no Kapton H cover) and for a back-up control sample.



a.

b.

c.

Fig. 10 MISSE 2 Scattered Atomic Oxygen Characterization Experiment: a). Post-flight photograph of the scattering chamber inside MISSE 2 E5 tray, b). Cross-section illustration of experiment, and c). Scattered AO angular erosion distribution.

The effective erosion yield for Kapton H of the scattered AO was found to be 6.54 x 10^{-25} cm^3/atom which is 21.8% of that of LEO AO for Kapton H. Details of the experiment and the results are reported by Banks et al., 2006.[12]

4.4. Double SiOx-Coated Kapton Ground to Space Erosion Correlation Experiment (Mass Loss) (MISSE 2 & 4)

4.4.1. Experiment Description and Results

The ability to predict the durability of materials in the LEO environment by exposing them in ground-based facilities is important because one can achieve test results sooner, expose more types of materials, and do it much more cost effectively than to test them in flight. Flight experiments to determine the durability of groups or classes of materials that behave similarly are needed in order to provide correlation of how much time in ground-based facilities represents a selected duration in LEO for the material type of interest. An experiment was designed and flown on the ram facing surfaces of MISSE 2 (approximately 4 years of exposure in LEO) and MISSE 4 (approximately 1 year of exposure in LEO) in order to develop this type of correlation between ground-based radio frequency (RF) plasma exposure, ground-based thermal energy directed AO beam exposure, and LEO exposure for coated Kapton based on mass loss. The experiment consisted of four samples (two for each MISSE flight) of Kapton H polyimide coated with approximately 1300 angstroms of silicon dioxide by Sheldahl, Inc. Two of the samples were exposed to an AO effective fluence of approximately 6 x 10^{19} atoms/cm^2 in a RF plasma prior to flight and the remaining two were exposed to a thermal energy directed beam to an AO effective fluence of approximately 1 x 10^{21} atoms/cm^2 prior to flight. Mass change for each sample was measured for the ground facility exposures. One of the RF plasma exposed samples, and one of the directed beam exposed samples was then flown on MISSE 2 and the remaining pair was flown on MISSE 4 for comparison. The directed beam exposed samples have not been analyzed yet but the pre-flight RF plasma exposed samples were exposed again post-flight in the RF plasma and the mass loss was recorded. This second exposure was performed in order to determine if the erosion would be the same as it had been in the same facility pre-flight, which would indicate if the sample had been damaged or not during flight, and hence if defects on the surface were those that were resident pre-flight. The slopes of the mass change vs. fluence plots were then used to develop a correlation factor for predicting the durability of coated Kapton in a RF plasma.

Results of these tests are shown in Figure 11 for the RF plasma exposed samples. Comparison of the slopes on the plots shows that there is good agreement between the pre-flight and post-flight mass loss data. The correlation factor for RF ground-based exposure to in-flight exposure for coated Kapton is approximately 18 ± 2.[13] This would indicate that exposure in a ground-based RF plasma system for a particular effective AO fluence would produce the same amount of erosion for a coated Kapton sample with approximately a factor of 18 more fluence exposure in LEO. This knowledge can be used to more accurately predict the performance of coated polymers such as coated Kapton in LEO through ground-based exposure testing.

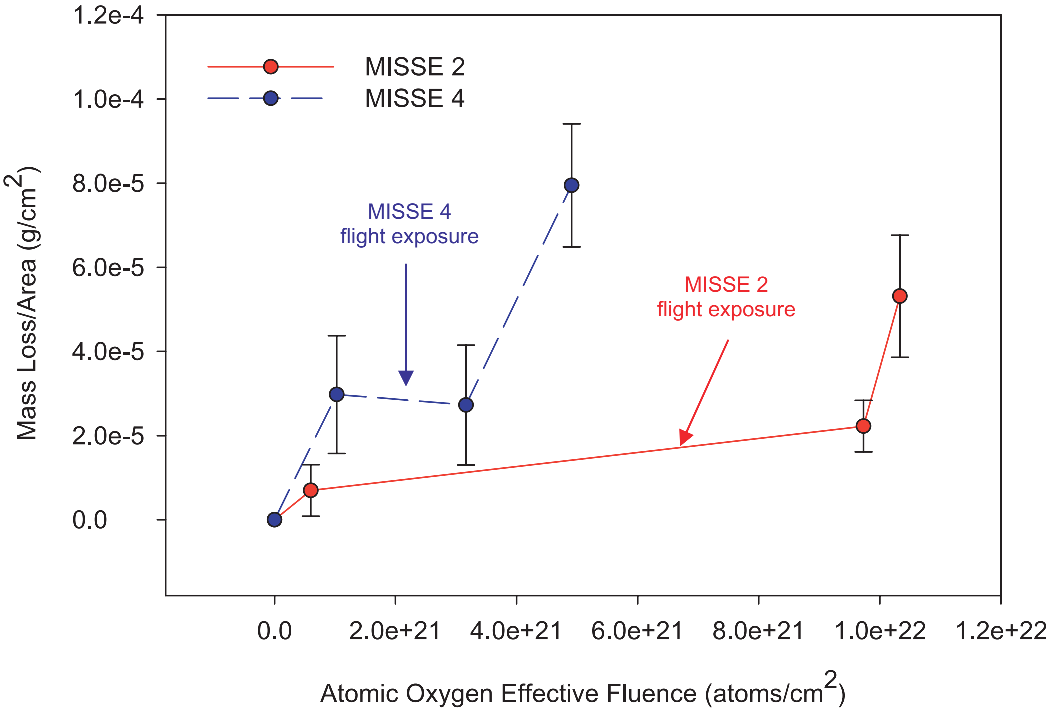
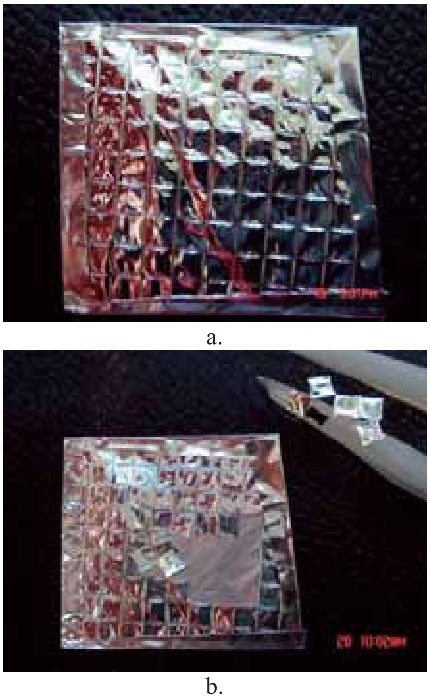


Fig. 11 Mass loss data for MISSE 2 and MISSE 4 RF plasma samples for ground pre-flight, during flight and ground post flight exposure to AO.

4.4.2. Application of MISSE 2 Results to Hubble Space Telescope (HST) Servicing Mission 4 (SM4)

For HST SM4, it was necessary to determine if there would be a hazardous condition for astronauts and the equipment if the double aluminized Kapton thermal insulation blanket covering the outside of HST near the site of the proposed EVA would be damaged enough by exposure to the environment that pieces of the blanket would break off during the EVA. A section of the insulation blanket used on HST was exposed in an RF plasma to the point that the blanket began to break apart. In order to determine the amount of real time this would represent in LEO, the MISSE Double SiO_x Coated Kapton Ground to Space Erosion Correlation Experiment correlation results were used comparing the RF plasma erosion for coated Kapton to that in LEO on MISSE. The effective fluence to make the blanket fail in the RF plasma facility was multiplied by the RF facility correlation factor 18 to obtain the space fluence that this would represent. Results were able to show that the condition of the thermal blanket at the time of servicing mission 4 would not pose a hazard for the EVA. Figure 12a and 12b show the thermal blanket after an equivalent exposure of that near the servicing mission and at failure, respectively. The fluence required to make the blanket fail was much greater than that which HST would experience prior to the servicing mission. These tests, which utilized the MISSE flight data for ground-facility calibration, directly impacted the decision to eliminate a planned SM4 EVA task (Bay 7 multilayer insulation coverage), thus freeing time to perform other crucial tasks and potentially reducing critical EVA time.

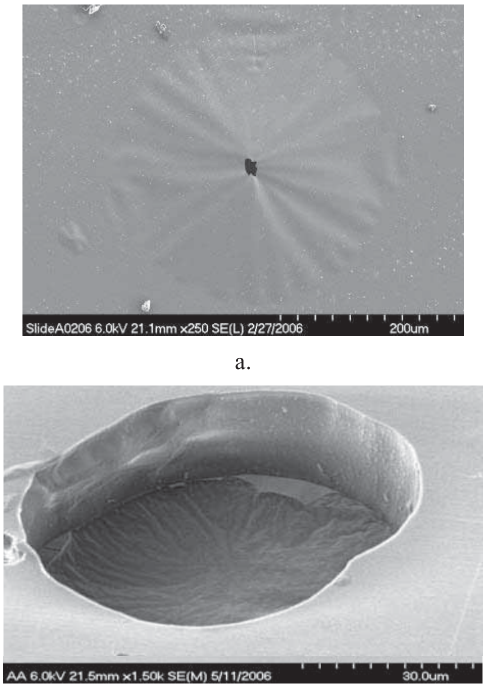

a.

b.

Fig. 12 Photo of HST Kapton thermal blanket: a). Segment after effective AO exposure near that for HST servicing mission 4 and b). At point of failure showing segments of the quilted thermal blanket detaching.

4.5. AO Undercutting Erosion SiO_x Double-Coated Kapton H (Undercut Cavities) (MISSE 2 & 4)

The AO Undercutting Erosion SiO_x Double-Coated Kapton H investigation is similar to the Double SiO_x-Coated Kapton Ground to Space Erosion Correlation Experiment, but the erosion characterization in this experiment was based on undercut cavity growth in addition to mass loss, for both in-space AO exposure (hyperthermal) and RF plasma AO exposure (thermal). There are a total of four samples of 0.001" (0.025 mm) thick Kapton H polyimide coated with ≈1300 angstroms of silicon dioxide by Sheldahl, Inc. that were flown on MISSE 2 and MISSE 4. Two of the four samples were exposed to an AO effective fluence of 4.03 x 10^{21} atoms/cm^2 in a RF plasma prior to flight, and the undercut cavities and mass loss were documented prior to flight. One of the pre-exposed samples and one unexposed sample were flown on MISSE 2, and one of the pre-exposed samples and one of the unexposed samples were flown on MISSE 4. Mass and defect cavities (same cavities as documented pre-flight) were characterized after MISSE LEO AO exposure and the rate of undercut growth was determined. Figure 13a shows a defect site in the protective coating of the MISSE 2 flight sample. Figure 13b shows an image of the shape of an undercut cavity post-flight.



a.

b.

Fig. 13 Protective coating defect and undercut cavities: a). Undercut cavity at a protective coating defect site in MISSE 2 flight sample, and b). Undercut cavity after removal of top SiO_X protective coating.

The growth of the undercut cavities was found to be significantly smaller in LEO than in a RF plasma asher environment. Figure 14 compares optical microscope photos of a pair of defect sites after two different RF plasma AO fluences. In most cases of pin window defect sites in the SiO_x protective coating, the AO exposure in space did not cause the pin windows to tear or open up in any manner which suggests that the mass loss in the protected polymer is a rather uniform and linear progression with time. Results of this experiment are reported by Snyder et al.[14]

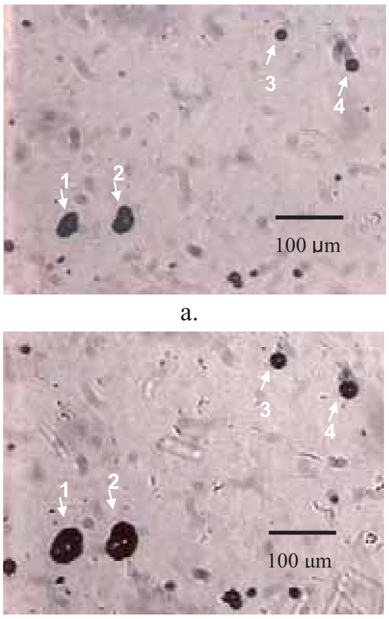


Fig. 14 Optical photos showing growth in undercut cavities after two fluences in a RF Plasma Asher: a). 2 x 10^{21}atoms/cm^2, and b). 4 x 10^{21} atoms/cm^2.

4.6. Polymer Film Thermal Control (PFTC) & Gossamer Materials Experiments (MISSE 1-4)

The main objective of the Glenn Polymer Film Thermal Control (PFTC) and Gossamer Materials experiments on MISSE 1-4 was to assess radiation and temperature effects on optical and mechanical properties of a variety of currently used and candidate thermal control materials. The materials included: traditionally used Teflon® FEP and Kapton®, various thin polymer film materials with and without coatings for light-weight inflatable and deployable structures, and polymer films with conductive coatings for charge dissipation. The development of these experiments is fully described by Dever et al., in reference 15 and is summarized here. Coatings are listed and defined in Table 5 and samples are listed in Table 6. For polymers with coatings, the material description indicates the various layers from the front space-facing surface to the back surface in the following format: front surface coating(s) if used/ polymer/back surface coating(s). Also shown in Table 6 are the MISSE experiment PECs and whether the samples were on a carrier surface which was AO-facing (ram facing) or non-AO facing (wake facing). The various analyses that were planned for each material type are also indicated.

Tensile test samples were fabricated using a die manufactured according to specimen “Type V” under the American Society for Testing and Materials (ASTM) Standard D-638. In order to occupy the least area possible on the MISSE trays, tensile specimen holders were designed to allow the gage area of samples to receive full space exposure while the grip ends were wrapped around mandrels (~4.8 mm diameter) at the edges of the gage area and secured underneath the exposed gage area. Specimens for optical property measurements were approximately 1” (2.54 cm) diameter. Results of optical properties analysis and tensile testing of MISSE 1 and MISSE 2 specimens are summarized in the sections below. Full details on the analyses of the MISSE 1 & 2 PFTC and Gossamer Materials experiments are provided by Dever et al., 2006.[16]

4.6.1. Optical Results

Tables 7 and 8 show optical properties changes for the MISSE 2 PFTC (AO-facing) samples and Gossamer Materials (non-AO-facing) samples, respectively. As shown in Table 7, the uncoated FEP/VDA sample on the MISSE 2 AO exposure tray experienced a significant decrease in thermal emittance, a likely result of AO erosion, which had caused a loss in FEP thickness for this non-coated sample. Among samples on the AO-facing holder, the most significant increase in solar absorptance was for the TOR LM material ($\Delta\alpha$ ~0.15), which had undergone significant visible darkening, as shown in Figure 15.

Fig. 15 TOR LM, 38.1 μm thickness post-flight (left) compared to a pristine control (right).

Table 5. Coatings used on MISSE Glenn PFTC and Gossamer Materials Samples

Coating Name	Description
VDA	Vapor deposited aluminum (VDA)
SiO$_x$-8% PTFE (NASA GRC)	Ion beam co-sputter-deposited coating: 92 % (vol.) SiO$_x$ (where x≈2) and 8% (vol.) polytetrafluoroethylene (PTFE)
SiO$_2$/Al$_2$O$_3$/Ag/Al$_2$O$_3$	Silver composite coating (CCAg) with sputter deposited coating layers of Al$_2$O$_3$, followed by silver, Al$_2$O$_3$, and SiO$_2$
Ge	Sputter deposited germanium coating
Ag/Niobium	Sputter deposited silver followed by a niobium layer
ATO/PbO	Sputter deposited coating layers of antimony tin oxide (ATO) and lead oxide (PbO)
ATO	Sputter deposited antimony tin oxide

Table 6. Glenn Polymer Film Thermal Control and Gossamer Materials Samples on MISSE 1-4 and Planned Analyses

MISSE PEC: Direction Experiment Facing: Experiment:	**MISSE 1 & 2 Ram PFTC**	**MISSE 1 & 2 Wake Gossamer**	**MISSE 3 & 4 Ram PFTC**	**MISSE 3 & 4 Wake Gossamer**
Material				
25.4 μm CP1/VDA		O, T		O
SiO_x-8%PTFE/25.4 μm CP1/VDA	O, T		O, T(3)	
25.4 μm CP1 (stack)	E [6+3]		E [18+3]	
25.4 μm CP1 strip without seam				T
25.4 μm CP1 strip with seam				T
25.4 μm Upilex-S/VDA		O, T		O, T(2)
92% SiO_x-8% PTFE/25.4 μm Upilex-S/VDA	O, T		O, T(3)	
25.4 μm Upilex-S (stack)	E [6+3]		E [18+3]	
25.4 μm Kapton HN/VDA		O, T		O, T
92% SiO_x-8% PTFE/25.4 μm Kapton HN/VDA	O, T		O, T(3)	
CCAg/25.4 μm Kapton HN/VDA	O, T		O, T(2)	
127 μm Kapton HN (stack)	E [2+1]		E [6 +1]	
127 μm Kapton H (stack)	E [2+1]		E [6+1]	
25.4 μm Kapton E/VDA				O, T
Ge/25.4 μm Kapton XC (black)/Nomex scrim	OE [1]		OE [1]	
127 μm FEP/VDA	OE [1]			
50.8 μm FEP/VDA		O, T		T
50.8 μm FEP (stack of 10)				OT
50.8 μm FEP/VDA with 50.8 μm FEP cover layer				T
127 μm FEP/Ag/Niobium			OE [1]	
ATO/PbO/127 μm FEP/Ag/Niobium				T
ATO/ 127 μm FEP/Ag/Niobium	O			
92% SiO_x-8% PTFE/127 μm FEP/VDA	O, T		O, T(3)	
92% SiO_x-8% PTFE/127 μm FEP/VDA, in tension			T(3)	
92% SiO_x-8% PTFE/50.8 μm FEP/VDA			O, T(3)	
25.4 μm polyphenylene benzobisoxazole (PBO)		O, T		O, T
38.1 μm TOR LM	O		O, T(2)	
Sapphire (Al_2O_3) disk	W(2)		W(2)	

E = erosion yield specimen
[#] = Number of sample layers stacked together as 1 sample
O = optical properties specimen
OE = sample used for both optical and erosion yield measurements
T = tensile specimen
OT = specimen for optical and mechanical properties measurements
W = witness for contamination
(#) = Number of samples included in experiment

Table 7. Solar Absorptance and Thermal Emittance of Ram-Facing MISSE 2 PFTC Experiment Samples

Sample Description	**Solar Absorptance**			**Thermal Emittance**		
	Flight	**Control**	**$\Delta \alpha$**	**Flight**	**Control**	**$\Delta \varepsilon$**
92% SiO_x-8% PTFE/127 μm FEP/VDA	0.139	0.149	-0.010	0.858	0.862	-0.004
127 μm FEP/VDA	0.133	0.126	0.007	0.833	0.857	-0.024
ATO/127 μm FEP/Ag/Niobium	0.083	0.087	-0.004	0.868	0.872	-0.004
92% SiO_x-8% PTFE/25.4 μm Kapton HN/ VDA	0.368	0.361	0.007	0.699	0.698	0.001
CCAg/25.4 μm Kapton HN/VDA	0.105	0.088	0.017	0.578	0.615	-0.037
Ge/25.4 μm Black Kapton/Nomex scrim	0.539	0.502	0.037	0.877	0.874	0.003
92% SiO_x-8% PTFE/25.4 μm Upilex S/VDA	0.509	0.464	0.045	0.751	0.690	0.061
92% SiO_x-8% PTFE/25.4 μm CP1/VDA	0.283	0.233	0.050	0.660	0.661	-0.001
38.1 μm TOR LM*	0.287	0.136	0.151	Not Measured		

* TOR LM was non-opaque. Solar absorptance was calculated based on reflectance and transmittance. Thermal emittance, measured with an infrared reflectometer, was not measured for this non-opaque sample.

Table 8. Solar Absorptance and Thermal Emittance of Wake-Facing MISSE 2 Gossamer Materials Experiment Samples

Sample Description	Solar Absorptance			Thermal Emittance		
	Flight	Control	Δ α	Flight	Control	Δ ε
50.8 μm FEP/VDA	0.128	0.120	0.008	0.706	0.741	-0.035
25.4 μm Kapton HN/VDA	0.400	0.346	0.054	0.648	0.677	-0.029
25.4 μm Upilex S/VDA	0.487	0.437	0.050	0.649	0.675	-0.026
25.4 μm CP1/VDA	0.255	0.223	0.032	0.544	0.637	-0.093

As shown in Table 8, polymer films, Kapton HN, Upilex S, and CP1, all showed moderate increases in solar absorptance (Δα ~0.03 to 0.05). Also, as shown in Table 8, all of these “non-AO” wake facing polymer films experienced significant decreases in thermal emittance, the likely result of the AO erosion. Whereas these samples were on wake-facing trays, unexpected ISS maneuvers caused brief ram-exposure of the wake-facing surfaces, resulting in exposure to some AO (≈2 x 10^{20} atoms/cm^2). Also, note that no optical properties are given for the PBO sample which was completely eroded/degraded post-flight.

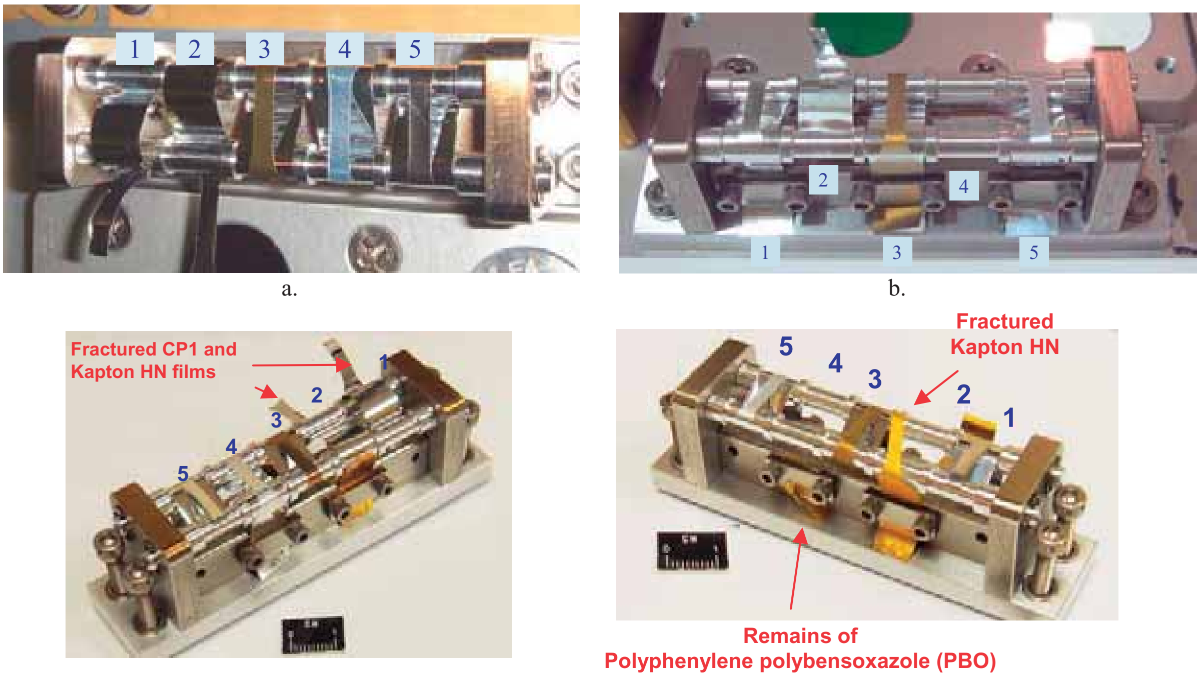
4.6.2. Tensile Results

Figure 16 shows photographs of the MISSE 1 tensile samples post-flight. Mechanical properties are provided in Table 9 for the tensile test samples which were intact post-flight. For samples already broken by the time of sample de-integration, samples were not tensile tested, and their condition is noted in the table.

5. MISSE 3 & 4 Experiments

Glenn has eight materials durability experiments (with a total of 71 samples) that were flown as part of MISSE 3 & 4. Table 10 provides a list of the Glenn MISSE 3 & 4 experiments along with the on-orbit orientation, the individual experiment objective and the number of samples. As stated before, the Glenn MISSE 3 & 4 experiments were all passive experiments. The MISSE 3 & 4 trays were successfully flown and retrieved after 1 year of space exposure. Figure 17 shows on-orbit photos of both ram- and wake-facing surfaces of MISSE 3 & 4 (Trays 1 and 2, respectively). Post-flight sample documentation and analyses have begun on some of these experiments.

The following MISSE 3 & 4 experiments were very similar to experiments flown on MISSE 1 & 2, and thus are described in the MISSE 1 & 2 Experiment sections above: Double SiO_x-Coated Kapton (Mass Loss), AO Undercutting Erosion (Undercut Cavities), AO Scattering Chamber, Spacecraft Silicone Experiment, Polymer Film Thermal Control & Gossamer Materials Experiments (2 experiments) and Stacked FEP Experiment (listed as part of the Polymer Film Thermal Control & Gossamer Materials Experiments). The Electromagnetic Interference Shielding experiment was the only experiment flown on MISSE 3 & 4, which was not also flown on MISSE 1 & 2. The following section describes this experiment.



a. b.

c. d.

Fig. 16. Post-flight Photographs of MISSE 1 tensile holders: a). 1-Q1 at time of de-integration, b). 2-Q2 at time of de-integration, c). 1-Q1 showing broken samples, and d). 2-Q2 showing broken samples.

Table 9. Mechanical Properties of MISSE 1 (1-Q1 and 2-Q2 Holder) PFTC and Gossamer Materials Samples

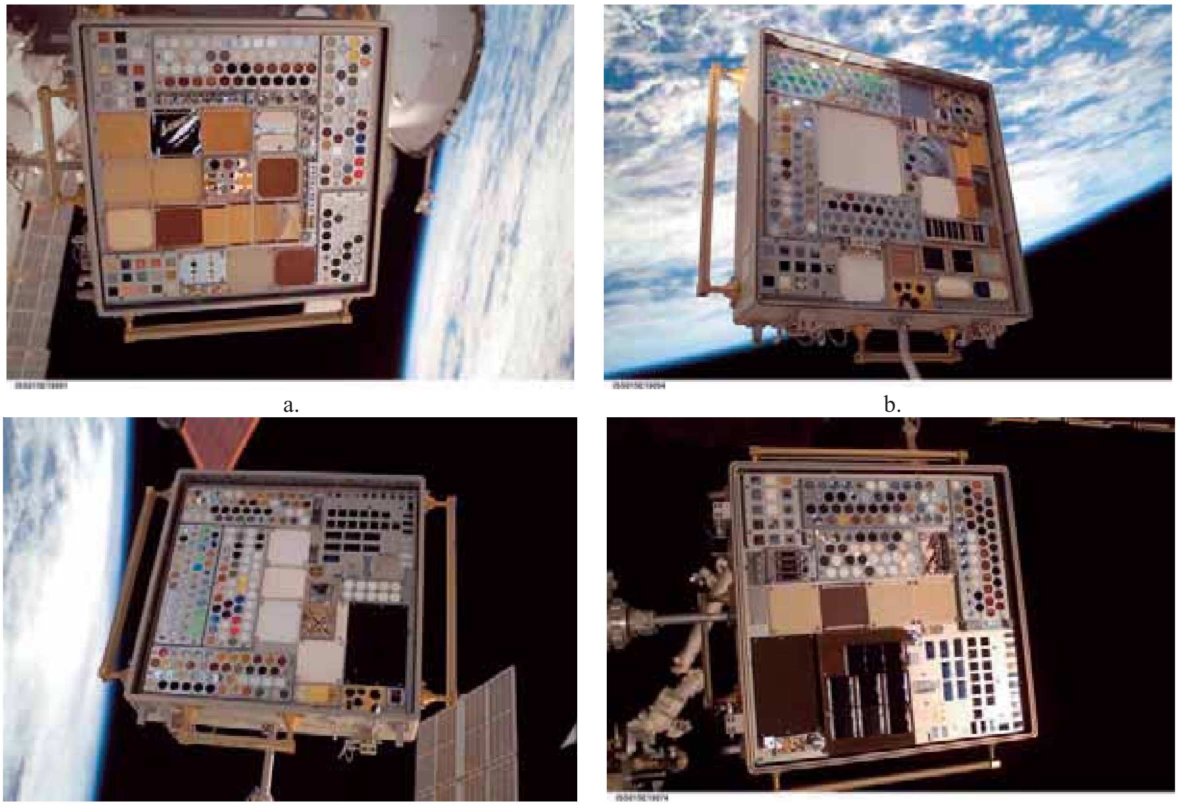
Sample Description	**UTS (MPa)**			**Elongation (%)**		
	Flight	**Controls, Avg. (2)**	**% Loss**	**Flight**	**Controls, Avg. (2)**	**% Loss**
MISSE 1,1-Q1 Holder (AO-Facing):						
1 - 92% SiO_x-8% PTFE/25.4 μm CP1/VDA	Sample broken during flight due to AO erosion at coating crack					
2 - 92% SiO_x-8% PTFE/25.4 μm Kapton HN/VDA	Sample broken during flight due to AO erosion at coating cracks					
3 - 92% SiOx-8% PTFE/25.4 μm Upilex S/ VDA	210.5	330.2	36.2	4.1	12.6	67.5
4 - 92% SiOx-8% PTFE/127 μm FEP/VDA	13.6	19.4	29.7	62.2	234.2	73.4
5 - CCAg/25.4 μm Kapton HN/VDA	133.8	203.7	34.3	7.9	36.2	78.2
MISSE 1, 2-Q2 Holder ("Non-AO" Tray):						
1 - 25.4 μm CP1/VDA	88.9	87.4	-1.8	6.7	7.9	14.6
2 - 25.4 μm Kapton HN/VDA	AO eroded due to unplanned ISS maneuvers – too eroded to test					
3 - 25.4 μm Upilex-S/VDA	AO eroded due to unplanned ISS maneuvers – too eroded to test					
4 - 25.4 μm PBO	Sample observed to be broken during flight					
5 - 50.8 μm FEP/VDA	13.9	18.2	23.4	26.7	181.1	85.3

Table 10. Glenn's MISSE 3 & 4 Experiments (71 Samples)

Glenn Experiment	**Orientation**	**# Samples**	**Experiment Objective**
Double SiO_x-Coated Kapton (Mass Loss)	Ram	2	To determine AO undercutting rate dependence in space as compared to ground-facility (mass loss)
AO Undercutting Erosion (Undercut Cavities)	Ram	2	To determine AO undercutting rate dependence in space as compared to ground-facility (undercut cavities)
AO Scattering Chamber	Ram	1	To determine scattered AO erosion characteristics for undercutting modeling
Spacecraft Silicones	Ram	4	To determine changes in optical properties and nanomechanical hardness for ground-testing
Polymer Film Thermal Control (PFTC)	Ram & Wake	42	To assess radiation and temperature effects on a variety of currently used and candidate thermal control materials
Gossamer Materials	Ram & Wake	15	To assess solar exposure, radiation, and temperature effects on candidate materials for gossamer structures
Stacked FEP	Wake	1	To determine gradient in FEP embrittlement as a function of depth into the stack
Electromagnetic Interference Shielding	Wake	4	To determine the environmental durability of radiation shielding composites

6. **MISSE 5 Experiments** (4 experiments, 105 samples)

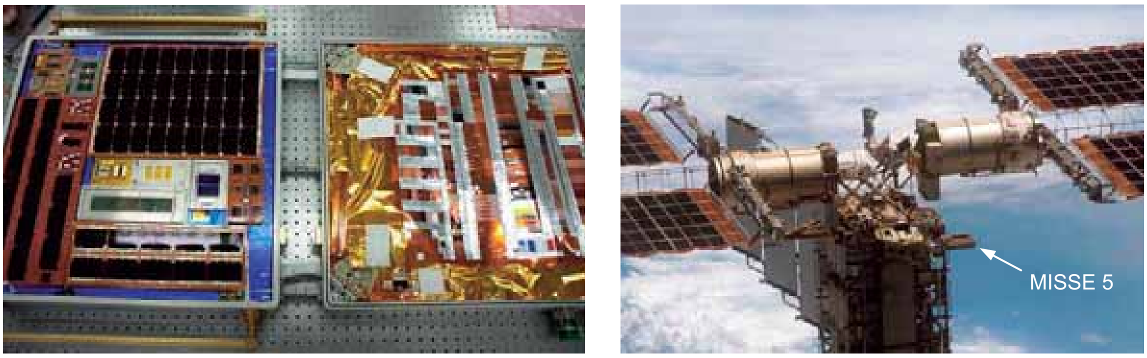
MISSE 5 was placed in a zenith/nadir position on the ISS during the STS-114 mission, shortly after retrieval of MISSE 1 & 2. Hence MISSE 5 was launched before MISSE 3 & 4, which were launched and placed outside of ISS in August 2006 during the STS-121 mission. MISSE 5 contained two active and one passive investigations: The FTSCE, an active experiment that tested the performance of 36 current and advanced generation solar cells for use on future spacecraft; The active Second Prototype Communication Satellite System (PCSat-2) that provided a communications system and tested the Amateur Satellite Service off-the-shelf solution for telemetry command and control; and the passive MISSE 5 Thermal Blanket Materials Experiment, which consisted of several individual experiments to measure the degradation of more than 200 materials in the space environment. Figure 18 shows a pre-flight photograph of MISSE 5 and an on-orbit photo taken during the STS-114 mission. MISSE 5 was exposed to the LEO space environment for 13 months. It was retrieved during the STS-115 mission in September 2006. The flight experiment was examined post-flight at the Naval Research Laboratory in October 2006. Figure 19 shows on-orbit and post-flight photos of the Thermal Blanket Materials Experiment.



a. b.

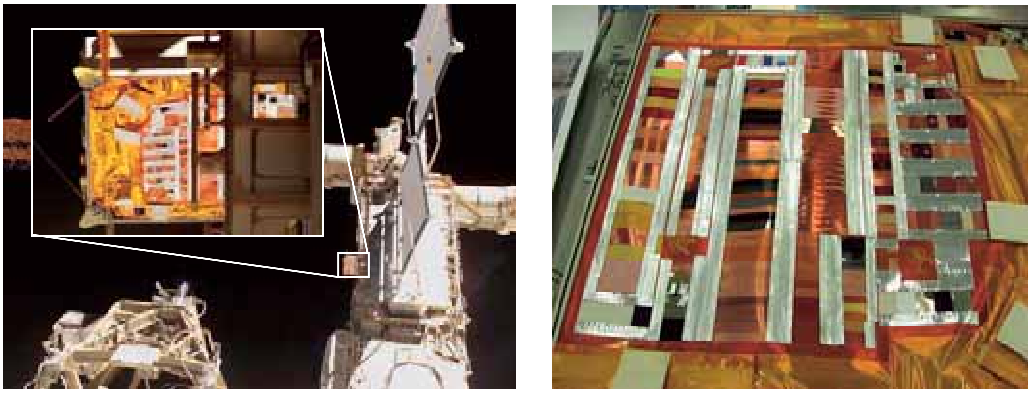
c. d.

Fig. 17 On-orbit photos of MISSE 3 & 4 taken during Expedition 15: a). PEC 3 Tray 1 (ram facing), b). PEC 3 Tray 2 (wake facing), c). PEC 4 Tray 1 (ram facing), and d). PEC 4 Tray 2 (wake facing).



a. b.

Fig. 18 MISSE 5: a). Pre-flight, and b). On-orbit photo taken during STS-114 of the zenith facing experiments.



a. b.

Fig. 19 MISSE 5 Thermal Blanket Experiment: a). On-orbit photo taken during STS-114, and b). Post-flight.

Table 11. Glenn's MISSE 5 Thin Film Polymers Experiments (85 Glenn & 20 Team Cooperative Samples)

Glenn Experiment	# Samples	Experiment Objective
Polymer Film Thermal Control (PFTC)	33	Assess solar exposure, radiation, and temperature effects on currently used and candidate thermal control materials
PEACE Polymers	49	Determine AO erosion yield of a wide variety of polymers with low solar radiation
Spacecraft Silicones	3	Determine changes in optical properties and nanomechanical hardness for ground-testing
Team Cooperative (Fluorinated Polymers)	20	Determine space environmental durability of fluorinated polymers (w/ Boeing, NASA MSFC & Montana State University)

NASA Glenn has four thin film polymer durability experiments (with 105 samples) flown as part of the MISSE 5 Thermal Blanket Materials Experiment. These experiments are listed in Table 11 along with the number of samples and the individual experiment objective. The Thermal Blanket Materials Experiment consists of thin film or flexible samples that were taped and then stitched onto a Kapton blanket. Post-flight sample documentation and analyses have begun on the Glenn MISSE 5 experiments.

6.1. PEACE Polymers and Spacecraft Silicones Experiments (MISSE 5)

The MISSE 5 PEACE Polymers experiment consists of 49 - 0.5" (1.27 cm) x 1.5" (3.81) rectangular samples, with a total of 53 different polymer materials, exposed to the space environment on the exterior of ISS as part of the MISSE 5 Thermal Blanket Experiment. The majority of samples were thin film flexible polymers, as required. But, a few samples were rigid. Those samples were cut into small pieces and sandwiched between two pieces of either Kapton H or Kapton HN using Y966 acrylic adhesive, and a window was cut into the space exposed Kapton cover providing a window for exposure. Because the samples were taped and then sewn on the Kapton blanket substrate, and hence mass loss was not possible, all samples were dusted with fine salt-spray particles to provide protection from AO erosion, so that recession depth measurements could be made post-flight for Ey determination.

The MISSE 5 PEACE Polymers experiment contains the same set of polymers as the MISSE 2 experiment, with numerous additional polymers. While the MISSE 2 polymers were exposed to high AO fluence along with solar radiation exposures, the MISSE 5 polymers were exposed to low AO with very low solar radiation exposure.[17] Table 12 provides a comparison of the two experiments and their various on-orbit exposures. Hopefully, with the two experiments receiving different AO/solar radiation ratios (provided in Table 12), the combined data will provide highly desired space-flight information on the synergistic effects of solar exposure on the AO erosion of polymers. The MISSE 5 PEACE Polymers experiment has been returned to Glenn for post-flight analyses and post-flight photo-documentation has been conducted.

The Spacecraft Silicones Experiment contains three different spacecraft silicones: DC 93-500 (1.0 x 1.5" (2.54 x 3.81 cm)), CV 1144 (1.0 x 1.5" (2.54 x 3.81 cm)) and MD944 adhesive tape (0.5 x 1.5" (1.27 x 3.81 cm)). It is desired to evaluate the changes in surface hardness with space exposure and compare the data with other flight data and ground-laboratory exposed samples.

6.2. Polymer Film Thermal Control (PFTC) (MISSE 5)

The MISSE 5 PFTC materials experiment consists of 33 tensile specimens including many of the same types of polymer films exposed in the Glenn MISSE 1-4 Gossamer Materials and PFTC experiments. The goal of this experiment is to examine effects of the anti-solar, or nadir facing, space environment on mechanical properties changes of polymer films. Eleven types of specimens were included, each in triplicate. Configurations of these polymer film samples are shown in Table 13. Results from this experiment will be compared to ram and wake facing polymers in the MISSE 1-4 Gossamer Materials and PFTC experiments.

6.3. Team Cooperative Experiment (MISSE 5)

The Team Cooperative Fluorinated Polymers Experiment is a collaborative effort between NASA Glenn, NASA Marshall Space Flight Center, Boeing Phantom Works and Montana State University. The objective of this experiment was to determine the space environmental durability of fluorinated polymers in a nadir-facing orientation. Specifically, it is desired to provide evidence of degradation mechanisms, to relate degradation rates to structural features, to provide selected property measurements of the material specimens, and to correlate the results with other flight experiments. The experiment consists of 20 – 0.75" (1.91 cm) x 2.5" (6.35 cm) rectangular samples. The MISSE 5 Team Cooperative Experiment samples are listed in Table 14. Each of the samples was salt-spray dusted in a ¼" wide strip at one end, to allow for post-flight recession depth measurements to be made. Recession rate measurements using Kapton H indicate an AO fluence exposure of ~1.8 x 10^{20} atoms/cm^2.[17] Initial results of analyses can be found in reference 17.

Table 12. Comparison of the MISSE 2 & MISSE 5 PEACE Polymers Experiments

	MISSE 2 PEACE	**MISSE 5 PEACE**
# Samples	41	52 (56 materials)
Ey Characterization Technique	Mass loss	Recession depth
Orientation	Ram	Nadir
AO Fluence (atoms/cm^2)	8.43×10^{21}	1.81×10^{20}
Solar Exposure (Equivalent Sun Hours, ESH)	6300 (≈770 albedo, 5530 direct)	525 (≈360 albedo, 165 direct)
AO/Solar Ratio (atoms/cm2 ESH)	1.3×10^{18}	3.5×10^{17}

Table 13. MISSE 5 PFTC Samples

Polymer (Film Thickness)	**Sample Configurations Exposed**		
	Uncoated	**Coated (SiO_x-8% PTFE)**	**Coated (other)**
Teflon FEP (50.8 μm)	X	X	
Upilex S (25.4 μm)		X	
CP1 (25.4 μm)		X	
Kapton E (50.8 μm)	X		Si (front), VDA (back)
PTFE (76.2 μm)	X	X	
Kapton HN (50.8 μm)	X	X	
TOR LM (50.8 μm)	X		

Table 14. MISSE 5 Team Cooperative Experiment Sample List

MISSE 5	**Chemical Name**	**Trade Name**
B-01	Polytetrafluoroethylene (PTFE)	PTFE T-100
B-02	0.1 mil Kapton over PTFE	PTFE T-100
B-03	0.3 mil Kapton over PTFE	PTFE T-100
B-04	Fluorinated ethylene propylene (FEP)	Teflon FEP
B-05	0.3 mil Kapton over FEP	Teflon FEP
B-06	0.3 mil Kapton over THV	AMD 313
B-07	Crystalline polyvinylfluoride (PVF) w/ white pigment	White Tedlar
B-08	Ethylene-tetrafluoroethylene (ETFE) or Tetrafluoroethylene-ethylene copolymer	Tefzel LZ
B-09	Perfluoroalkoxy (PFA)	Teflon PFA LP
B-10	Tetrafluoroethylene/ hexafluoro propylene/vinylidene fluoride (THV)	AMD 313
B-11	Ethylene-chlorotrifluoroethylene (ECTFE)	Halar 300
B-12	Polyvinylidene fluoride (PVDF)	Kynar 740
B-13	Amorphous fluoropolymer (AF)	Teflon AF 1601
B-14	Polyimide (PMDA)	Kapton H
B-15	0.3 mil Kapton over PVDF	Kynar 740
B-16	Polyethylene (PE)	Alathon
B-17	Polypropylene (PP)	Profax, C28 PP
B-18	0.3 mil Kapton over PVF w/ white pigment	White Tedlar
B-19	Polychlorotriflfuoroethylene (PCTFE)	Aclar, Kel-F, Neoflon M-300
B-20	Ag/Fluorinated ethylene propylene (FEP)	Silvered-Teflon

6.4. The Forward Technology Solar Cell Experiment (MISSE 5)

Glenn’s participation on MISSE 5 also included a substantial contribution to MISSE 5’s primary experiment, the “Forward Technology Solar Cell Experiment” (FTSCE) built by the Naval Research Lab.[18] The goal of FTSCE was to rapidly put current and future generation space solar cells on orbit and provide in-situ performance measurements for these technologies. Glenn designed and built the measurement electronics and software for the FTSCE.[19] Figure 20 shows the FTSCE measurement electronics consisting of nine data acquisition (DAC) boards and a motherboard that managed communication and data storage and measurement acquisition. Additionally, Glenn provided thin film solar cells and GaAs/Si cells for the experiment.[20] Results for many of the solar cells are detailed in reference 21 and 22.

For MISSE 7 Glenn is designing a communications interface board to route and manage communications of 20 active experiments. It provides a bi-directional RS485 bus to experiments and routes data and commands via the ISS 1553B low rate telemetry bus to and from the ground for both 7A and 7B. Glenn also has four active experiments on MISSE 7A consisting of AO fluence monitors (discussed in Section 8.2), a Makel hydrogen/oxygen sensor, a demonstration of SiC Junction Field Effect Transistors (JFETs) designed for low-power analog and digital circuits in extreme environments, and a re-flight of the MISSE 5 FTSCE, called FTSCE-II on MISSE 7A.

7. MISSE 6A & 6B Experiments (6 active & 5 passive experiments, 168 samples)

Table 15 provides a list of the Glenn MISSE 6A & 6B experiments along with the objective, number of samples, the on-orbit orientation, and whether it is an active or passive experiment. There are a total of 11 Glenn experiments, six are active and 5 are passive. As noted previously, MISSE 6 was delivered to ISS during the STS-123 mission, and both 6A and 6B were placed outside of the Columbus Module on March 22, 2008 in ram/wake orientations. Figure 21 is a photo showing the location of MISSE 6A & 6B on the Columbus module, and includes a close-up image of the ram surfaces of both PECs. These images were taken during the STS-123 mission.

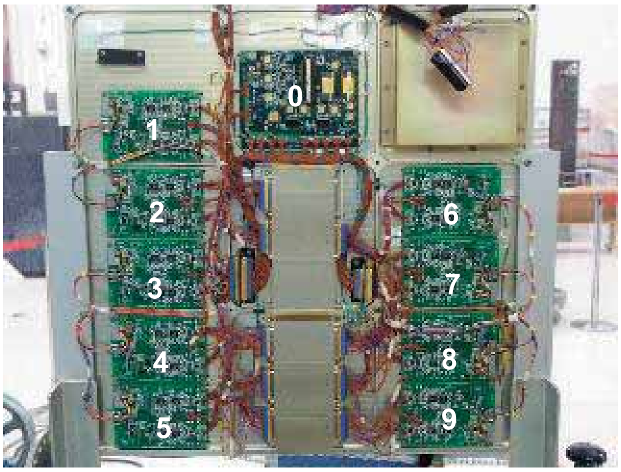
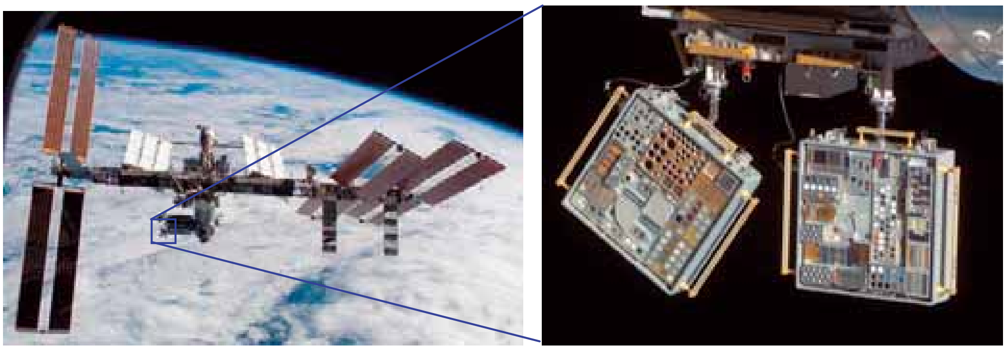


Fig. 20 Photograph of the DAC (1-9) boards and main microprocessor board (0) that perform the FTSCE electrical measurements. The metal box in the upper right is the power control unit (PCU). The metal boxes in the center route wires from the solar cells mounted on the opposite side and serve to maintain a Faraday cage around the measurement electronics.[18]

Table 15. Glenn's MISSE 6A & 6B Experiments (168 Samples)

Glenn Experiment	**6A or 6B Orientation**	**# Samples**	**Experiment Objective**	**Active / Passive**
Stressed PEACE Polymers Experiment	6A Ram	27	To determine if the AO Ey is dependent upon stress	P
AO Pinhole Camera (Stressed PEACE)	6A Ram	1	To document the arrival direction of AO impinging upon the MISSE 6A ram tray	P
Solar Cells for Exploration Missions (Stressed PEACE)	6A Ram	2	To evaluate silicone (DC 93-500) coated triple junction solar cells with and without polyhedral oligomeric silsesquioxane (POSS) coatings	P
Polymer Film Tensile Experiment	6A Wake & 6B Ram	3 Active & 38 Passive	To measure radiation induced tensile failure of stressed and unstressed thin film polymer tensile samples	A & P
Indium Tin Oxide (ITO) Degradation Experiment	6A Wake & 6B Ram	4	To investigate the effects of space solar exposure on optical and electrical properties on ITO coatings	A
Cermet Coatings and Thermal Control Paints Experiments	6A Wake & 6B Ram	8	To evaluate the LEO durability of Cermet coatings	A
Atomic Oxygen Fluence Monitor	6B Ram	1	To actively measure the cumulative AO fluence arriving at the surface of the PEC	A
Scattered Space Atomic Oxygen Experiment (SSAOE)	6B Ram	4 Active & 9 Passive	To actively measure direct ram & scattered AO erosion and to passively measures angular distribution of AO scattered from inclined angle	A & P
LIDS Seals for CEV	6B Ram & Wake	50	To evaluate 3 candidate elastomers for the primary mating interface seal for LIDS	P
New Thermal Control Paints Experiment	6B Wake	15	To evaluate the LEO durability of newly developed thermal control paints	P
Polymer Strain Experiment	6B Wake	6	To measure radiation-induced strain in thin film polymers as a function of exposure time on-orbit	A



a. b.

Fig. 21 Photographs of MISSE 6A and 6B: a). Location on the ISS Columbus Module, and b). Close-up image of the ram surfaces of 6A (left) and 6B (right).

7.1. Stressed PEACE Polymers Experiment (MISSE 6A)

Several retrieved MISSE 1 & 2 samples appeared to have preferentially eroded at high stress locations; an example of this is observed in several of the tensile samples in the Glenn PFTC & Gossamer Materials Experiments. Therefore, the objective of the Stressed PEACE Polymers Experiment is to compare the AO Ey of stressed and non-stressed polymers to determine if the AO erosion rate is dependent upon stress while in LEO. This experiment utilizes 2 passive experiment trays that each hold 15 – 1" (2.54 cm) square samples. Stressed sample holders were designed to fit into the 2.54 cm square area. One of the stressed sample holders loaded with a flight sample is shown in Figure 22. The experiment includes 11 stressed/non-stressed polymer pairs (PTFE, FEP, Upilex-S, CP1, Kapton CB, Kapton XC, Kapton E, Kapton H, Mylar A, low oxygen PE, and DC 93-500 silicone) and 4 polymer samples that were partially or completely eroded through all sample layers during the MISSE 2 PEACE Polymers experiment (high temperature polyimide resin PMR-15, PEI, PBI, ADC). The samples for erosion yield were thin film polymers (1 - 20 mils or 0.0254 - 0.508 mm thick) and were stacked to survive a multiple year mission (ADC was 47 mils or 1.2 mm thick). The total thickness of the stressed samples was chosen to be 20 mils (0.508 mm), so that the surface flexural stress on each sample would be the same. The samples for Ey will be characterized based on pre-flight and post-flight mass. Also included in this experiment are 2 passive solar cells with silicone and POSS coatings being evaluated for short duration or CEV-type missions, a Kapton H AO fluence witness sample and an Atomic Oxygen Pinhole Camera. The pinhole camera will document the arrival direction of AO during the mission. Atomic oxygen will pass through an orifice in a thin aluminum plate and impinge upon a Kapton H disk. The Kapton H disk will have sodium chloride salt particles on it to allow profilometry of the eroded Kapton surface to measure the amount of fluence in any particular direction. A pre-flight photograph of the Stressed PEACE Polymers Experiment is provided in Figure 23.

Fig. 22 A Stressed PEACE Polymers Experiment stressed sample holder with the Kapton H flight sample.

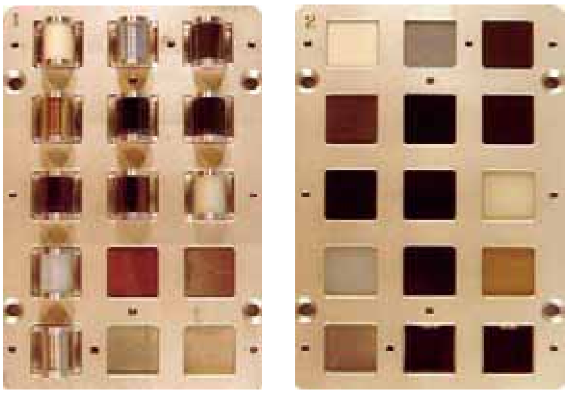


Fig. 23 Pre-flight photograph of the Stressed PEACE Polymers Experiment.

7.2. Polymer Film Tensile Experiment (MISSE 6A & 6B)

The MISSE 6 Polymer Film Tensile Experiment will measure radiation induced tensile failure of stressed and unstressed thin film polymer tensile samples. Forty-one tensile specimens were installed flat in samples holders. Twenty-nine samples were loaded with no tension and 10 samples were installed with an applied stress through a spring-loading mechanism. Examples of samples loaded under these stressed and non-stressed conditions are shown in Figure 24. Two additional samples were pulled tight when loaded. The polymer film samples in these experiments included Kapton HN, Kapton E, Kapton XC, Teflon FEP, CP1 and DC 93-500 silicone. The spring-loaded samples were mounted with stresses that represent the functional stresses expected on the James Webb Space Telescope (JWST) sunshield and potential stresses on solar sails. Depending on the application being studied, backside or front surface aluminum coatings were applied and/or other protective coatings, such as SiO_x-PTFE, were included. The resistance across the length of three samples is actively monitored on-orbit to document tensile failure versus exposure. Seven stressed and 17 unstressed samples are mounted on MISSE 6A Tray 2 (wake facing) and are being exposed to solar radiation with minimal AO. Three stressed, 12 unstressed and 2 tightly pulled samples are mounted on MISSE 6B Tray 1 (ram facing) and are being exposed to AO and solar radiation.

Fig. 24 Two sets of tensile test samples in fixtures on MISSE 6 Polymer Film Tensile Experiment. For each set, the left hand sample is installed in a spring-loaded fixture to apply stress and the right hand sample is installed with no tensile stress applied.

7.3. Indium Tin Oxide (ITO) Degradation Experiment (MISSE 6A & 6B)

The purpose of the ITO Degradation Experiment is to investigate the effects of space solar exposure on optical and electrical properties of transparent conductive ITO coatings. Two experiment fixtures will be included on MISSE 6; one is located on MISSE 6A Tray 2 (wake facing) receiving solar radiation with minimal AO, and one is located in MISSE 6B Tray 1 (ram facing) receiving AO and solar radiation. These experiments will actively measure changes in transmittance of quartz with and without an ITO coating and will actively monitor the resistance of the ITO coating over time on-orbit. Figure 25a shows an exploded drawing of the experiment and Figure 25b is a pre-flight photograph showing a top view of one of the experiment fixtures.

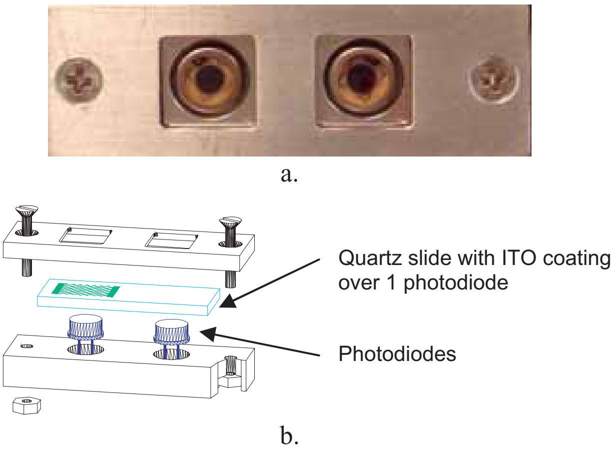


Fig. 25 Indium Tin Oxide Degradation Experiment showing: a). a breakout schematic of the experiment, and b). a photograph showing a top view of the experiment.

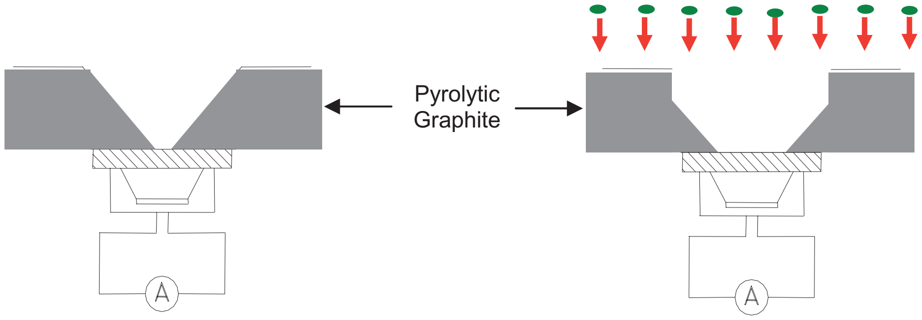
7.4. Cermet Coatings and Thermal Control Paints Experiment (MISSE 6A & 6B)

The objective of the Cermet Coatings and Thermal Control Paints Experiment is to evaluate the in-space durability of newly developed cermet coatings and thermal control paints. It is an active experiment with two sets of four samples (each 0.5” (1.27 cm) in diameter). One set is being flown on the wake side of 6A and the second is being flown on the ram side of 6B. The cermet coatings (2 samples per set) were developed originally for solar Stirling space power systems and may have terrestrial applications.[23] One sample has a titanium and aluminum oxide cermet coating. The second sample has a molybdenum and aluminum oxide cermet coating. The thermal control paints (2 samples per set) are described in the New Thermal Control Paints Experiments section (Section 7.8). These thermal control paints were developed under the Small Business Innovative Research (SBIR) Phase II entitled “Next Generation Advanced Binder Chemistries for High Performance, Environmentally Durable Thermal Control Material Systems”. In this SBIR effort, thermal control coating development was based on lithium silicate chemistry. The coatings in the Cermet Coatings and Thermal Control Paints Experiment were applied to thermally isolated nickel disks that are each instrumented with a thermocouple and the temperature data will be stored in on-board data loggers. A pre-flight photograph of one set of samples is shown in Figure 26.

Fig. 26 Pre-flight photograph of one set of Cermet Coatings and Thermal Control Paints Experiment samples.

7.5. Atomic Oxygen Fluence Monitor (MISSE 6B)

A Glenn developed Atomic Oxygen Fluence Monitor is being flown on the ram side of MISSE 6B to actively measure the AO fluence accumulated with time. The sensor utilizes two wedge shaped sheets of pyrolytic graphite, which erode with AO exposure allowing sunlight to increasingly enter into a photodiode, as shown in Figure 27. The short circuit current from a photodiode under two pyrolytic graphite wedges is compared the short circuit current from an identical photodiode, which is exposed to unobstructed sunlight in the Glenn ITO experiment to measure the erosion of the graphite. Because the erosion yield of pyrolytic graphite is known to be 4.15 x 10^{-25} cm^3/atom from MISSE 2 [6,7] the AO fluence can be measured by knowing the ratio of short circuit currents. One significant advantage of this measurement technique is that the geometry of the pyrolytic graphite produces a linear dependence upon AO fluence using a material with a well characterized LEO erosion yield. A pre-flight photo of the Atomic Oxygen Fluence Monitor is provided in Figure 28.



a

b

Fig. 27 Schematic diagram of the Atomic Oxygen Fluence Monitor: a). Prior to AO exposure, and b).. After AO exposure.

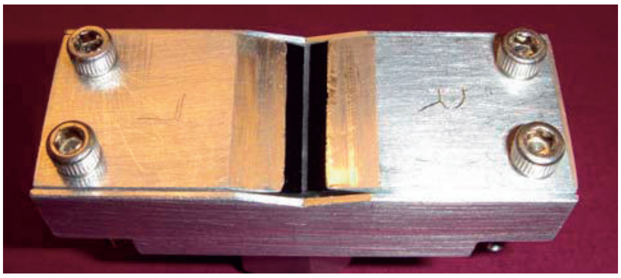


Fig. 28 MISSE 6B Atomic Oxygen Fluence Monitor.

7.6. Scattered Space Atomic Oxygen Experiment (SSAOE) (MISSE 6B)

The objective of the SSAOE is to actively measure direct ram and scattered AO erosion in LEO, and to passively measure the angular distribution and relative erosion rate of LEO ram AO scattered from an inclined angle. The SSAOE is being flown on the ram side of MISSE 6B. To measure, and thus be able to compare direct ram and scattered AO erosion, this experiment compares the in-situ erosion of opaque diamond-like carbon (DLC) exposed to direct ram AO to DLC exposed to only thermally accommodated scattered space AO. The scattered AO experiment is set inside a cylindrical scattering chamber where ram AO scatters off a fused silica slide tilted at a 45° angle from the incoming flux. Photodiodes are placed behind DLC coated fused silica slides and the Ey of direct ram and scattered AO will be determined by increases in the transmittance of light through the eroded DLC coatings. The light sources for the ram and scattered experiments are the sun and a light bulb, respectively. Uncoated fused silica covered photodiodes are placed next to the DLC-coated fused silica covered photodiodes for light calibration. To passively measure the angular distribution of LEO ram AO scattered from an inclined angle, salt-dusted Kapton H polyimide lines a second passive cylindrical scattering chamber, again with a fused silica slide set at a 45° angle. From this chamber the effective Ey of Kapton H will be determined as a function of ejection angle. A schematic diagram of the SSAOE is provided in Figure 29. Pre-flight photos of the inside of the SSAOE are provided in Figure 30. This experiment also includes 8 ram-facing small passive samples for Ey determination (Kapton H, CV-1144 silicone, polyphaphazene, carborane-siloxane, FEP, Teflon AF-1600, HRG-3/AB (epoxy-silane), HRG-3/AO (epoxy-silane)).

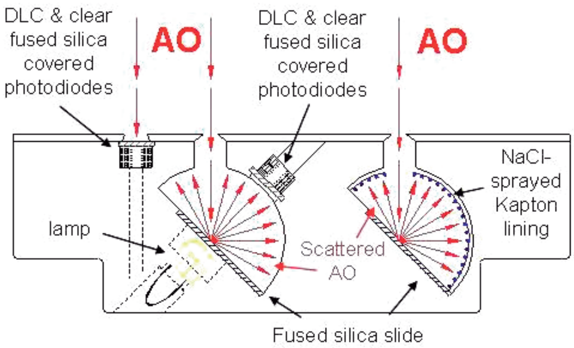
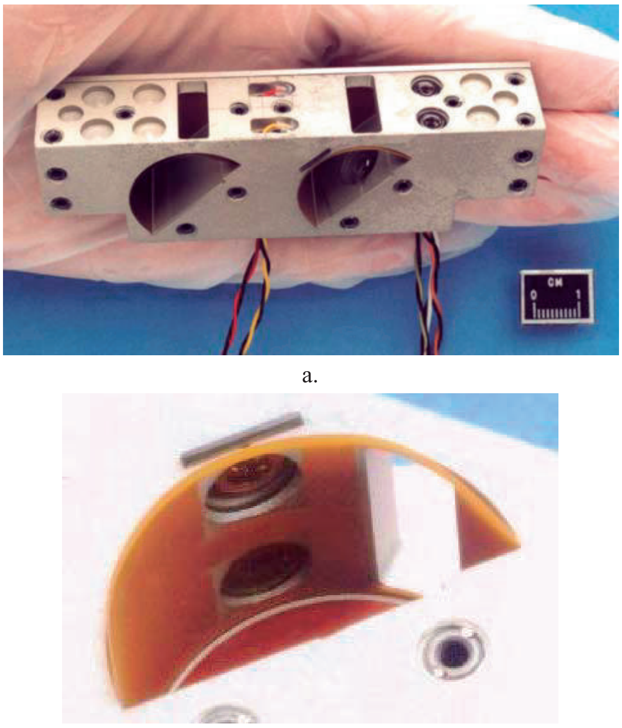


Figure 29. Schematic diagram of the SSAOE.



a.

b.

Fig. 30 Photographs of SSAOE: a). Experiment with side panel removed (the internal light bulb is visible), and b). Close-up of photodiodes inside the scattering chamber.

7.7. Low Impact Docking System (LIDS) Seals for Crew Exploration Vehicle (CEV) (MISSE 6B)

The objective of the LIDS Seals for CEV experiment is to expose three candidate elastomers to the space environment in LEO to evaluate their applicability as material for the primary mating interface seal for the LIDS. The mating interface seal, shown in Figure 31, is a mission critical, life support subsystem. Leakage through this interface seal results in an unrecoverable loss of breathable air for astronauts. Understanding the durability of materials that comprise LIDS seals is critical to fulfilling proposed Constellation missions. The materials used between mating spacecraft to help seal in cabin air will be exposed to the space environment prior to docking. The AO, radiation, and meteoroid and debris impacts found in space have been shown to damage seal materials. Individual space environments can be simulated on Earth. However, in-space testing is an essential part of assessing the synergistic effects of combined exposures to the LEO environment in the development of durable seal materials. The LIDS experiment on MISSE 6B utilizes two types of hardware, specimen holder A and specimen holder B. Specimen holder A, shown in Figure 32a, holds 15 o-ring samples and is being flown on both the ram and wake sides of 6B. These trays of samples will be used to evaluate the effects of the combined space environment on candidate seal materials, including leakage rate, weight, durometer & dimensional changes. Specimen holder B, shown in Figures 32b and 32c, holds 1 set of two o-rings under compression. A total of 20 sets of samples are being flown on the wake side of 6B to evaluate the seal-on-seal adhesion forces (pre & post-fight) to assess effect of long term engagement in the space environment.

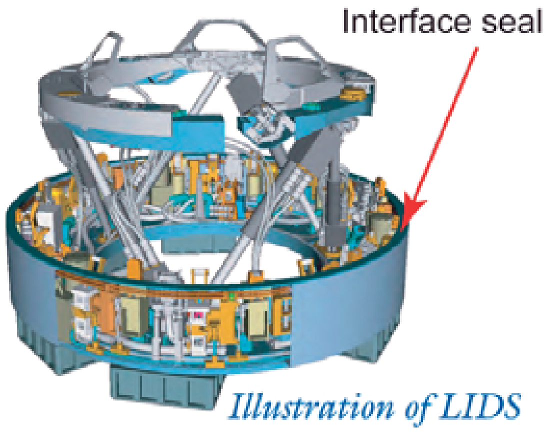
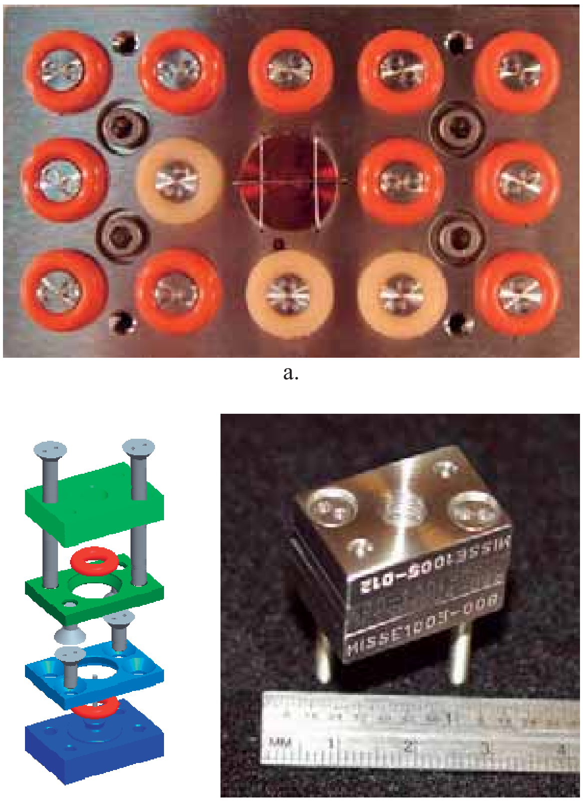


Fig. 31 Illustration of LIDS showing the primary mating interface seal.

7.8. New Thermal Control Paints Experiments (MISSE 6B & 7B)

The objectives of the MISSE 6 & 7 New Thermal Control Paints Experiments are to evaluate the in-space durability of newly developed thermal control paints. The MISSE 6 New Thermal Control Paints Experiment is a passive experiment flown on the wake side of MISSE 6B. It consists of 15 – 1” square (2.54 cm) samples. The MISSE 7 Thermal Control Paints Experiment is similar to the MISSE 6 Cermet Coatings and Thermal Control Paints Experiment. It is an active experiment consisting of two sets of four samples each 0.5” (1.27 cm) in diameter. One set of samples will be flown on the ram side of 7B, and the second will be flown on the wake side of 7B. The coatings are applied to thermally isolated nickel disks. In the 7B experiment each sample is instrumented with a temperature transducer and the temperature data will be sent through a communications interface to the ISS and then back to Earth by telemetry. The New Thermal Control Paints Experiment includes new thermal control paints that are being developed for light weight composite radiators for Fission Surface Power applications.[24]



a.

b. c.

Fig. 32 LIDS Seals for CEV experiment: a). Specimen holder A with 15 o-ring samples (the center sample is a control sample covered with a Kapton H AO fluence sample), b). Exploded view of specimen holder B with 1 set of o-ring samples, and c). Pre-flight photograph of specimen holder B.

The New Thermal Control Paints Experiments thermal control paint technology is derived from two Phase II Small Business Innovative Research (SBIR) investments: 1) next generation thermal control paint matrix materials based on lithium silicate chemistry, and 2) next generation thermal control paint pigment materials based on microgel encapsulation.[25] The first effort focused on Zn assisted lithium alumino silicate nano-cluster binders that provided interconnecting channels as percolating paths for electrical conductivity. The goal was to provide increased space radiation stability by creating binders that prevent surface charging and deep charging via percolating paths and appropriate secondary emission mechanisms for the desired reliability in high radiation environments. The nano-clusters in the matrix materials also offered the advantage of having a negative coefficient of thermal expansion (CTE), which facilitates CTE-tailoring to match the paint to the underlying composite. The second effort, developed under SBIR Phase II entitled "Robust Engineered Thermal Control Material Systems for Crew Exploration Vehicle (CEV) and Prometheus Needs" focused on developing pacified beta alumina coated with lithium silicate nanoclusters suitable for plasma spraying. The goal was to develop new thermal control material systems which can be dielectrically engineered, tailored for CTE matching to composite substrates, and which are durable to space radiation exposure at elevated operating temperatures up to 600 °C.

The passive MISSE 6B Thermal Control Paints Experiment contains thermal control material systems developed in the first SBIR effort (with Zn assisted lithium alumino silicate nano-cluster binders). In this experiment, the Zn assisted lithium alumino silicate nano-cluster binders that provided interconnecting channels were applied to aluminum and composite samples, all utilizing a heritage zinc oxide pigment. Some samples were prepared by conventional water spraying while others were prepared by plasma spraying. Selected samples were prepared having the heritage zinc oxide pigment encapsulated in glass-frit. All samples were evaluated before flight for their optical properties and any changes in optical properties will be documented by post-flight optical properties characterization. A pre-flight photograph of the MISSE 6B New Thermal Control Paints Experiment is shown in Figure 33. The MISSE 7B active Thermal Control Paints Experiment contains thermal control materials developed in the second SBIR effort on microgel encapsulated pigment particles capable of being plasma sprayed.

.

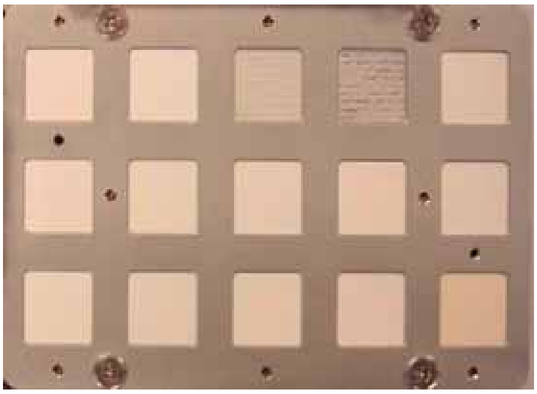


Fig. 33 Pre-flight photograph of the MISSE 6B New Thermal Control Paints Experiment.

7.9. Polymer Strain Experiment (MISSE 6B)

One of the observations of degraded polymers of retrieved MISSE 1 & 2 flight trays was environmentally induced shrinkage that contributes to polymer cracking and/or curling. This shrinking, cracking and curling phenomenon was observed in-space in the aluminized-Teflon FEP multilayer insulation covering the HST. On Hubble, the magnitude of cracks induced in the Teflon insulation has been observed to be on the order of meters in length. Curling of cracked insulation through environmental induced surface strain of the Teflon has allowed the underlying components to be directly exposed to the space environment; hence the insulation is no longer functioning properly for thermal control. The objective of the MISSE 6 Polymer Strain Experiment, being flown on the wake side of MISSE 6B, is to measure radiation and thermal exposure-induced strain in thin film polymers as a function of exposure time in LEO.

In the Polymer Strain Experiment six long thin opaque rectangular polymer film samples are positioned in the hardware such that one end of the polymer sample is held securely in place, while the other end is left unattached and hence free to shrink or expand. The free end is positioned inside one end of the hardware that contains a small light emitting diode (LED) and a photodiode, placed above and below the free end of the sample, respectively, as shown in Figure 34. As the polymer sample shrinks (or expands) due to environmentally induced interactions, the photodiode short circuit current will change in proportion to the strain of the sample. Small gauge wires lay over the polymer film samples to keep the samples from curling on-orbit. The experiment has been calibrated and can measure length changes as small as ~ 1%. Table 16 lists the thin film samples along with their mission relevance. A pre-flight photograph of the Polymer Strain Experiment is provided in Figure 35.

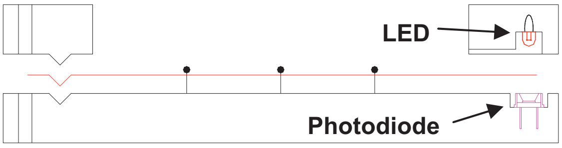


Fig. 34 Cross-section schematic view of the Polymer Strain Experiment.

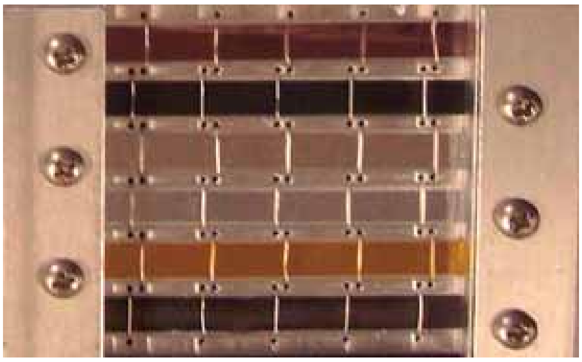


Fig. 35 Pre-flight photograph of the MISSE 6B Polymer Strain Experiment.

Table 16. MISSE 6B Polymers Strain Experiment Samples

Sample #	Material	Mission Relevance
1	Si/2 mil Kapton E/VDA/Inconel/VDA	JWST sunshield candidate
2	1 mil Kapton XC	JWST wiring insulation material
3	VDA/1 mil CP1	Solar sail material
4	2 mil FEP/VDA	Common thermal control material
5	1 mil Kapton HN/VDA	Common thermal control material
6	2 mil FEP/carbon coating	Elevated temperature FEP

Table 17. Glenn's MISSE 7A & 7B Materials Experiments (120 Samples)

MISSE 7 Experiment	7A or 7B Orientation	# Samples	Objective	Active or Passive
Zenith Polymers Experiment	7A Zenith	15	To determine the effect of solar exposure on the AO Ey of fluoropolymers (high solar/low AO exposure)	P
AO Fluence Monitor	7A & 7B Ram & Wake	4	To actively measure the cumulative AO fluence arriving at the surface of the PEC	A
LIDS Seals for CEV	7A Zenith, 7B Ram & Wake	34*	To characterize the performance of candidate seal materials when subjected to the synergistic effects of the space environment in low Earth orbit (LEO)	P
Polymers Experiment	7B Ram & Wake	27	For AO Ey determination and to determine if AO erosion of high & low ash containing polymers is dependent on fluence	P
AO Scattering Chamber (Polymer Experiment)	7B Ram	1	To determine scattered AO erosion characteristics for undercutting modeling (30° tilt base)	P
AO Pinhole Camera (Polymer Experiment)	7B Ram	1	To document the arrival direction of AO impinging upon the MISSE 7 experiment tray	P
Flexural Stress Effects Experiment	7B Wake	24	To examine the role of surface flexural stress on space environment induced polymer degradation	P
New Thermal Control Paints Experiment	7B Wake	8	To evaluate the durability of next generation white thermal control paints developed under a GRC Phase II SBIR for Fission Surface Power applications	A
Spacesuit Fabrics Exposure Experiment	7B Wake	6	To identify and evaluate the effect of long term ultraviolet radiation upon pristine and dust-damaged spacesuit fabric.	P

** Four LIDS o-ring seal samples will be flown as 1 sample on the Zenith Polymers Experiment*

8. MISSE 7A & 7B Experiments (3 active & 6 passive, 120 samples)

Table 17 provides a list of the Glenn MISSE 7A & 7B materials experiments along with the on-orbit orientation, the objectives, number of samples and whether they are active or passive. There are a total of nine experiments; three will be active and six will be passive. As noted before, the MISSE 7A experiments will be placed in a zenith/nadir orientation and MISSE 7B will be placed in a ram/wake orientation. In additional to these materials experiments, Glenn is designing the communications interface board to route and manage communications between 20 active experiments on MISSE 7A and the ISS.

8.1. Zenith Polymers Experiment (MISSE 7A)

The objective of the Zenith Polymers Experiment is to determine the effect of solar exposure on the AO Ey of fluoropolymers under high solar/low AO exposure. This passive experiment will be flown in the zenith facing orientation as part of MISSE 7A, and includes 15 - 1" (2.54 cm) square samples. Seven different fluoropolymers: (PTFE, FEP, CTFE (Kel-f), ETFE (Tefzel), PVDF (Kynar), ECTFE (Halar) and PVF (clear Tedlar), are being flown along with low oxygen PE. These polymers were flown as part of the MISSE 2 and MISSE 5 PEACE Polymers experiments, and therefore the Ey for the same polymers under 3 different LEO solar/AO exposures should provide data on whether or not there is a synergistic effect of solar radiation on the AO erosion, as is currently being debated in the space environmental durability community. Samples of Al-FEP and silvered-Teflon FEP (Ag-FEP) are also being flown to determine the effect of metallization on AO Ey, and to characterize changes in optical properties. A Kapton H witness sample will be included for AO fluence characterization.

Four additional samples are included in the Zenith Polymers Experiment: JWST sunshield material (Si/2 mil Kapton E/VDA), Orion LIDS seal sample and two barrier coating samples. The Orion LIDS seal sample will include four small o-rings mounted together in a 1" (2.54 cm) area. The o-rings will be comprised of 2 types of materials: Parker

S0383-70 and Esterline ELA-SA-401. These four zenith facing o-rings are part of the LIDS Seals for CEV experiment. The barrier coating samples include two samples of coated Teflon FEP to evaluate AO and VUV barrier coatings. One sample is sectioned in half with two different thicknesses (~10 and ~40 nm) of Al_2O_3 coatings on FEP. This coating will protect against oxygen atoms, but will transmit VUV light. The coating should also act as a barrier to the escape of volatile reaction products. The second sample is a multilayer coated FEP sample. The coating consists of a thin layer (~30 nm) of TiO_2 on top of a thinner layer (~10 nm) of Al_2O_3. This multilayer coating should protect against AO and VUV light. These samples will be compared with an identical TiO_2 (~30 nm)/Al_2O_3 (~10 nm) coated FEP sample being flown in the ram facing direction as part of the MISSE 7B Polymers Experiment (see Section 8.4).

8.2. Atomic Oxygen Fluence Monitor (MISSE 7A & 7B)

Four Glenn Atomic Oxygen Fluence Monitors are being flown on MISSE 7 to actively measure the cumulative AO fluence arriving at the surface of the PEC. Monitors will be positioned on each of the 4 PEC surfaces (7A zenith & nadir and 7B ram & wake). Whereas the MISSE 6 AO fluence monitor uses reference photodiodes from other experiments to compare the output from the pyrolytic graphite photodiode, the MISSE 7 fluence monitor was designed with its own reference photodiode next to the pyrolytic graphite photodiode. The geometry is almost identical for each MISSE 7 AO fluence monitor diode, which should result in more accurate fluence versus time data. A photograph of a MISSE 7 AO fluence monitor is provided in Figure 36.

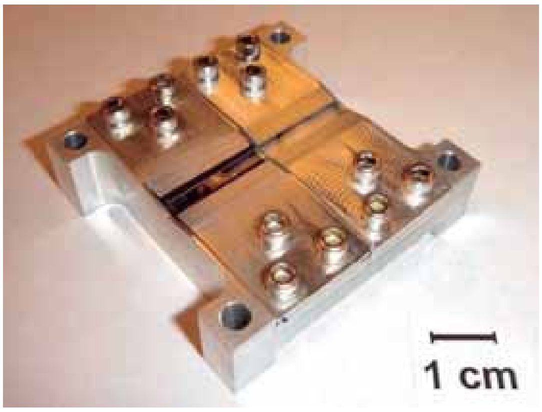


Fig. 36 MISSE 7A & 7B AO fluence monitor.

8.3. Low Impact Docking System (LIDS) Seals for Crew Exploration Vehicle (CEV) (MISSE 7A & 7B)

The objective of the MISSE 7 LIDS Seals for CEV experiment is similar to MISSE 6, namely to characterize the performance of candidate seal materials when subjected to the synergistic effects of the space environment in LEO. The materials used between mating spacecraft to help seal in cabin air will be exposed to the space environment prior to docking. Figure 37 shows the specimen holder that will be utilized on MISSE 7B, and will be flown on both the ram and wake sides of MISSE 7B. The differences between the MISSE 6 and 7 seals experiments are as follows: 1) MISSE 6 is flying as-received material and MISSE 7B will fly 10 seals that have received the same AO pre-treatment planned for LIDS seal, 2) ISS side of the LIDS will be an aluminum flange and hence MISSE 7B will test ISS aluminum with the correct surface coatings and finishes (12 samples), and 3) other seal applications employ RTV adhesives, therefore MISSE 7B will include one of these adhesives, thus helping with its flight qualification (6 samples). Figure 37 shows only 1 large RTV sample, but 3 samples will be flown on each holder. Kapton H AO fluence samples are also included in each holder (2 samples). As mentioned previously, the LIDS Seals for CEV experiment includes 4 small o-rings that will receive zenith exposure as part of the MISSE 7A Zenith Polymers Experiment.

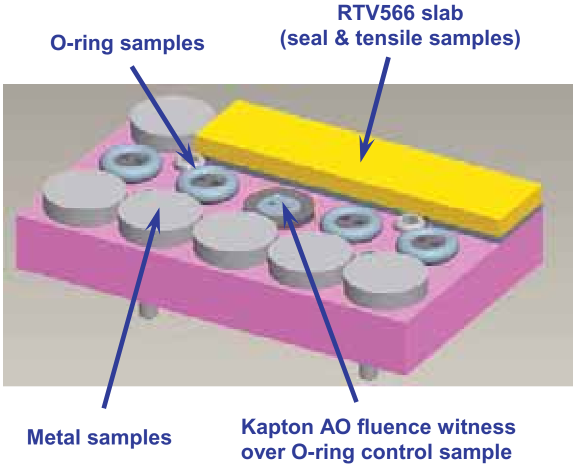


Fig. 37 MISSE 7B LIDS Seals for CEV experiment holder.

8.4. Polymers Experiment (MISSE 7B)

The MISSE 7B Polymers Experiment includes a variety of passive samples to investigate the effects of AO and radiation (ram samples) or radiation with minimal AO (wake samples). This experiment includes 29 samples: 26 on the ram side of 7B and 3 on the wake side of 7B. Table 18 provides a list of each of the MISSE 7B Polymers Experiment samples along with the individual sample objectives, the sample sizes and the on-orbit orientations. The Polymers Experiment is a collaborative effort with researchers from the Japan Aerospace Exploration Agency (JAXA), Towson University, Montana State University, ManTech SRS Tech., Inc., ATK, NASA Langley Research Center (LaRC), the National Institute of Aerospace, and Hathaway Brown School. Several of the samples are being co-investigated with Hathaway Brown School and Towson University as educational outreach efforts.

The MISSE 7B AO Scattering Chamber, flown as part of the MISSE 7B Polymers Experiment, will differ from the MISSE 2 and MISSE 4 AO Scattering Chamber experiments in that scattering in the 7B experiment will be off an aluminum surface that provides an angle of attack 30° from normal, rather than 0° from normal. The 30° tilted base will provide information on the angular distribution of scattered AO with respect to incident angle.

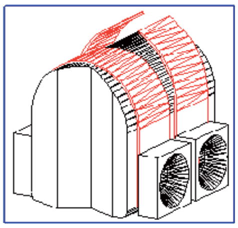
Table 18. MISSE 7B Polymers Experiment (29 Samples)

Sample	**Sample Objective**	**Square (inch)**
Ram Side Samples		
Kapton H	AO Fluence witness	1
Vespel	JAXA: For AO Ey determination (compare to Kapton H)	1
White Tedlar	To determine if AO erosion of high ash containing polymers is dependent on fluence (compare MISSE 2)	1
0.5 mil Kapton H/White Tedlar		1
1.0 mil Kapton H/White Tedlar		1
Kapton HN	To determine if AO erosion of low ash containing polymers is dependent on fluence (compare to MISSE 2 Ey)	0.75
0.5 mil Kapton H/Kapton HN		0.75
1.0 mil/Kaptn H/Kapton HN		0.75
Polyethylene (low oxygen PE)	For AO Ey determination & predictive model verification	0.75
Polymethylpentene (PMP)		0.75
Polyethersulfone (PES)		0.75
Polyamide-imide (Torlon)		0.75
Polyvinyl alcohol (PVOH)		0.75
Cellulose Nitrate (CN)		0.75
Aluminized-Teflon FEP	To determine the effect of metallization on AO Ey & characterize changes in optical properties	0.75
HOPG parallel to AO/HOPG perpendicular to AO/Single crystal Class 2A diamond	Highly oriented pyrolytic graphite HOPG: for AO Ey crystal orientation determination & Diamond: verify Ey = 0	1
FEP/PTFE/POM/PEO	Towson University Education: "Quartered" salt-sprayed samples for recession depth & AO morphology studies	1
Kapton H/Mylar/PE/PG		1
AO Scattering Chamber	AO scattering chamber with 30° tilted base to check angular distribution of scattered AO	1
Atomic Oxygen Pinhole Camera	To track the arrival direction of AO during the mission	1
Kapton H	AO Fluence witness	0.75
TiO_2/Al_2O_3/FEP	Montana State University: To study AO & VUV barrier coatings	1
CORIN (AO resistant polyimide)	ManTech SRS Tech., Inc.: To determine AO Ey	0.75
Urethane/Vectran Mesh	ATK: Demonstrate alternative AO protection for Vectran	0.75
Orion UltraFlex solar array sample (blanket & cell frontside material)	ATK: To validate the survivability in LEO key UltraFlex solar array blanket materials	1.5
Orion UltraFlex solar array sample (blanket & cell backside material)		1.5
Wake Side Samples		
POSS coated Kapton HN	NASA LaRC: Dust mitigation for Exploration Mission Systems	0.75
POSS coated abraded Kapton HN		0.75
CORIN (AO resistant polyimide)	ManTech SRS Tech., Inc.: To assess UV degradation without the effects of AO	0.75

Included in the MISSE 7B Polymers Experiment are several Exploration Mission relevant samples. ATK Orion UltraFlex passive samples are being flown to validate the survivability in the LEO environment of key UltraFlex solar array blanket materials. Two 1.5" samples are being flown: one sample composed of front side blanket assembly materials, and one sample composed of backside blanket assembly materials. An ATK urethane/Vectran mesh sample will also be included for durability assessment. Also being flown are POSS coated Kapton HN samples from NASA LaRC/National Institute of Aerospace. These samples are being investigated for lunar dust mitigation applications.

8.5. Flexural Stress Effects Experiment (MISSE 7B)

The objective of the MISSE 7B Flexural Stress Effects Experiment is to examine the role of surface tensile flexural stress on space environment induced polymer cracking. The experiment includes two sets of 12 polymer thin film samples wrapped around mandrels of two different diameters (see Figure 38). The samples, as shown in Fig. 38b from left to right, are: DC 93-500 silicone (1), SiO_x/Kapton HN (1), Kapton HN/VDA (1), FEP/VDA (2), CP1/VDA (1), VDA/CP1 (1), Si/Kapton E/VDA/Inconel/VDA (3) and Kapton XC (2). The mandrel diameters are 0.25" (0.635 cm) and 0.375" (0.953 cm). The Flexural Stress Effects Experiment will be flown on the wake side of MISSE 7B. This experiment includes the same sample materials (and of the same thickness) flown as part of MISSE 6 Polymer Film Tensile Experiment. Between the two experiments, performance of flat and unstressed films can be compared with performance of tensile stressed and flexural stressed films.



a.

b.

Fig. 38 Flexural Stress Experiment: a). Illustration of sample mounting and failure, and b). Pre-flight photo of one mandrel.

8.6. New Thermal Control Paints Experiment (MISSE 7B)

The active MISSE 7B New Thermal Control Paints Experiment is summarized along with the MISSE 6 New Thermal Control Paints Experiment in Section 7.8 above.

8.7. Spacesuit Fabrics Exposure Experiment (MISSE 7B)

The Spacesuit Fabrics Exposure Experiment is a passive experiment to fly on the wake side of MISSE 7B. The objective is to evaluate the long term space exposure durability of state-of-the-art orthofabrics and Apollo era fabrics, both pristine and damaged by dust abrasion. Spacesuits for use at a future lunar outpost are envisioned to be used for a much longer time than those for Apollo. Indeed, one concept is to have the spacesuits reside outside the lunar habitat and have the astronauts climb in through the back of the spacesuit. In such a case, the suit itself would be exposed to the ultraviolet (UV) radiation environment for a long time, even when not in use. It is well known that lunar dust is a serious issue. Figure 39 shows Apollo 12 astronaut Alan Bean in a heavily dust covered spacesuit. Therefore, there is a concern of UV radiation degradation of both pristine, and dust abraded, spacesuit fabrics.

A total of six 0.47" (12 mm) square fabric samples will be flown. Three state-of-the-art orthofabrics will be flown, including one pristine sample, one lightly dust damaged sample, and one heavily dust damaged sample. The dust damaged samples will be abraded with lunar simulant. Three Apollo era fabrics will be flown, including one pristine sample, one lightly dust damaged sample (lunar simulant), and one sample damaged by actual lunar dust (a section of the left knee of Alan Bean's Apollo 12 spacesuit). The fabric samples were documented photographically, and by both atomic force microscopy (AFM) and scanning electron microscopy (SEM), prior to flight. These techniques were chosen because they are non-destructive analysis techniques. Upon return, the coupons will be re-photographed and re-submitted for AFM and SEM analyses to identify and evaluate the effect of long term UV radiation upon the fabric. A photograph of the Spacesuit Fabrics Exposure Experiment is provided in Figure 40.

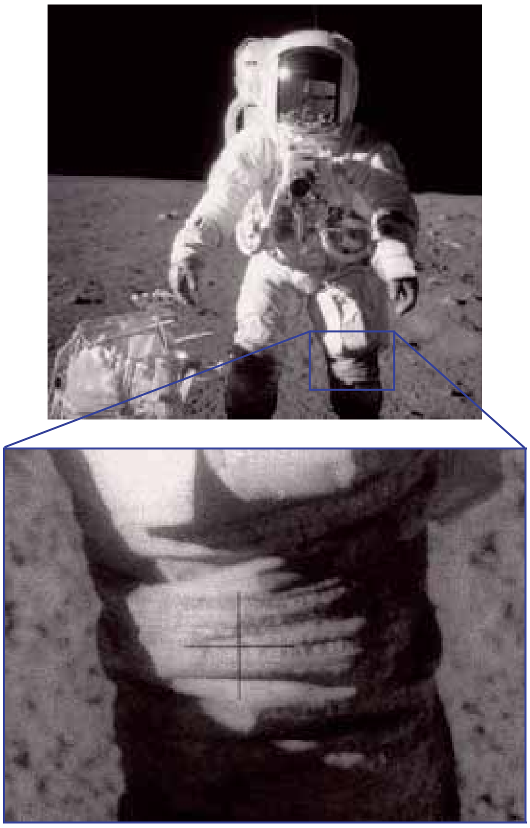


Fig. 39 Apollo 12 photograph showing the extent of lunar dust on Alan Bean's spacesuit; with a close-up of his left knee.

Fig. 40 Spacesuit Fabrics Exposure Experiment: the top row contains modern orthofabrics and the bottom row contains Apollo era β-cloth. The bottom middle sample is from Alan Bean's Apollo 12 spacesuit left knee.

9. Summary and Conclusions

This paper introduces space environmental durability issues in LEO and provides an overview of Glenn's 39 passive and active MISSE 1-7 materials flight experiments. The Glenn MISSE experiments address AO effects such as erosion and undercutting of polymers, AO scattering, stress effects on AO erosion, and in-situ AO fluence monitoring. Several experiments address solar radiation effects such as radiation induced polymer shrinkage, stress effects on radiation degradation of polymers, and radiation degradation of ITO coatings and spacesuit fabrics. Experiments also address combined AO and solar radiation effects on thermal control films, paints and cermet coatings. Experiments with Orion CEV seals and UltraFlex solar array materials are also being flown. Several experiments, such as the MISSE 2 & 4 Double SiO_x-Coated Kapton Ground to Space Erosion Correlation Experiments were designed to provide ground-facility to in-space calibration data thus enabling more accurate in-space performance predictions based on ground-laboratory testing. Numerous experiments, such as the MISSE 6A Stressed PEACE Polymers and the MISSE 6B Polymer Strain Experiment were designed based on observations of materials damage from prior retrieved MISSE experiments. The MISSE 2 PEACE Polymers experiment contains the widest variety of well-documented polymers exposed to identical long duration LEO AO conditions, and provides AO Ey data for 39 different polymers. Results from Glenn MISSE experiments have impacted spacecraft missions, such as the HST SM4 and Exploration Mission spacecraft such as COTS.

10. Acknowledgments

The authors would like to acknowledge and thank numerous additional principal and co-investigators for their involvement in the Glenn MISSE experiments, and for their contributions to this paper. In particular we thank: Bruce Steinetz (NASA Glenn), Henry de Groh (NASA Glenn), Aaron Snyder (NASA Glenn), James Gaier (NASA Glenn), Frank Lam (Jacobs Sverdrup), Debbie Waters (ASRC Aerospace Corp. at NASA Glenn), Phil Jenkins (Naval Research Laboratory), Mike Krasowski (NASA Glenn), Norman Prokop (NASA Glenn), Patty Hunt (Hathaway Brown School) and the entire PEACE team. In addition, with great appreciation we acknowledge the many students and NASA summer interns who have made significant contributions to many of these experiments over the years.

We also gratefully acknowledge the opportunity to fly these MISSE experiments and give our thanks to the MISSE program sponsors and managers. In particular, we would like to thank the following for their support of our experiments: Gary Pippin (Boeing Phantom Works), Bill Kinard (Retired, NASA Langley Research Center), Rob Walters (Naval Research Laboratory) and Phil Jenkins (Naval Research Laboratory). Lastly, we would also like to acknowledge that part of this work was sponsored by NASA Glenn Research Center's Independent Research & Development (IR&D) Program.

11. References

[1] B. A. Banks, K. K. de Groh and S. K. Miller, "Low Earth Orbital Atomic Oxygen Interactions with Spacecraft Materials," Materials Research Society Symposium Proceedings 2004, NN8.1; also NASA/TM-2004-213400, November 2004.

[2] J. A. Townsend, P. A. Hansen, J. A. Dever, K. K. de Groh, B. A. Banks, L. Wang and C. He, "Hubble Space Telescope Metallized Teflon FEP Thermal Control Materials: On-Orbit Degradation and Post-Retrieval Analysis," High Performance Polymers 11 (1999) 81-99.

[3] J. Townsend, C. Powers, M. Viens, M. Ayres-Treusdell and B. Munoz, "Degradation of Teflon FEP following Charged Particle Radiation and Rapid Thermal Cycling" Proc. Space Simulation Conf. NASA CR-1998-208598, 201-209.

[4] G. Pippin, "Summary Status of MISSE-1 and MISSE-2 Experiments and Details of Estimated Environmental Exposures for MISSE-1 and MISSE-2," AFRL-ML-WP-TR-2006-4237, Technical Operations Support (TOPS) II (Delivery Order 0011), Air Force Research Laboratory, Wright-Patterson Air Force Base, OH 45433-7750

[5] J. A. Dever, S. K. Miller, E. A. Sechkar and T. N. Wittberg, "Preliminary Analysis of Polymer Film Thermal Control and Gossamer Materials Experiments on MISSE 1 and MISSE 2," Proceedings of the 2006 National Space & Missile Materials Symposium in conjunction with the 2006 MISSE Post-Retrieval Conference, June 26-30, 2006, Orlando, FL.

[6] K. K. de Groh, B. A. Banks, C. E. McCarthy, R. N. Rucker, L. M. Roberts and L. A. Berger, "MISSE 2 PEACE Polymers Atomic Oxygen Erosion Experiment on the International Space Station," High Performance Polymers, 2008 (in-print).

[7] K. K. de Groh, B. A. Banks, C. E. McCarthy, R. N. Rucker, L. M. Roberts and L. A. Berger, "MISSE PEACE Polymers Atomic Oxygen Erosion Results," Proceedings of the 2006 National Space & Missile Materials Symposium, Orlando, Florida, June 26 - 30, 2006; also NASA TM-2006-214482, November 2006.

[8] B. A. Banks, K. K. de Groh and J. A. Backus, "Atomic Oxygen Erosion Yield Predictive Tool for Spacecraft Polymers in Low Earth Orbit," NASA TM, 2008 (in-print).

[9] A. H. Stambler, K. E. Inoshita, L. M. Roberts, C. E. Barbagallo, K. K. de Groh and B. A. Banks, "Ground-Laboratory to In-Space Atomic Oxygen Correlation for the PEACE Polymers," Proceedings of the 9th International Space Conference "Protection of Materials and Structures From Space Environment" (ICPMSE-9), May 19-23, 2008 in Toronto, Canada, 2008 (in-print).

[10] K. K. de Groh and T. A. McCollum, "Low Earth Orbit Durability of Protected Silicone for Refractive Photovoltaic Concentrator Arrays," Journal of Spacecraft and Rockets, Vol. 32, No. 1, Jan-Feb 1995, 103-109.

[11] K. K. de Groh, B. A. Banks and D. Ma, "Ground-to-Space Effective Atomic Oxygen Fluence Correlation for

DC 93-500 Silicone," Journal of Spacecraft and Rockets, Vol. 43, No. 2, March-April 2006, 414-420.

[12] B. A. Banks, K. K. de Groh and S. K. Miller, "MISSE Scattered Atomic Oxygen Characterization Experiment," Proceedings of the 2006 National Space & Missile Materials Symposium, Orlando, Florida, June 26 - 30, 2006; also NASA TM-2006-214355, May 2006.

[13] S. K. Miller, B. A. Banks and G. Tollis, "MISSE Results Used for RF Plasma Ground Testing to Space Correlation for Coated Kapton," Proceedings of the 9th International Space Conference "Protection of Materials and Structures From Space Environment" (ICPMSE-9), May 19-23, 2008, Toronto, Canada, 2008 (in-print).

[14] A. Snyder, B. A. Banks and D. L. Waters, "Undercutting Studies of Protected Kapton H Exposed to In-Space and Ground-Based Atomic Oxygen," Proceedings of the 10th International Symposium on Materials in a Space Environment & 8th International Conference on Protection of Materials and Structures in a Space Environment, Collioure, France, June 19 – 23, 2006, ESA SP-616, Sept. 2006.

[15] J. Dever, S. Miller, R. Messer, E. Sechkar and G. Tollis, "Exposure of Polymer Film Thermal Control Materials on the Materials International Space Station Experiment (MISSE)," AIAA 2001-4924, October 2001; also NASA TM-2002-211363, February 2002.

[16] J. A. Dever, S. K. Miller and E. A. Sechkar, "Effects of the Space Environment on Polymer Film Materials Exposed on the Materials International Space Station Experiment (MISSE 1 and MISSE 2)," Proceedings of the 10th International Symposium on Materials in a Space Environment & 8th International Conference on Protection of Materials and Structures in a Space Environment, Collioure, France, June 19 – 23, 2006, ESA SP-616, Sept. 2006.

[17] M. Finckenor, K. de Groh, T. Minton, A. Brunsvold and G. Pippin, "Post-Flight Analysis of Selected Fluorocarbon and other Thin Film Polymer Specimens Flown on MISSE-5," Presentation given at the National Space and Missiles Materials Symposium (NSMMS), held June 25-29, 2007 in Keystone, Colorado.

[18] R. J. Walters, J. C. Garner, S. N. Lam, J. A. Vazquez, W. R. Braun, and R. E. Ruth, J. R. Lorentzen, R. Bruninga, P. P. Jenkins, J. M. Flatico, D. M. Wilt, M. F.Piszczor, L. C. Greer, and M. J. Krasowski, "Materials on the International Space Station Experiment-Forward Technology Solar Cell Experiment," NASA CP-2005-213431, 2005.

[19] M. Krasowski, L. Greer, J. Flatico, P. Jenkins, D. Spina, "A Hardware and Software Perspective of the Fifth Materials on the International Space Station Experiment (MISSE-5)," NASA Technical Memorandum, NASA TM-2005-213840, August, 2005.

[20] D. Wilt, M. Piszczor, M. Krasowski, P. Jenkins, R. Walters and S. Messenger, "Advanced Solar Cell Technology Testing Aboard Materials International Space Station Experiment 5 (MISSE5)," Proceedings of the 2nd International Energy Conversion Engineering Conference, AIAA-2004-5580, 2004.

[21] P. P. Jenkins, R. J. Walters, L. C. Greer, M. J. Krasowski, J. M. Flatico, CDR R. Bruninga (Ret.), CDR D. Myre, J. R. Lorentzen, K. Crist, K. Edmondson and A. Boca, "In-Flight Performance Of III-V Multi-Junction Solar Cells From The Forward Technology Solar Cell Experiment," Proceedings of the 33rd IEEE Photovoltaics Specialists Conference, May 11-15, 2008, to be published.

[22] D. Wilt, A. Pal, S. Ringel, E. Fitzgerald, P. Jenkins and R. Walters, "Final Results from the MISSE5 GaAs on Si Solar Cell Experiment", Proceedings of the 33rd IEEE Photovoltaics Specialists Conference, May 11-15, 2008, to be published.

[23] D. A. Jaworske and T. Raack, "Cermet Coatings for Solar Stirling Space Power," Thin Solid Films, Vol. 469-470, 2004, 24-30.

[24] D. A. Jaworske, D. E. Beach and J. L. Sanzi, "Heat Rejection Systems Utilizing Composites and Heat Pipes: Design and Performance Testing," 5th International Energy Conversion Engineering Conference, St. Louis, MO, AIAA-2007-80969, June 2007.

[25] D. A. Jaworske, J. A. Dever and M.S. Deshpande, "Initial Evaluation of White Thermal Control Paints Incorporating Lithium Silicate Chemistry," 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference 23 - 26 Apr 2007, Waikiki, Hawaii, AIAA-2007-2200, April 2007.