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Analysis of International Space Station Vehicle Materials Exposed on Materials International Space Station Experiment From 2001 to 2011

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LIST OF ACRONYMS AND SYMBOLS

AO	atomic oxygen
CAA	chromic acid anodized
DI	deionized
ELC	EXPRESS Logistics Carrier
ESCA	electron spectroscopy for chemical analysis
ESH	equivalent sun hour(s)
EXPRESS	EXpedite the PRocessing of Experiments to Space Station
HPGT	high-pressure gas tank
ISS	International Space Station
ITO	indium tin oxide
LDEF	Long Duration Exposure Facility
MISSE	Materials on International Space Station Experiment
MLI	multilayer insulation
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NiAc	nickel acetate
O	oxygen
ORMatE R/W	Optical Reflector Materials Experiment ram/wake
PEC	passive experiment container
PFOA	perfluorooctanoic acid
POSA	Passive Optical Sample Assembly
PTFE	polytetrafluoroethylene
SAA	sulfuric acid anodize
SiO_x	silicon oxide
STS	Space Transportation System
TOR	Triton oxygen resistant
TP	Technical Publication
UV	ultraviolet

NOMENCLATURE

α	absorptance
α_s	solar absorptance
ε	emittance, thermal emittance

TECHNICAL PUBLICATION

ANALYSIS OF INTERNATIONAL SPACE STATION VEHICLE MATERIALS EXPOSED ON MATERIALS INTERNATIONAL SPACE STATION EXPERIMENT FROM 2001 TO 2011

1. INTRODUCTION

Since August 2001, the Materials on International Space Station Experiment (MISSE) has provided a wealth of space environmental effects data on a variety of materials and spacecraft components. Many of these materials samples were chosen to provide engineering data for the International Space Station (ISS) vehicle itself. These data are vital for mission planning and life extension of the ISS. This Technical Publication (TP) is a compilation of several conference presentations[1–14] and previously unpublished data. This is by no means a complete set of MISSE data, but the authors have attempted to include the most pertinent from MISSE-1 through MISSE-7 for materials and processes engineers. MISSE-8 is on orbit, so analyses of these samples have not yet been performed. MISSE-8 is scheduled for return in 2014.

Reference 15 is a good source of information on MISSE polymer materials not covered in this TP. The National Aeronautics and Space Administration (NASA) gives no recommendation, endorsement, or preference, either expressed or implied, concerning materials and vendors used.

Unless otherwise specified, solar absorptance (α_s) measurements were made with an AZ Technology Laboratory Portable Spectroreflectometer model 300. Infrared emittance (ε) measurements were made with an AZ Technology TEMP 2000A infrared reflectometer. Changes of ±0.01 in these optical properties are not considered statistically significant.

2. ENVIRONMENTAL DEFINITIONS

MISSE is a series of materials flight experiments, the first two of which were delivered to the ISS during Space Transportation System-105 (STS-105) in 2001. Experiments developed by principal investigators were loaded onto hinged, suitcase-like containers, called passive experiment containers (PECs), and were exposed to the space environment on the exterior of the ISS. During transport to the ISS on the Space Shuttle, the PECs were closed with the samples facing each other for protection; once the Space Shuttle reached the ISS, the PECs were attached to its exterior during an extravehicular activity and opened back-to-back, exposing the samples to space. In the MISSE suite (MISSE-1 through MISSE-8), 10 PECs and one smaller tray, together containing thousands of samples, have been flown in various external locations on the ISS. (See table 1.) Figure 1 shows the ISS locations of MISSE-1 through MISSE-8. Note that the earlier MISSE flights were numbered for each PEC, so that MISSE-1 and MISSE-2 flew together, as did MISSE-3 and MISSE-4. The later flights were single numbers with different letters for each PEC, e.g., MISSE-6A and MISSE-6B.

Table 1. Mission exposure summary of MISSE-1 through MISSE-8.

MISSE	Launch Mission	Placed Outside ISS	Location on ISS	Tray Orientation	Retrieval Mission	Retrieved From ISS	Exposure (yr)
1, 2	STS-105	8/16/01	MISSE 1: High-pressure gas tank (HPGT) MISSE 2: Quest Airlock	Ram and wake	STS-114	7/30/05	3.95
3, 4	STS-121	8/3/06*	MISSE 3: HPGT MISSE 4: Quest Airlock	Ram and wake	STS-118	8/18/07	1.04
5	STS-114	8/3/05	Aft P6 trunion pin handrail	Zenith and nadir	STS-115	9/15/06	1.12
6A, 6B	STS-123	3/22/08	Columbus Laboratory	Ram and wake	STS-128	9/1/09	1.45
7A, 7B	STS-129	11/23/09	EXPRESS Logistics Carrier 2 (ELC 2) on the S3 Truss	7A: Zenith and nadir 7B: Ram and wake	STS-134	5/20/11	1.49
8 and ORMatE-III R/W	STS-134	8: 5/20/11; ORMatE-III R/W: 7/12/11**	ELC 2 on the S3 Truss	8: Zenith and nadir; ORMatE-III R/W: ram and wake	Manifested on SpaceX Dragon	Retrieved 7/9/13 and stored in ISS	On orbit

*Deployed during Expedition 13
**Deployed during STS-135

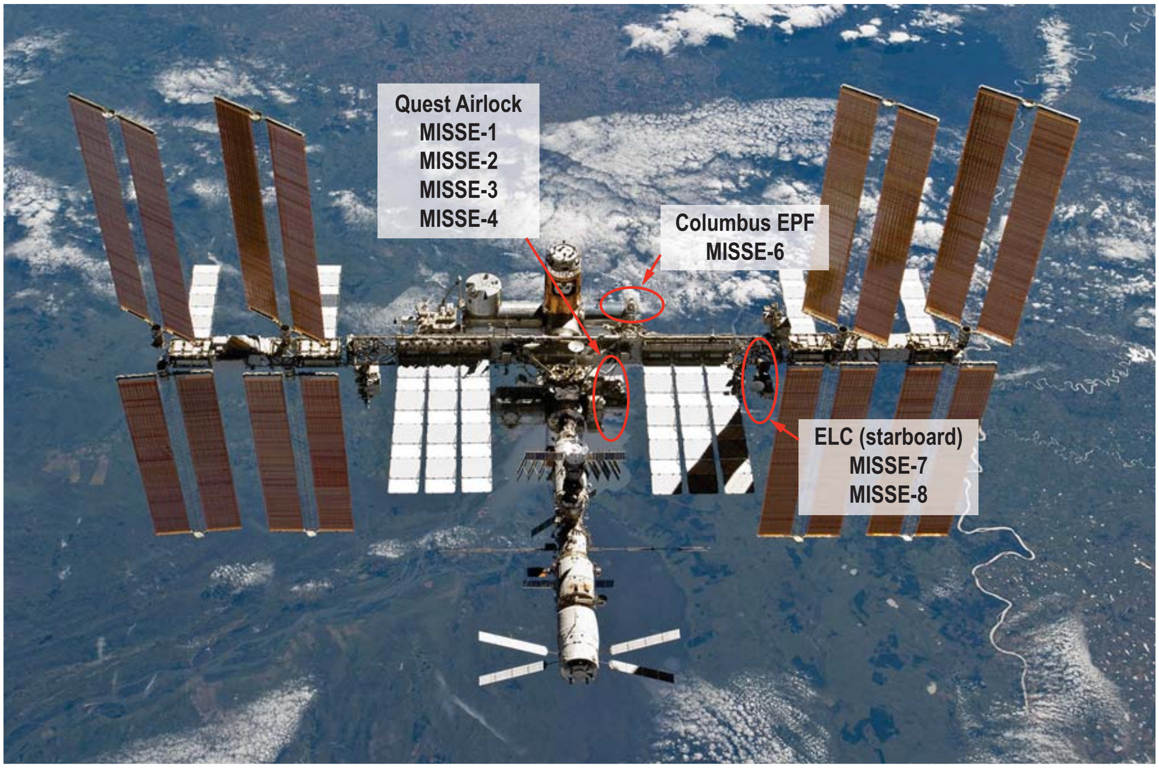

Figure 1. Locations of MISSE-1 through MISSE-4 and MISSE-6 through MISSE-8 on the ISS.

With participants from NASA, the Department of Defense, industry, and academia, MISSE is the longest running multiorganization technology, development, and materials testing project on the ISS. It has provided many tangible benefits for the Agency and its partners, with the flight data impacting many space programs. MISSE flight data have provided a great wealth of space performance and environmental durability data and enable lifetime prediction of new materials and components that may be used in future spaceflight. Published MISSE data, photographs, and some raw data files are being gathered in a database in the Materials and Processes Technical Information System.

The MISSE PECs are flown in either a ram/wake orientation, i.e., leading edge/trailing edge facing, or a zenith/nadir orientation, i.e., space facing/Earth facing. Each of these orientations provides different space environmental exposures. For example, samples in a ram orientation receive the greatest amount of atomic oxygen (AO) exposure combined with solar radiation exposure, while those in a wake orientation receive solar radiation exposure with very little AO exposure. Zenith-facing samples receive the highest amount of solar radiation and grazing AO exposure, and nadir-facing samples receive little solar exposure (only ambient reflected solar exposure) with grazing AO exposure.

The design of the MISSE suitcases allows for materials on one side to receive either a higher fluence of AO or higher incident ultraviolet (UV) radiation. MISSE-5 and MISSE-7A were positioned so that one side of each faced in the zenith direction for the most sunlight, and the other side faced in the nadir direction. All other MISSE experiments discussed in this TP were ram-/wake-facing. While the ram-facing side was intended to receive the most AO, this does not mean that the wake side did not receive any AO. The ISS has many orientations, including one during which the MISSE experiment wake side faced the ram direction. In general, the wake side samples received an order of magnitude less AO than the ram side samples. This means that, while material darkening related to UV radiation is sometimes more obvious on the wake side samples, these samples still experience AO erosion or bleaching.

MISSE samples were exposed just past the solar cycle maximum and through the solar minimum. Thus, samples exposed on MISSE-7 were exposed to twice as much AO as those samples on MISSE-6, even though MISSE-6 was exposed for 1 month less than MISSE-7.

The reader should not assume that, because one material survived for a year on orbit, it would survive a year in any orbit, any environment, any orientation, at any point in the solar cycle. It is critical to model the expected use environment and choose materials accordingly.

The environmental data are presented in numerical order rather than chronological order, as MISSE-5 was flown before MISSE-3 and MISSE-4. For simplicity, only AO and UV environment definitions are given. Details of these environments may be found in references 16–19. (Material effects related to particulate radiation or micrometeoroid/space debris impacts on MISSE were negligible.)

2.1 MISSE-1 and MISSE-2

MISSE-1 and MISSE-2 were deployed in August 2001 during STS-104 and retrieved in July 2005 during STS-114. They were attached to the Quest Airlock (fig. 2). The intended duration was 1 year, but retrieval was delayed because of the Space Shuttle *Columbia* accident. Table 2 presents their environments in terms of AO fluence (given as oxygen atoms/cm^2) and UV radiation in equivalent sun hours (ESH).

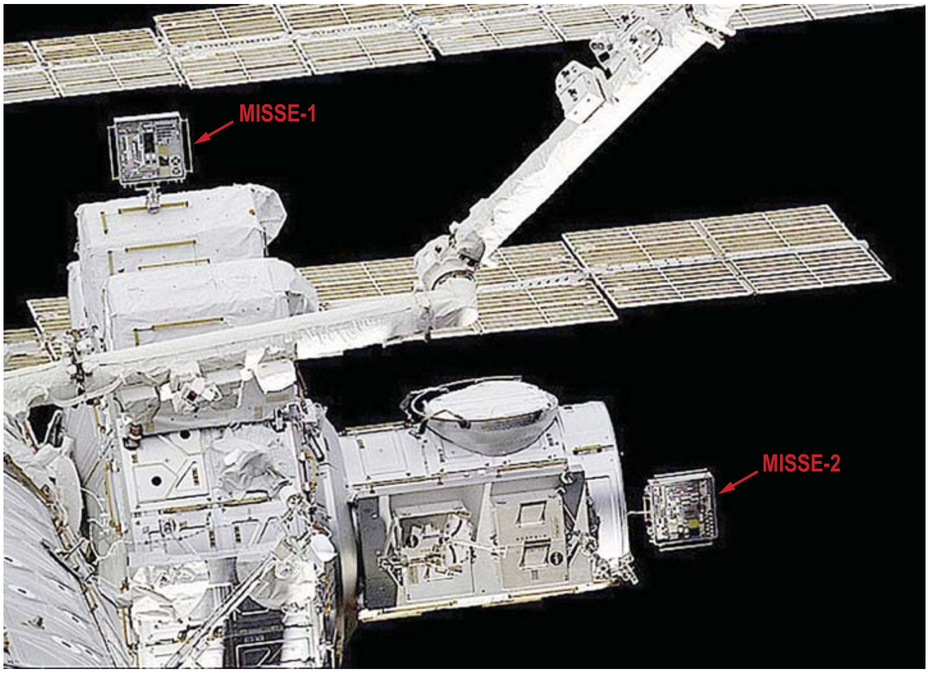

Figure 2. MISSE-1 and MISSE-2 on the Quest Airlock. Photograph taken during the STS-108 mission.

Table 2. MISSE-1 and MISSE-2 environments.

	AO Fluence (atoms/cm^2)	UV Radiation (ESH)
MISSE-1 ram-facing side	9×10^{21} (est.)	5,400 – 6,400
MISSE-1 wake-facing side	$1.1 - 1.3 \times 10^{20}$	4,500 – 5,600
MISSE-2 ram-facing side	$8 - 9 \times 10^{21}$	5,000 – 6,700
MISSE-2 wake-facing side	$1.7 - 2 \times 10^{20}$	4,800 – 6,200

2.2 MISSE-3 and MISSE-4

MISSE-3 and MISSE-4 were deployed in August 2006 during STS-121 and retrieved in August 2007 during STS-118. They were attached to the Quest Airlock in the same locations as MISSE-1 and MISSE-2. Table 3 presents their environments.

Table 3. MISSE-3 and MISSE-4 environments.

	AO Fluence (atoms/cm^2)	UV Radiation (ESH)
MISSE-3 ram-facing side	$1.2 - 1.3 \times 10^{21}$	1,750
MISSE-3 wake-facing side	1.9×10^{20}	790
MISSE-4 ram-facing side	2.1×10^{21}	1,590
MISSE-4 wake-facing side	3.6×10^{20} (est.)	995

2.3 MISSE-5

MISSE-5 was deployed in July 2005 during STS-114 and retrieved in July 2006 during STS-115. It was attached to the P6 truss (fig. 3), when P6 was mounted on the Z1 truss. Solar cells made up the zenith-facing side, while a blanket of materials samples covered the nadir side. The AO fluence for the nadir-facing side was 1.8×10^{20} atoms/cm^2, and the estimated UV exposure was 160 ESH.

Figure 3. MISSE-5 on P6 truss; nadir side visible.

2.4 MISSE-6

MISSE-6A and MISSE-6B were deployed in March 2008 during STS-123 and retrieved in September 2009 during STS-128. They were attached to the Columbus module (fig. 4). Table 4 presents their environments.

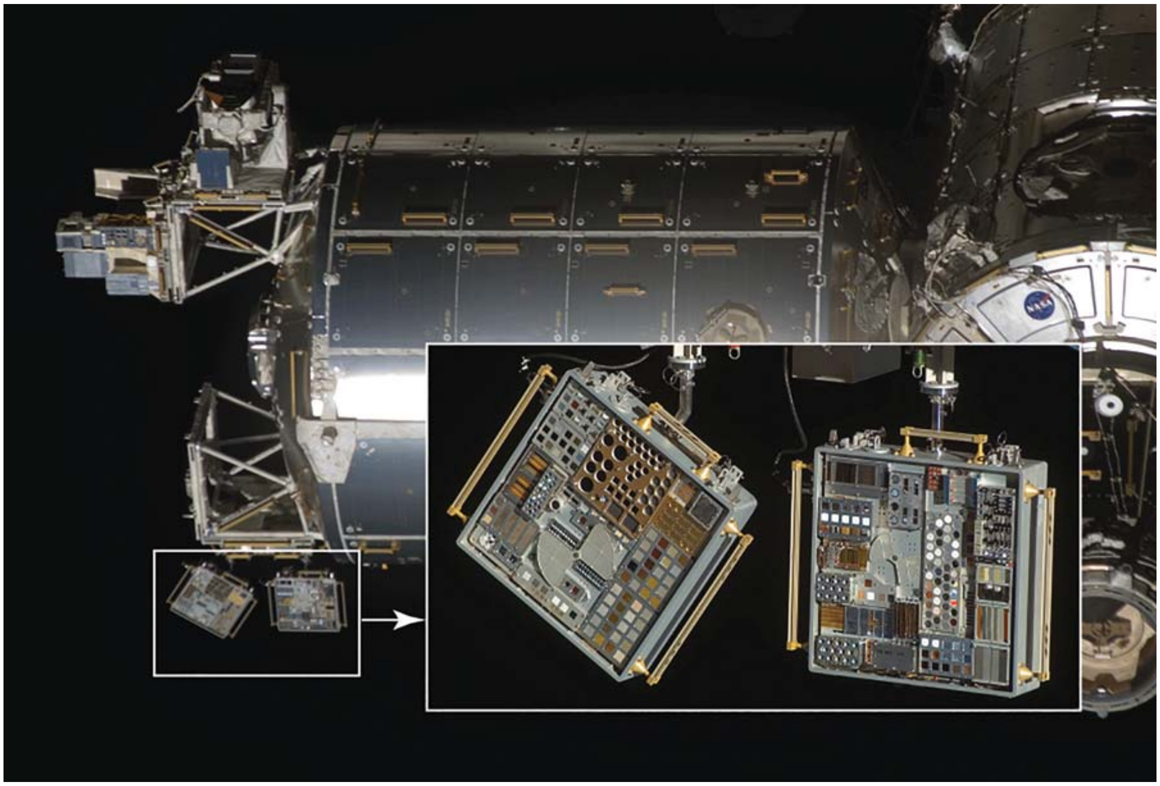

Figure 4. MISSE-6A (left) and MISSE-6B (right) attached to the Columbus module.

Table 4. MISSE-6A and MISSE-6B environments.

	AO Fluence (atoms/cm^2)	UV Radiation (ESH)
MISSE-6A ram-facing side	2×10^{21}	2,600
MISSE-6A wake-facing side	1.4×10^{20}	1,950
MISSE-6B ram-facing side	2×10^{21}	2,600
MISSE-6B wake-facing side	1.2×10^{20}	1,950

2.5 MISSE-7

MISSE-7A and MISSE-7B were deployed in November 2009 during STS-129 and retrieved in May 2011 during STS-134. They were attached to the EXpedite the PRocessing of Experiments to Space Station (EXPRESS) Logistics Carrier 2 (ELC-2) (fig. 5). Table 5 presents environmental data for MISSE-7B. Similar data for MISSE-7A, which was a zenith-/nadir-facing experiment, were not available at time of publication.

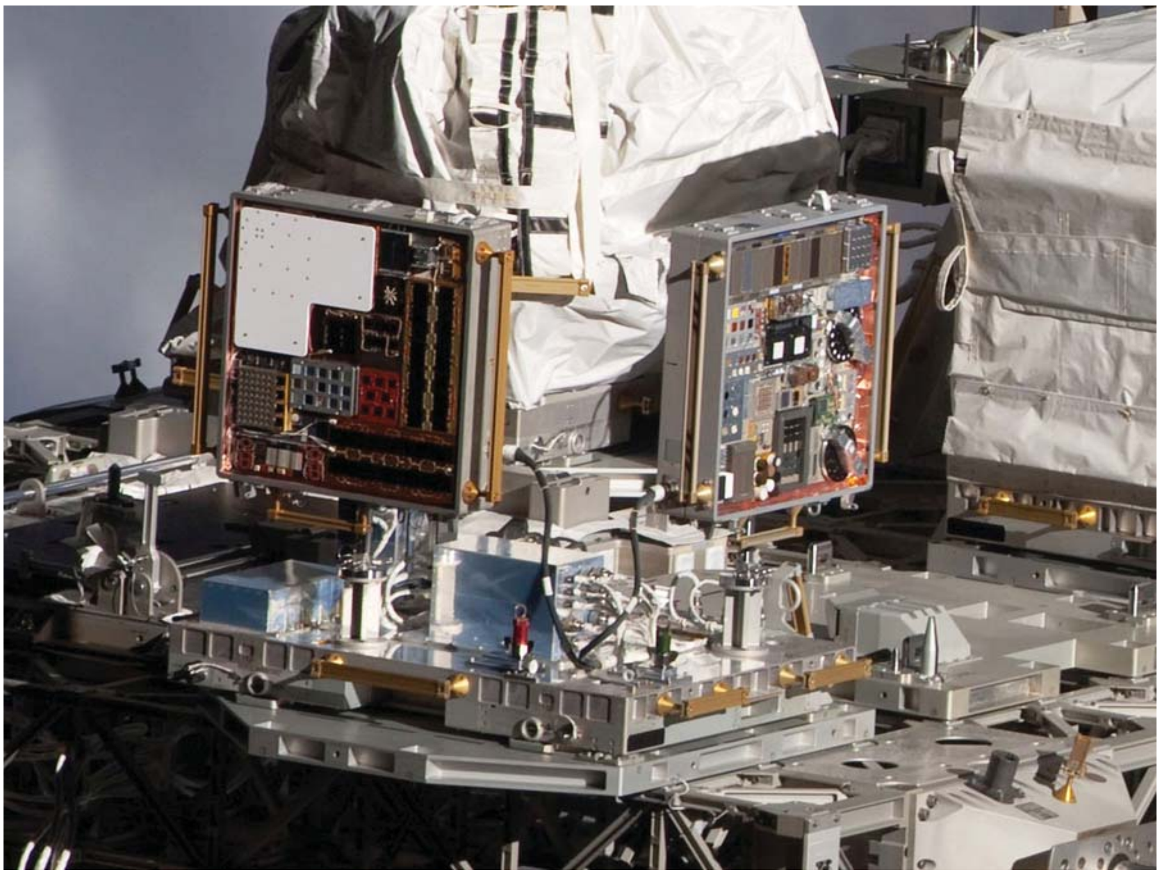

Figure 5. MISSE-7A (left) and MISSE-7B (right) on ELC-2.

Table 5. MISSE-7B environment.

	AO Fluence (atoms/cm^2)	UV Radiation (ESH)
MISSE-7B ram-facing side	4.2×10^{21}	2,400
MISSE-7B wake-facing side	2.9×10^{20}	2,000

3. CONTAMINATION

Molecular contamination can skew the results of a space environmental effects investigation. Several optical witness samples were flown on each MISSE experiment to monitor contamination and to indicate how well the ISS contamination control plan was working. When possible, electron spectroscopy for chemical analysis (ESCA) and ellipsometry were performed on these optical witness samples to determine contaminant buildup.

There have been instances of localized contamination on the MISSE experiments, but overall, they have been fairly clean, on the order of 500 Å of silicate or less. This amount is enough to affect sensitive optics but not enough to impact radiator performance. Figure 6 shows the worst case of contamination observed by ESCA, which was a gold optical witness sample flown on the wake side of MISSE-2 for nearly 4 years. A similar gold mirror flown on the ram side of MISSE-2 only had 50 Å of silicate. This measurement was in good agreement with ellipsometry results.

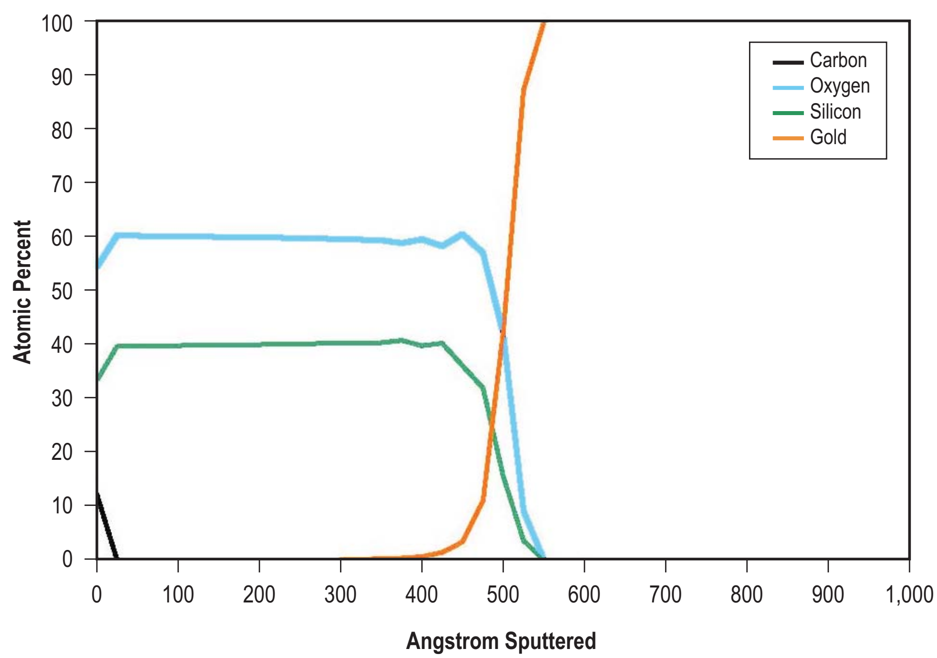

Figure 6. ESCA of gold mirror from MISSE-2 wake side.

4. SURFACE TREATMENTS FOR METALS

This section covers chemical conversion coatings in accordance with MIL-DTL-5541F, Military Specification: Chemical Conversion Coatings on Aluminum and Aluminum Alloys,[20] and anodic coatings in accordance with MIL-A-8625, Military Specification: Anodic Coatings for Aluminum and Aluminum Alloys,[21] for aluminum. These coatings are mainly for corrosion protection, but much of the ISS anodized aluminum structure was tailored for a specific range of α_s and ε for passive thermal control.

In this section, Anadite, George, and Mooney refer to the specific vendors contracted for surface treatments: Anadite, Inc.; George Industries; and Mooney Anodize. Samples labeled Boeing or Marshall Space Flight Center (MSFC) were processed by the respective in-house fabrication shops.

4.1 Conversion Coatings

All of the conversion coatings on 2219 aluminum were flown on the MISSE-3 ram and wake sides. The iridite on 2195 aluminum-lithium alloy was flown on the MISSE-6B wake side. Table 6 lists the optical properties of the MISSE conversion coatings.

Table 6. Optical properties of MISSE conversion coatings.

		Preflight	Postflight	Δ	Environment
Anadite chromate on 2219-T851 MISSE-3 ram	α	0.50	0.51	0.01	1,750 ESH
	ε	0.07	0.07	–	1.2×10^{21} O atoms/cm^2
Anadite chromate on 2219-T851 MISSE-3 wake	α	0.49	0.49	–	790 ESH
	ε	0.07	0.07	–	1.9×10^{20} O atoms/cm^2
George chromate on 2219-T851 MISSE-3 ram	α	0.35	0.40	0.05	1,750 ESH
	ε	0.05	0.06	0.01	1.2×10^{21} O atoms/cm^2
George chromate on 2219-T851 MISSE-3 wake	α	0.35	0.42	0.07	790 ESH
	ε	0.07	0.07	–	1.9×10^{20} O atoms/cm^2
Boeing chromate on 2219-T851 MISSE-3 ram	α	0.47	0.48	0.01	1,750 ESH
	ε	0.05	0.06	0.01	1.2×10^{21} O atoms/cm^2
MSFC 12-4 iridite on 2195 MISSE-6 wake	α	0.31	0.31	–	1,950 ESH
	ε	0.05	0.04	–0.01	1.2×10^{20} O atoms/cm^2

4.2 Chromic Acid Anodized Aluminum

As previously mentioned, most of the ISS structure and meteoroid/debris shields are chromic acid anodized (CAA) aluminum. While there is a wealth of CAA data from the Long Duration Exposure Facility (LDEF)[22] there are only a few data points for MISSE, and these are mainly for comparison to other anodize types. CAA aluminum (6061-T6), flown on the wake side of MISSE-6, had a slight increase in α_s from 0.32 to 0.34 and a slight decrease in ε from 0.49 to 0.46. Several of the older sample trays are CAA aluminum. While preflight data for these trays were not available, postflight measurements were 0.28 to 0.31 for α_s and 0.66 to 0.67 for ε.

4.3 Sulfuric Acid Anodized Aluminum

Sulfuric acid anodize (SAA) became more widely used as the Environmental Protection Agency restricted the use of chromium. This restriction also led to the elimination of sodium chromate, used to seal SAA. MIL-A-8625, Type II, calls for sodium chromate, nickel acetate (NiAc), cobalt acetate, or hot water seal. Cobalt acetate seal has not been flown on MISSE. Data from the earlier Passive Optical Sample Assembly-I (POSA-I) experiment indicated that anodized aluminum treated with either NiAc or nickel fluoride would darken after only 800 ESH of UV radiation.[23] The authors recommend hot deionized (DI) water seal for MIL-A-8625, Type II anodize.

Table 7 contains the optical property data for a variety of MISSE SAA aluminum samples. These do not include the SAA with preflight contamination, which are discussed in reference 8. Measurements made directly on sample trays, frames (example shown in fig. 7), and baseplates are included in table 8.

Table 7. Optical properties for SAA aluminum samples.

		Preflight	Postflight	Δ	Environment
SAA on 2219-T851, DI seal MISSE-2 ram	α	0.47	0.48	0.01	6,600 ESH
	ε	0.86	0.88	0.02	9×10^{21} O atoms/cm^2
Anadite SAA on 2219-T851 MISSE-3 ram	α	0.41	0.42	0.01	1,750 ESH
	ε	0.89	0.88	–0.01	1.2×10^{21} O atoms/cm^2
Anadite SAA on 2219-T851 MISSE-3 wake	α	0.46	0.48	0.02	790 ESH
	ε	0.89	0.88	–0.01	1.9×10^{20} O atoms/cm^2
George SAA on 2219-T851 MISSE-3 ram	α	0.42	0.48	0.06	1,750 ESH
	ε	0.90	0.88	–0.02	1.2×10^{21} O atoms/cm^2
George SAA on 2219-T851 MISSE-3 wake	α	0.41	0.47	0.06	790 ESH
	ε	0.90	0.87	–0.03	1.9×10^{20} O atoms/cm^2
Boeing SAA on 2219-T851 MISSE-3 ram	α	0.44	0.49	0.05	1,750 ESH
	ε	0.88	0.85	–0.03	1.2×10^{21} O atoms/cm^2
Boeing SAA on 2219-T851 MISSE-3 wake	α	0.40	0.46	0.06	790 ESH
	ε	0.87	0.84	–0.03	1.9×10^{20} O atoms/cm^2
George SAA on 7075-T3751 MISSE-3 ram	α	0.44	0.49	0.05	1,750 ESH
	ε	0.87	0.87	–	1.2×10^{21} O atoms/cm^2

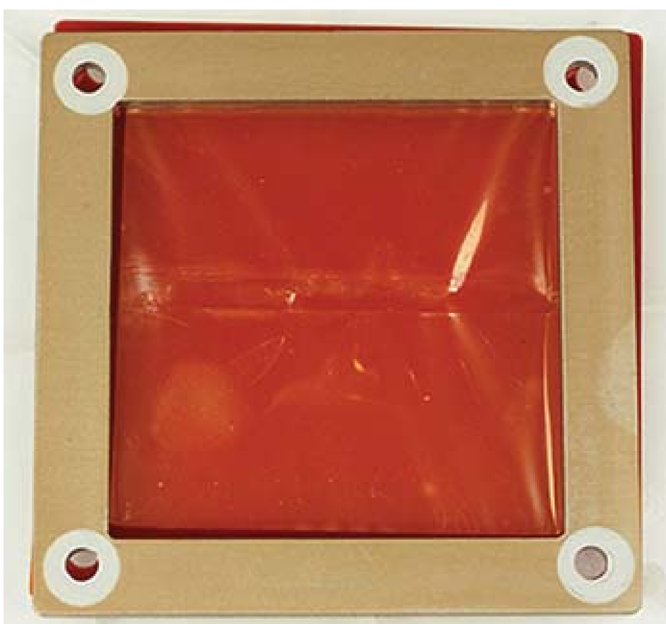

Figure 7. SAA aluminum frame, probably with NiAc seal. Lighter circles are where washers shielded the aluminum from UV radiation and are the original color of the frame.

Table 8. Optical properties for SAA aluminum hardware.

		Unexposed	Exposed	Δ	Environment
N1 frame NiAc seal, MISSE-2 wake	α	0.46	0.56	0.10	5,700 ESH
	ε	0.83	0.83	–	1×10^{20} O atoms/cm^2
N2 frame NiAc seal, MISSE-2 wake	α	0.49	0.57	0.08	5,700 ESH
	ε	0.84	0.83	–0.01	1×10^{20} O atoms/cm^2
N3 frame NiAc seal, MISSE-1 wake	α	0.49	0.59	0.10	5,400 ESH
	ε	0.84	0.84	–	1.2×10^{20} O atoms/cm^2
N4 frame NiAc seal, MISSE-1 wake	α	0.46	0.57	0.11	5,400 ESH
	ε	0.83	0.83	–	1.2×10^{20} O atoms/cm^2
Sample tray hot DI water, MISSE-6 ram	α	0.44	0.43	–0.01	2,600 ESH
	ε	0.85	0.85	–	2×10^{21} O atoms/cm^2
Sample tray hot DI water, MISSE-6 wake	α	0.43	0.43	–	1,950 ESH
	ε	0.85	0.85	–	1.2×10^{20} O atoms/cm2
Unknown seal baseplate, MISSE-7B ram	α	0.49	0.52	0.03	2,400 ESH
	ε	0.87	0.87	–	4.2×10^{21} O atoms/cm^2
Unknown seal baseplate, MISSE-7B wake	α	0.49	0.53	0.04	2,000 ESH
	ε	0.87	0.87	–	2.9×10^{20} O atoms/cm^2

The anodize instructions for the MISSE-7B baseplate specified hot DI water seal, but the baseplate visibly darkened (fig. 8). Different batches of SAA from the same plating shop for MISSE-7B did not darken. Chemical analysis has not yet been performed to determine the presence of nickel.

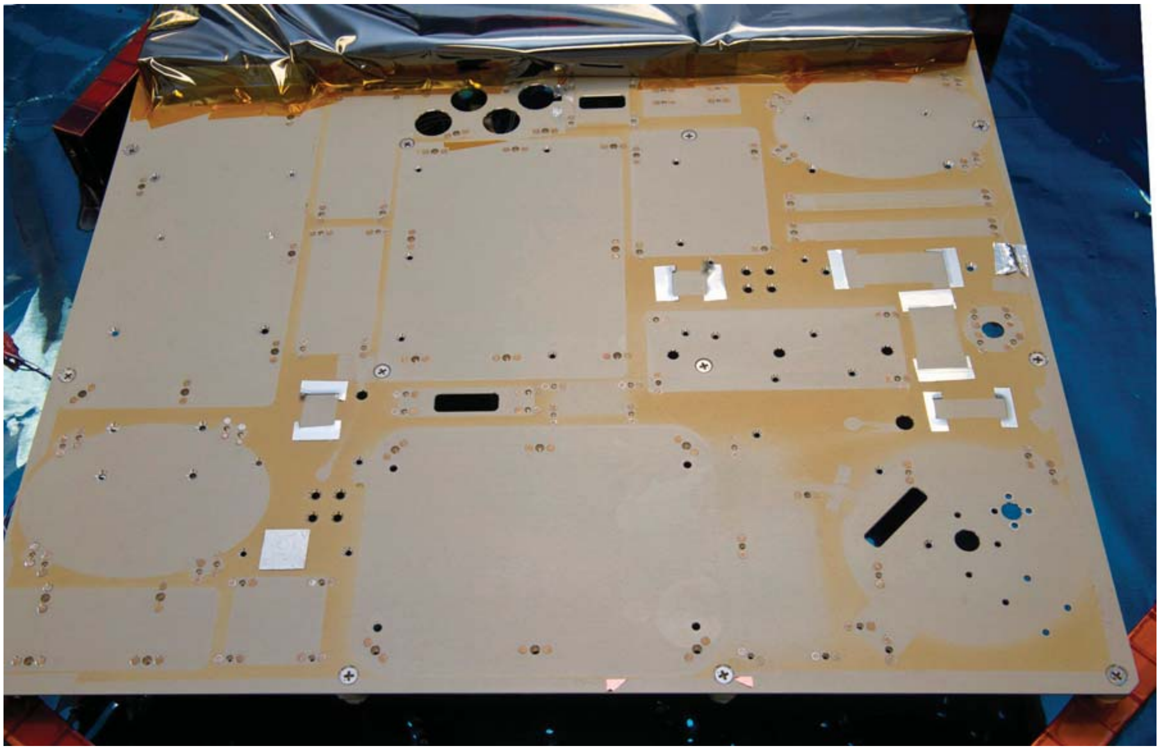

Figure 8. MISSE-7B wake baseplate after most of the samples had been removed, showing UV darkening where the aluminum was exposed.

Several class 2, or dyed anodize, samples have been flown on MISSE. Optical property data are presented only for the black dyed anodize. Concerns regarding gold, blue, and red anodize center on color maintenance, not on optical properties. Yellow anodize is used to indicate areas that can hold an astronaut, such as handrails and tether points. Red anodize is used to indicate no-touch zones, such as areas of hypergolic residue from engine ports or where high temperatures may damage the astronaut's gloves. Early tests of dyed anodize during the Space Station Freedom program caused some concern, where yellow and red anodizes changed in simulated space environments to nearly the same shade of brown. Previous space environment testing of dyed anodize is discussed in reference 24. The Aacron, Inc., dyed anodize samples flown on MISSE-2 maintained their color with 6,600 ESH of UV and 8×10^{21} atoms/cm^2 of AO (fig. 9).

Figure 9. Postflight MISSE-2 dyed anodize samples.

It should be noted that attempts at MSFC to black dye anodize aluminum-lithium alloy, specifically AL 2195, have been unsuccessful to date. The black dye particles can be wiped off after processing. Table 9 lists optical properties for black dyed anodized aluminum.

Table 9. Optical properties for black dyed anodized aluminum.

		Preflight	Postflight	Δ	Environment
7075 clad with 7072 MISSE-2 AaCron	α	0.90	0.90	–	6,600 ESH
	ε	0.85	0.85	–	8×10^{21} O atoms/cm^2
6061-T6x MISSE-7B ram Mooney anodize	α	0.71	0.70	–0.01	2,400 ESH
	ε	0.86	0.87	0.01	4.2×10^{21} O atoms/cm^2
6061-T6x MISSE-7B wake Mooney anodize	α	0.69	0.68	–0.01	2,000 ESH
	ε	0.86	0.86	–	2.9×10^{20} O atoms/cm^2

4.4 Electroless Nickel

Electroless nickel is used on fluid and electrical connectors. It is usually covered with multilayer insulation (MLI) for thermal control, but there was enough concern for possible exposure of electroless-nickel-plated parts to include samples on MISSE-6. These samples were processed by AZ Technology of Huntsville, AL. This coating appeared to be stable in a low Earth orbital environment (table 10).

Table 10. Optical properties for electroless nickel.

		Preflight	Postflight	Δ	Environment
MISSE-6 ram	α	0.42	0.41	–0.01	2,600 ESH
	ε	0.09	0.09	–	2×10^{21} O atoms/cm^2
MISSE-6 wake	α	0.39	0.39	–	1,950 ESH
	ε	0.09	0.09	–	1.2×10^{20} O atoms/cm^2

5. THERMAL CONTROL COATINGS

Whether as part of an active thermal control system or simple passive thermal control, coatings such as Z-93 must maintain their optical properties and mechanical integrity.

5.1 White Potassium Silicate Binder Coatings

Passive thermal control coatings with potassium silicate binder have shown good durability in the space environment, provided they are properly applied and kept free of contamination. Zinc oxide pigment in a potassium silicate binder, sold as Z-93 by Alion Science and Technology Corporation (formerly known as IITRI) or AZ93 by AZ Technology, has been flown on every MISSE experiment. (Tables 11 and 12 list optical properties for these two companies' products, respectively.) Z-93 and Z-93P have been used interchangeably in other documents. The original Z-93 used PS7 potassium silicate binder, which was discontinued in the early 1990s. Coatings made with the replacement Kasil 2135 potassium silicate binder are designated Z-93P. Kasil 2130 has also been approved as a replacement binder. The reader should be aware of these differences when comparing data from before 1991 to MISSE data.

Table 11. Optical properties for Alion Science zinc oxide/potassium silicate coating.

		Preflight or Control	Postflight	Δ	Environment
Z-93P on aluminum, MISSE-2 ram	α	0.14	0.13	–0.01	6,000 ESH
	ε	0.91	0.90	–0.01	7.6×10^{21} O atoms/cm^2
Z-93P on aluminum, MISSE-2 wake	α	0.14	0.14	–	4,900 ESH
	ε	0.91	0.91	–	1.4×10^{20} O atoms/cm^2
Z-93P on aluminum, MISSE-3 ram	α	0.14	0.15	0.01	1,750 ESH
	ε	0.91	0.91	–	1.2×10^{21} O atoms/cm^2
Z-93P on aluminum, MISSE-4 wake	α	0.14	0.14	–	900 ESH
	ε	0.91	0.91	–	3.6×10^{20} O atoms/cm^2
Z-93P on aluminum, MISSE-6 ram	α	0.14	0.14	–	2,600 ESH
	ε	0.91	0.91	–	2×10^{21} O atoms/cm^2

Table 12. Optical properties for AZ Technology zinc oxide/potassium silicate coating.

		Preflight or Control	Postflight	Δ	Environment
AZ93 on 6061-T651(Boeing), MISSE-1 ram	α	0.16	0.15	–0.01	7,000 ESH
	ε	0.93	0.91	–0.02	9×10^{21} O atoms/cm^2
AZ93 on 6061-T6x (MSFC), MISSE-2 ram	α	0.15	0.15	–	6,000 ESH
	ε	0.92	0.92	–	7.6×10^{21} O atoms/cm^2
AZ93 on 6061-T6x, MISSE-3 ram	α	0.15	0.15	–	1,750 ESH
	ε	0.91	0.91	-	1.2×10^{21} O atoms/cm^2
AZ93 on 6061-T6x, MISSE-3 wake	α	0.15	0.16	0.01	790 ESH
	ε	0.91	0.91	–	1.9×10^{20} O atoms/cm^2
AZ93 on 6061-T6x, MISSE-4 ram	α	0.15	0.15	–	1,590 ESH
	ε	0.91	0.91	–	2.1×10^{21} O atoms/cm^2
AZ93 on 6061-T6x, MISSE-6B ram	α	0.17	0.17	–	2,600 ESH
	ε	0.91	0.91	–	2×10^{21} O atoms/cm^2
AZ93 on 6061-T6x, MISSE-6B wake	α	0.17	0.17	–	1,950 ESH
	ε	0.91	0.91	–	1.2×10^{20} O atoms/cm^2
AZ93 on 6061-T6x, MISSE-7B ram	α	0.16	0.16	–	2,400 ESH
	ε	0.91	0.91	–	4.2×10^{21} O atoms/cm^2
AZ93 on 6061-T6x, MISSE-7B wake	α	0.16	0.16	–	2,000 ESH
	ε	0.91	0.91	–	2.9×10^{20} O atoms/cm^2
AZ93 on Composite, MISSE-1 ram	α	0.15	0.16	0.01	5,700 ESH
	ε	0.91	0.91	–	9×10^{21} O atoms/cm^2
AZ93 on Kapton, MISSE-5 nadir	α	0.21	0.22	0.01	525 ESH
	ε	0.92	0.92	–	1.8×10^{20} O atoms/cm^2
AZ93 on Beta cloth, MISSE-6 ram	α	0.17	0.17	–	2,600 ESH
	ε	0.92	0.92	–	2×10^{21} O atoms/cm^2
AZ93 on Kapton film, MISSE-6 wake	α	0.18	0.18	–	1,950 ESH
	ε	0.92	0.92	–	1.2×10^{20} O atoms/cm^2

Not only is this material used on the Active Thermal Control System radiators, it is a bellwether for effects of contamination. Z-93P exposed on the POSA experiment on *Mir* increased in α_s from 0.15 to 0.23 because of 5,000 Å of contamination and only 571 ESH of UV radiation.[25] By contrast, the same coating was within instrument error of the original solar absorptance after 6,000 ESH exposure on MISSE-2.

Another class of coatings with potassium silicate binder uses zinc orthotitanate for the pigment. Alion Science YB-71P (with P again denoting the use of Kasil 2135 binder instead of the original PS7 binder) and AZ Technology AZ-70-WIZT were flown on MISSE-2. Tables 13 and 14 list the optical properties for these two companies' products, respectively.

Table 13. Optical properties for Alion Science zinc orthotitanate/potassium silicate coating.

		Preflight or Control	Postflight	Δ	Environment
YB-71P on aluminum MISSE-2 ram	α	0.12	0.11	–0.01	6,000 ESH
	ε	0.86	0.87	0.01	7.6×10^{21} O atoms/cm^2
YB-71P on aluminum MISSE-2 wake	α	0.12	0.12	–	4,900 ESH
	ε	0.86	0.87	0.01	1.4×10^{20} O atoms/cm^2
YB-71P on aluminum MISSE-3 ram	α	0.12	0.12	–	1,750 ESH
	ε	0.87	0.88	0.01	1.2×10^{21} O atoms/cm^2
YB-71P on aluminum MISSE-4 wake	α	0.12	0.12	–	900 ESH
	ε	0.87	0.88	0.01	3.6×10^{20} O atoms/cm^2

Table 14. Optical properties for AZ Technology zinc orthotitanate/potassium silicate coating.

		Preflight or Control	Postflight	Δ	Environment
AZ70-WIZT on aluminum MISSE-1 ram	α	0.09	0.09	–	5,700 ESH
	ε	0.91	0.90	–0.01	9×10^{21} O atoms/cm^2
AZ70-WIZT on aluminum MISSE-2 ram	α	0.10	0.10	–	6,000 ESH
	ε	0.91	0.91	–	7.6×10^{21} O atoms/cm^2

5.2 White Silicone Binder Coatings

Thermal control coatings with low outgassing silicone binders are used when the surface is difficult to paint or when temperature and humidity cannot be controlled during the coating application. Some of these coatings tend to darken in UV but may still have acceptable end-of-life properties for certain missions, especially where AO may bleach the coating. The more commonly used silicone binder coatings are Alion Science's S13G/LO-1 and S13GP:6N/LO-1 and AZ Technology's AZ400. Tables 15 and 16 list the optical properties for these two companies' products, respectively.

Table 15. Optical properties for Alion Science zinc oxide/silicone binder coating.

		Preflight	Postflight	Δ	Environment
S13G/LO-1 on aluminum, MISSE-2 ram	α	0.20	0.20	–	6,000 ESH
	ε	0.89	0.89	–	7.6×10^{21} O atoms/cm^2
S13G/LO-1 on aluminum, MISSE-2 wake	α	0.20	0.45	0.25	4,900 ESH
	ε	0.89	0.87	–0.02	1.4×10^{20} O atoms/cm^2
S13GP:6N/LO-1 on aluminum, MISSE-2 ram	α	0.18	0.20	0.02	6,000 ESH
	ε	0.90	0.89	–0.01	7.6×10^{21} O atoms/cm^2
S13GP:6N/LO-1 on aluminum, MISSE-2 wake	α	0.18	0.34	0.16	4,900 ESH
	ε	0.90	0.90	–	1.4×10^{20} O atoms/cm^2
S13GP:6N/LO-1 on aluminum, MISSE-3 ram	α	0.18	0.20	0.02	1,750 ESH
	ε	0.90	0.90	–	1.2×10^{21} O atoms/cm^2
S13GP:6N/LO-1 on aluminum, MISSE-4 wake	α	0.18	0.23	0.05	900 ESH
	ε	0.90	0.89	–0.01	3.6×10^{20} O atoms/cm^2

Table 16. Optical properties for AZ Technology zinc oxide/silicone binder coating.

		Preflight	Postflight	Δ	Environment
AZ400 conductive on aluminum, MISSE-6 ram	α	0.23	0.23	–	2,600 ESH
	ε	0.92	0.91	–0.01	2×10^{21} O atoms/cm^2
AZ400 conductive on aluminum, MISSE-6 wake	α	0.23	0.23	–	1,950 ESH
	ε	0.92	0.92	–	1.2×10^{20} O atoms/cm^2
AZ400 on aluminum, MISSE-7 ram	α	0.15	0.16	0.01	2,400 ESH
	ε	0.85	0.86	0.01	4.2×10^{21} O atoms/cm^2
AZ400 on aluminum, MISSE-7 wake	α	0.15	0.16	0.01	2,000 ESH
	ε	0.85	0.85	–	2.9×10^{20} O atoms/cm^2

5.3 Black Potassium Silicate Binder Coatings

AZ Technology RM-550 black coating with the inorganic potassium silicate binder has been used on the ISS in various places, including the docking targets. Samples flown on MISSE-6 and MISSE-7 ram and wake maintained α_s of 0.97 and ε of 0.90.

6. MULTILAYER INSULATION MATERIALS

MLI blankets are composed of reflector layers of thin polymer films with metallization on one or both sides, usually with netting or another separator layer in between. MLI blankets on the ISS are usually 15 to 20 double-aluminized Kapton® reflector layers with outer and inner covers for ease of handling and durability in the space environment.

6.1 Beta Cloth

Beta cloth is a woven fiberglass mat impregnated with Teflon®. MLI blankets for ISS have usually been Saint-Gobain/Chemfab 500F with aluminization on one side and no polysiloxane. For Space Shuttle MLI blankets, the Chemfab 250F usually had ≈2% polysiloxane added for flexibility, but this was a contamination concern and caused the Chemfab 250F to darken more in UV.[26] Various samples of beta cloth have been flown on every MISSE: aluminized beta cloth samples taken from scraps left over from manufacturing the ISS MLI blankets are referred to as 'ISS batch,' 'plain' beta cloth refers to unaluminized beta cloth, and 'super' beta cloth and beta cloth 'plus' refer to a change to slightly larger glass denier in the weave. After the removal of perfluorooctanoic acid (PFOA) from the Teflon process in 2007, 'PFOA-free' beta cloth was manufactured.

Two samples of black beta cloth were flown on MISSE-5. This form of beta cloth has carbon black impregnated in the Teflon. Exposure to AO increased the α_s from 0.95 to 0.96 and 0.97, but ε was unchanged at 0.89.

It should be noted that beta cloth is slightly transmissive; therefore, the background used on the sample will affect the α_s measurement. Unless otherwise noted, a blackbody background was used for the optical property measurements listed in tables 17–20.

Table 17. Optical properties for aluminized beta cloth.

		Preflight or Control	Postflight	Δ	Environment
ISS batch, MISSE-2 ram	α	0.34	0.37	0.03	6,000 ESH
	ε	0.89	0.89	–	7.6×10^{21} O atoms/cm^2
ISS batch, MISSE-2 wake	α	0.34	0.38	0.04	5,700 ESH
	ε	0.89	0.89	–	1×10^{20} O atoms/cm^2
Boeing batch, MISSE-3 ram	α	0.34	0.38	0.04	1,750 ESH
	ε	0.89	0.89	–	1.2×10^{21} O atoms/cm^2
Lockheed batch, MISSE-3 ram	α	0.35	0.36	0.01	1,750 ESH
	ε	0.90	0.89	–0.01	1.2×10^{21} O atoms/cm^2
Lockheed batch, MISSE-4 wake	α	0.35	0.34	–0.01	790 ESH
	ε	0.90	0.89	–0.01	1.9×10^{20} O atoms/cm^2
ISS batch, MISSE-5 nadir	α	0.34	0.37	0.03	525 ESH
	ε	0.89	0.89	–	1.8×10^{20} O atoms/cm^2
ISS batch, MISSE-6 ram	α	0.36	0.41	0.05	2,600 ESH
	ε	0.87	0.88	0.01	2×10^{21} O atoms/cm^2
ISS batch, MISSE-6 wake	α	0.36	0.42	0.06	1,950 ESH
	ε	0.87	0.89	0.02	1.2×10^{20} O atoms/cm^2

Table 18. Optical properties for plain beta cloth.

		Preflight or Control	Postflight	Δ	Environment
With 966 adhesive to aluminum plate, MISSE-2 ram	α	0.29	0.30	0.01	6,000 ESH
	ε	0.91	0.90	–0.01	7.6×10^{21} O atoms/cm^2
With black background, MISSE-2 wake	α	0.35	0.38	0.03	5,700 ESH
	ε	0.89	0.89	–	1×10^{20} O atoms/cm^2
Aluminized Kapton background, MISSE-3 ram	α	0.29	0.31	0.02	1,750 ESH
	ε	0.89	0.89	–	1.2×10^{21} O atoms/cm^2
0.0127-cm (5-mil) aluminized Teflon MISSE-3 wake	α	0.28–0.29	0.29	0.01	790 ESH
	ε	–	0.89	–	1.9×10^{20} O atoms/cm^2

Table 19. Optical properties for super or plus beta cloth.

		Preflight or Control	Postflight	Δ	Environment
MISSE-2 ram	α	0.36	0.38	0.02	6,000 ESH
	ε	0.90	0.89	–0.01	7.6×10^{21} O atoms/cm^2
MISSE-2 wake	α	0.36	0.40	0.04	5,700 ESH
	ε	0.90	0.89	–0.01	1×10^{20} O atoms/cm^2
Kapton background, MISSE-5 nadir	α	0.27	0.30	0.03	525 ESH
	ε	0.89	0.89	–	1.8×10^{20} O atoms/cm^2

Table 20. Optical properties for PFOA-free beta cloth, black background.

		Preflight or Control	Postflight	Δ	Environment
MISSE-6 ram	α	0.35	0.37	0.02	2,600 ESH
	ε	0.89	0.89	–	2×10^{21} O atoms/cm^2
MISSE-6 wake	α	0.36	0.39	0.03	1,950 ESH
	ε	0.89	0.89	–	1.2×10^{20} O atoms/cm^2

6.2 Hook and Loop Tape Fastener

Aplix® hook and loop tape fastener samples (fig. 10) were flown on MISSE-2 and MISSE-3. For the ram-facing MISSE-2 samples, AO heavily eroded the polymeric hooks and loops into only nubs. The samples on the wake side of MISSE-3 indicated that fastener adhesion was still present after 1×10^{20} atoms/cm^2.

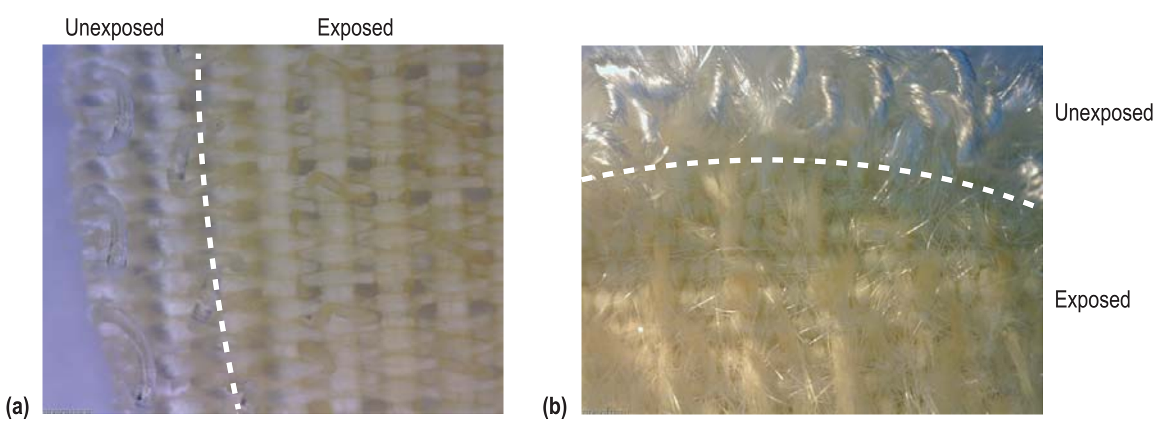

Figure 10. Aplix tape fastener samples from MISSE-2 ram side, showing UV darkening and nubs: (a) Hook and (b) loop.

6.3 Thread

One of the lessons from LDEF was the importance of thread selection for MLI blankets. Dacron™ thread used on a heat pipe experiment was completely eroded away during the 5.8-year exposure.[27] Aramid (Kevlar®) thread is occasionally used for short-duration exposures or where the blanket should be protected from AO, but most of the ISS MLI blankets use either fiberglass thread coated with polytetrafluoroethylene (PTFE) or stainless steel coated with PTFE. Triton Systems developed their Triton oxygen resistant (TOR) material into both cloth and thread for flight on MISSE-1 and MISSE-3 ram-facing sides. The sample in figure 11 was flown on MISSE-1 with Kapton film behind it. The Kapton indicated some AO erosion where the sewing needle had pierced the fabric; otherwise, this sample was in very good condition for an AO exposure of 9×10^{21} atoms/cm^2.

Figure 11. Triton TOR cloth and thread, MISSE-1 ram.
Octagon is where sample was exposed to space.

The 2-G1 sample from MISSE-2 was made up of old and new beta cloth, some with the aluminum light block layer or the Teflon removed, sewn with reinforced Kevlar thread (fig. 12). This thread was still intact after an AO exposure of 7.6×10^{21} atoms/cm^2.

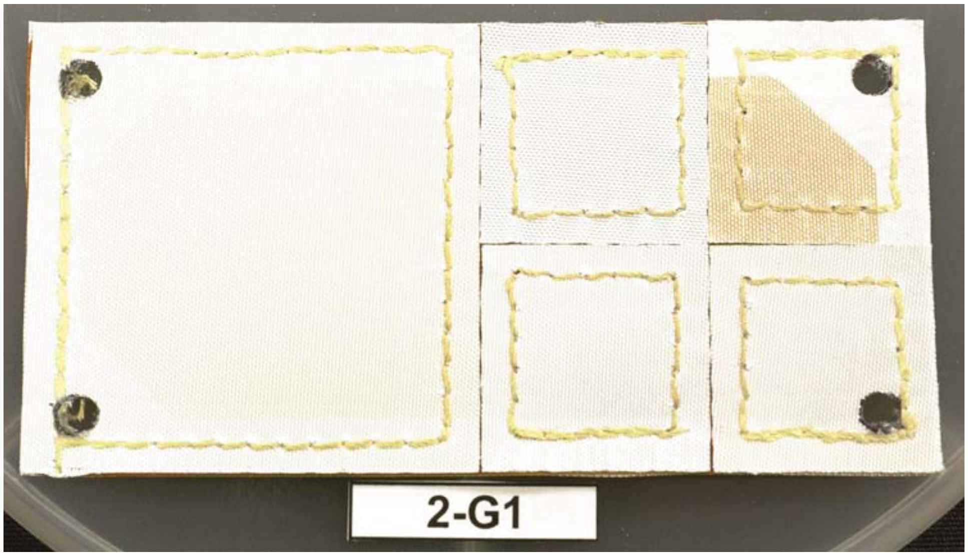

Figure 12. Samples of beta cloth sewn with reinforced thread.

7. POLYMERS

Teflon metallized with either aluminum or silver and Inconel is a common thermal control material on the ISS (tables 21 and 22). The usual thickness of the Teflon layer is 0.0254 cm (10 mil), though 0.00254 cm (1 mil), 0.00508 cm (2 mil), and 0.0127 cm (5 mil) samples have been flown on MISSE. In addition, some samples of silverized Teflon had a silicon oxide (SiO_x) protective coating (table 23).

Table 21. Optical properties for aluminized Teflon.

		Preflight or Control	Postflight	Δ	Environment
0.00508 cm (2 mil), MISSE-6 ram	α	0.12	0.12	–	2,600 ESH
	ε	0.65	0.65	–	2×10^{21} O atoms/cm^2
0.00508 cm (2 mil), MISSE-6 wake	α	0.12	0.12	–	1,950 ESH
	ε	0.65	0.65	–	1.2×10^{20} O atoms/cm^2

Table 22. Optical properties for silverized Teflon.

		Preflight or Control	Postflight	Δ	Environment
0.00508 cm (2 mil), MISSE-2 ram	α	0.07	0.07	–	6,000 ESH
	ε	0.64	0.59	–0.05	7.6×10^{21} O atoms/cm^2
0.0127 cm (5 mil), MISSE-2 ram	α	0.08	0.07	–0.01	6,000 ESH
	ε	0.78	0.77	–0.01	7.6×10^{21} O atoms/cm^2
0.0254 cm (10 mil), MISSE-2 ram	α	0.08	0.08	–	6,000 ESH
	ε	0.85	0.85	–	7.6×10^{21} O atoms/cm^2
0.00254 cm (1 mil), MISSE-2 wake	α	0.06	0.07	0.01	5,700 ESH
	ε	0.52	0.53	0.01	1×10^{20} O atoms/cm^2
0.00508 cm (2 mil), MISSE-2 wake	α	0.07	0.07	–	5,700 ESH
	ε	0.64	0.65	0.01	1×10^{20} O atoms/cm^2
0.0127 cm (5 mil), MISSE-2 wake	α	0.08	0.07	–0.01	5,700 ESH
	ε	0.78	0.79	0.01	1×10^{20} O atoms/cm^2
0.0127 cm (5 mil), MISSE-5 nadir	α	0.08	0.07	–0.01	525 ESH
	ε	0.78	0.78	–	1.8×10^{20} O atoms/cm^2
0.0254 cm (10 mil) with 966 adhesive MISSE-6 ram	α	0.07	0.09	0.02	2,600 ESH
	ε	0.85	0.85	–	2 x 10^{21} O atoms/cm^2
0.0254 cm (10 mil), MISSE-7B ram	α	0.09	0.10	0.01	2,400 ESH
	ε	0.85	0.85	–	4.2×10^{21} O atoms/cm^2
0.0254 cm (10 mil), MISSE-7B wake	α	0.09	0.09	–	2,000 ESH
	ε	0.85	0.85	–	2.9×10^{20} O atoms/cm^2
0.0254 cm (10 mil) with 966 adhesive, MISSE-7B ram	α	0.08	0.09	0.01	2,400 ESH
	ε	0.85	0.86	0.01	4.2×10^{21} O atoms/cm^2
0.0254 cm (10 mil) with 966 adhesive, MISSE-7B wake	α	0.08	0.09	0.01	2,000 ESH
	ε	0.85	0.86	0.01	2.9×10^{20} O atoms/cm^2

Table 23. Optical properties for silverized Teflon with SiO_x coating.

		Preflight or Control	Postflight	Δ	Environment
0.014 cm (5.5 mil), MISSE-1 ram	α	0.08	0.08	–	7,000 ESH
	ε	0.80	0.80	–	9×10^{21} O atoms/cm^2
0.014 cm (5.5 mil), MISSE-2 wake	α	0.08	0.08	–	5,700 ESH
	ε	0.80	0.80	–	1×10^{20} O atoms/cm^2

Indium tin oxide (ITO) coating on Kapton has been used on the ISS for both thermal control and static dissipation. Two different thickness of ITO were flown on MISSE-7, with the thicker ITO maintaining electrical properties of 1,500 to 1,600 Ω/□. The thinner, higher resistance ITO was still static dissipative but increased from 20,000 Ω/□ to 2 to 3×10^6 Ω/□. The change in properties for a 17-month exposure (table 24) indicates this material should be used for short duration only. Also, care should be taken in handling ITO-coated materials, as they are easily damaged.

Table 24. Optical properties for ITO on Kapton.

		Preflight or Control	Postflight	Δ	Environment
1500 Ω/□ MISSE-7B wake	α	0.40	0.40	–	2,000 ESH
	ε	0.79	0.79	–	2.9×10^{20} O atoms/cm^2
20,000 Ω/□ MISSE-7B wake	α	0.41	0.41	–	2,000 ESH
	ε	0.80	0.80	–	2.9×10^{20} O atoms/cm^2

8. OPTICAL MATERIALS

Magnesium fluoride windows were flown as optical witness samples for measuring contamination and also to protect certain samples, such as solar sail materials and the candidate sunshade material for the James Webb Space Telescope. This allowed UV radiation to reach the thin polymer films without their being exposed to AO. The longer exposure of the windows on MISSE-2 indicated an AO effect on their transmission capabilities, rather than contamination of the window material. Figure 13 compares two flight magnesium fluoride windows from MISSE with two from POSA-I with corresponding control samples. ESCA showed that the MISSE windows had ≈50 Å of SiO_x, as opposed to about 500 Å of SiO_x on the POSA windows.

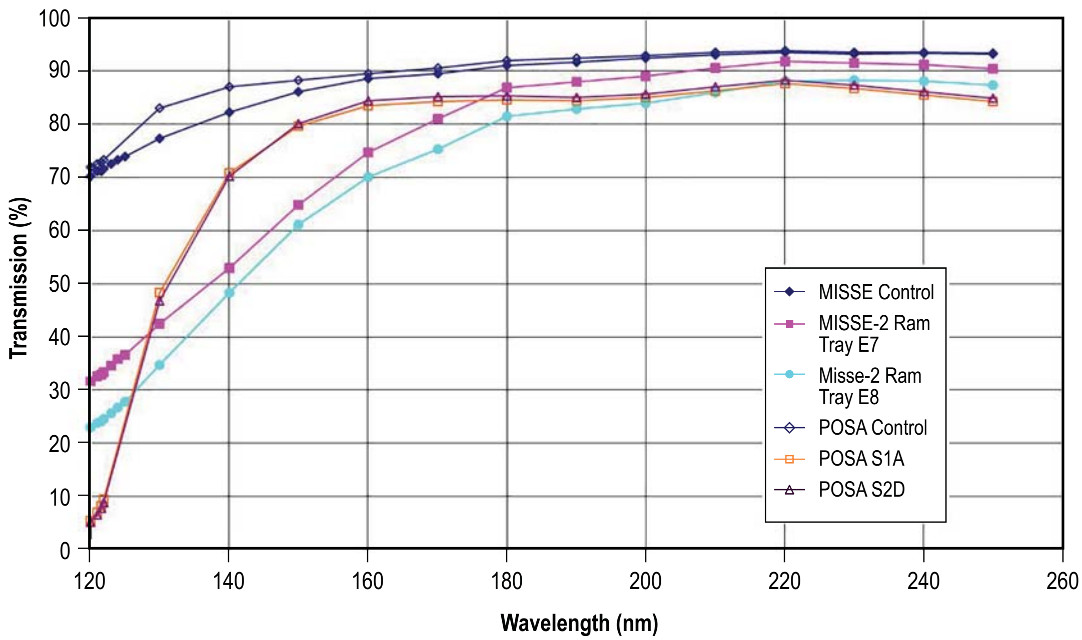

Figure 13. Comparison of MISSE versus POSA for vacuum UV transmission of magnesium fluoride.

Samples of Russian quartz similar to the Earth observation windows on the Zvezda Service Module were flown on both sides of MISSE-6B. Figure 14 shows a slight decrease in transmission in the UV wavelengths. These samples had no visible change in appearance.

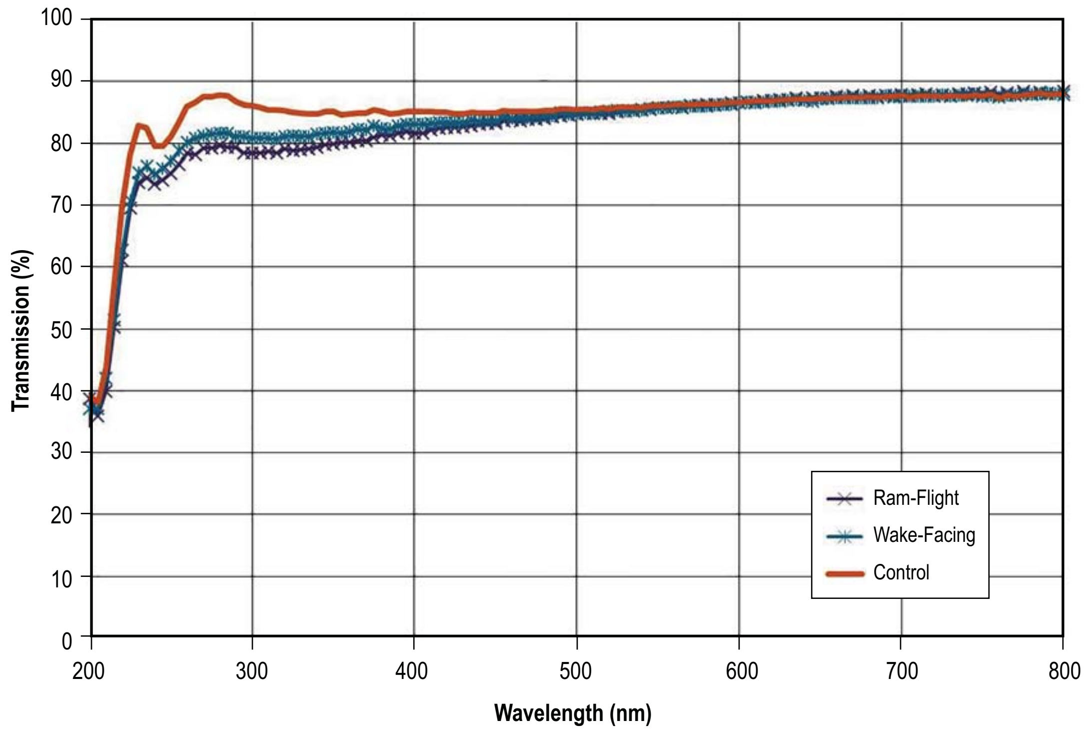

Figure 14. Transmission of Russian quartz samples flown on MISSE-6B.

Another set of samples flown on MISSE-6B was Hyzod® polycarbonate, used as scratch panes or debris panes protecting ISS windows. The polycarbonate has a protective coating, otherwise it would be heavily eroded by AO. Some UV darkening was observed (fig. 15), and the transmission measurements are presented in figure 16.

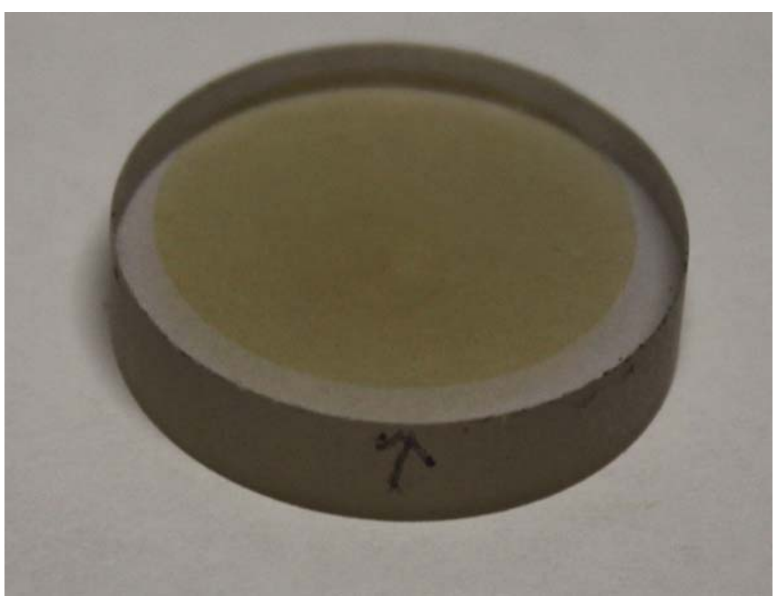

Figure 15. Hyzod polycarbonate flown on MISSE-6B wake side.

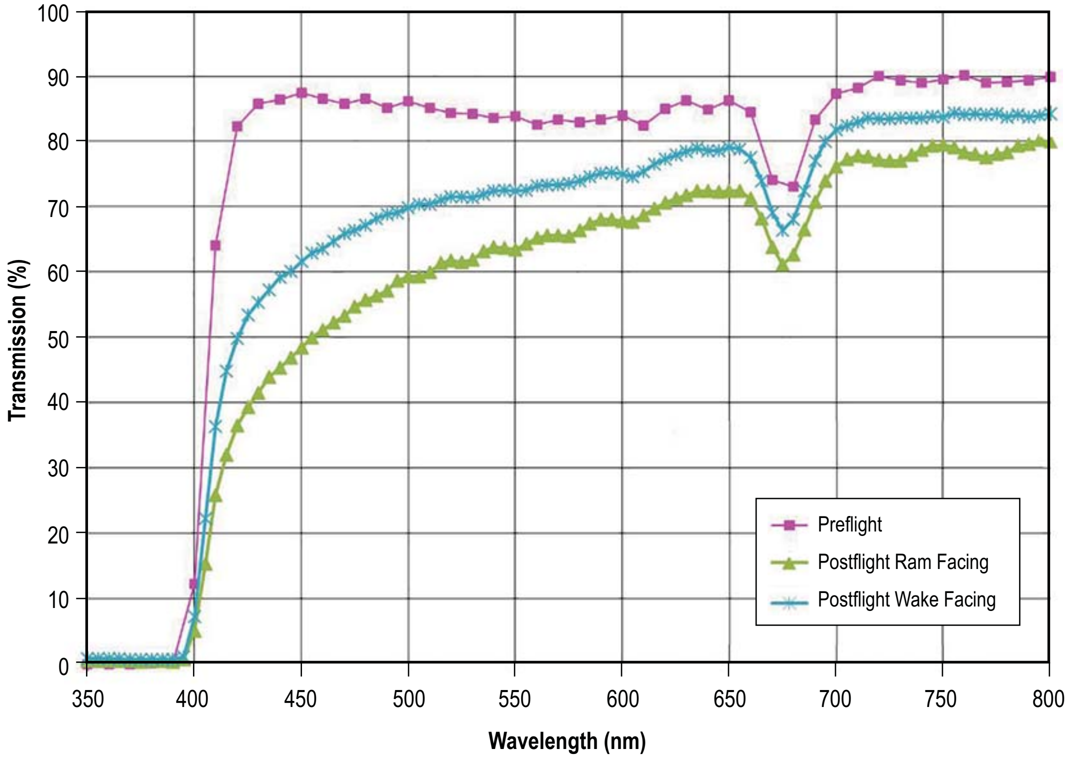

Figure 16. Visible wavelength transmission for Hyzod polycarbonate.

9. PART MARKING

9.1 Metalphoto®/Photofoil Labels

Metalphoto or Photofoil anodized aluminum foil labels have been produced for the ISS by the Johnson Space Center Decal Design and Production Facility. The early labels used oxalic acid anodize with a NiAc seal similar to the SAA process described in section 4.3; the seals darkened in a similar way when exposed to UV radiation. Figure 17 shows the striking visual difference between the NiAc-sealed labels and the nickel-free labels on the S1 segment.

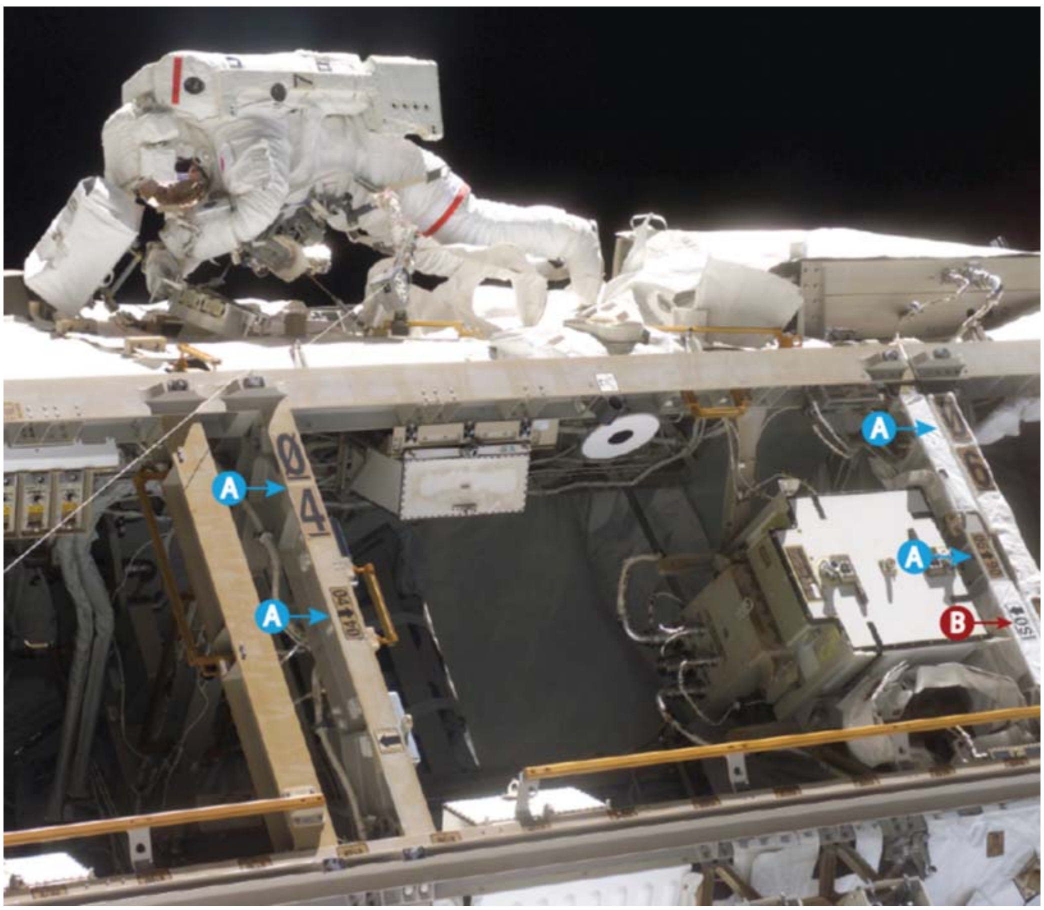

Figure 17. ISS S1 truss with (A) NiAc-sealed labels, which darkened, and (B) nickel-free labels, which were stable.

Metalphoto/Photofoil samples were flown on the MISSE-1 ram, the MISSE-2 wake, the MISSE-3 wake, the MISSE-4 ram, and the MISSE-7B ram and wake. Those samples containing nickel darkened considerably (fig. 18), with an average increase of 0.20 in α.

Figure 18. Metalphoto/Photofoil from MISSE-1 wake-facing side. White circles are where washers protected the surface from UV radiation.

9.2 Ink Stamp Labels

Ink stamp labels with an overcoat of clear Nusil CV-1144 silicone proved to be very durable on MISSE-1 ram and MISSE-3 ram (fig.19).

Figure 19. Ink stamp with clear overcoat from MISSE-1 ram-facing side.

10. DISCUSSION AND CONCLUSIONS

The information presented here was gathered to support life extension and sustaining engineering for the ISS. The specific conditions on another spacecraft must be considered when choosing materials; i.e., what works for low Earth orbit conditions may not work in a geosynchronous, Lagrangian, or a lunar environment. Materials that have been shown to darken in UV may not be suitable for long-duration missions. Some margin should be included in a design for unexpected degradation or contamination events. The MISSE experiments had low or localized contamination that did not significantly affect the results of space environmental effects. Sensible contamination control procedures should be enforced to minimize the impact of contamination on spacecraft thermal performance.

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14. ABSTRACT
Since August 2001, the Materials on International Space Station Experiment (MISSE) has provided data on a variety of materials and spacecraft components, including samples chosen to provide sustaining engineering and life extension data for the International Space Station vehicle itself. This Technical Publication is by no means a complete set of MISSE data but does provide changes in solar absorptance, infrared emittance, and visual appearance due to atomic oxygen, ultraviolet radiation, and thermal cycling in vacuum. Conversion coatings, anodizes, thermal control coatings with organic and inorganic binders, multilayer insulation components, optical materials, and part markings are discussed.

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