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Erosion Results of the MISSE 8 Polymers Experiment After 2 Years of Space Exposure on the International Space Station

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Abstract

Polymers and other oxidizable materials on the exterior of spacecraft in the low Earth orbit (LEO) space environment can be eroded due to reaction with atomic oxygen (AO). Therefore, in order to design durable spacecraft, it is important to know the LEO AO erosion yield (E_y , volume loss per incident oxygen atom) of materials susceptible to AO reaction. A spaceflight experiment, called the Polymers Experiment, which contained 42 samples, was developed to determine the effect of solar exposure on the AO E_y of fluoropolymers flown in ram, wake, or zenith orientations. The Polymers Experiment was exposed to the LEO space environment on the exterior of the International Space Station (ISS) as part of the Materials International Space Station Experiment 8 (MISSE 8) mission. The MISSE 8 mission included samples flown in a zenith/nadir orientation for 2.14 years in the MISSE 8 Passive Experiment Container (PEC), and samples flown in a ram/wake orientation for 2.0 years in the Optical Reflector Materials Experiment-III (ORMatE-III) tray. The experiment included Kapton H[®] witness samples for AO fluence determination in each orientation. This paper provides an overview of the MISSE 8 mission, a description of the flight experiment with details on the polymers flown, the characterization techniques used, the AO fluence for each exposure orientation, and the LEO E_y results. The E_y of Teflon fluorinated ethylene propylene (FEP) samples flown in ram, wake, and zenith orientations have been compared, and the E_y was found to be highly dependent on orientation and therefore environmental exposure. The FEP E_y was found to directly correlate with the solar exposure/AO fluence ratio showing the effect of solar radiation and/or heating due to solar exposure on FEP erosion. In addition, back-surface carbon painted FEP (C-FEP) flown in the zenith orientation had a significantly higher E_y than clear FEP or Al-FEP further indicating that heating has a significant impact on the erosion of FEP. This experiment provides valuable LEO flight data on the erosion of Teflon FEP, a commonly used spacecraft thermal insulation.

Acronym List

Al-FEP	aluminized-fluorinated ethylene propylene
Ag-FEP	silvered -fluorinated ethylene propylene
Al	aluminum
AO	atomic oxygen
ELC	EXPRESS Logistic Carrier
ESH	equivalent sun hours
EVA	extravehicular activity
E_y	erosion yield
FEP	fluorinated ethylene propylene
C-FEP	back-surface carbon painted fluorinated ethylene propylene
HB	Hathaway Brown School
HST	Hubble Space Telescope
ISS	International Space Station
LDEF	Long Duration Exposure Facility
LEO	low Earth orbit
MISSE	Materials International Space Station Experiment
MMOD	micrometeoroids and orbital debris
O ₂	diatomic oxygen
O ₃	ozone
PEACE	Polymer Erosion and Contamination Experiment
PEC	Passive Experiment Containers
PI	Polyimide
PTFE	polytetrafluoroethylene
PVF	polyvinyl fluoride
STS	space transportation system
UV	ultraviolet
VUV	vacuum ultraviolet
+XVV	X Axis Near Velocity Vector

Introduction

Polymers such as polyimide Kapton[®] and Teflon[®] fluorinated ethylene propylene (FEP) are commonly used spacecraft materials because of their flexibility and low density, as well as desirable electrical, thermal, and optical properties. Materials used on the exterior of spacecraft are subjected to many environmental threats that can cause degradation. In low Earth orbit (LEO), these threats include photon radiation, ultraviolet (UV) radiation, vacuum ultraviolet (VUV) radiation, x-rays, solar wind particle radiation (electrons, protons), cosmic rays, temperature extremes, thermal cycling, impacts from micrometeoroids and orbital debris (MMOD), spacecraft self-contamination, and atomic oxygen (AO). While all of these environmental exposures can cause degradation to spacecraft components, AO is a particularly serious structural, thermal, and optical threat, especially to exterior polymeric spacecraft components.

Atomic oxygen is formed in the LEO environment through photodissociation of diatomic oxygen (O₂). Short wavelength (<243 nm) solar radiation has sufficient energy to break the 5.12-eV O₂ diatomic bond in an environment where the mean free path is sufficiently long (~10⁸ m) that

the probability of re-association, or the formation of ozone (O_3), is small.^{1,2} In LEO, between the altitudes of 180 and 650 km, AO is the most abundant species.³

A number of processes can take place when an oxygen atom strikes a spacecraft surface as a result of its orbital velocity and the thermal velocity of the atoms. These include chemical reaction with surface molecules, elastic scattering, scattering with partial or full thermal accommodation, and recombination or excitation of ram species, which consists predominantly of ground state $O(^3P)$ atomic oxygen atoms.⁴ Atomic oxygen can react with polymers, carbon, and many metals to form oxygen bonds with atoms on the exposed surface. For most polymers, hydrogen abstraction, oxygen addition, or oxygen insertion can occur with the oxygen interaction pathways eventually leading to volatile oxidation products.^{5,6} This results in gradual erosion of hydrocarbon or halocarbon material, with the exception of silicone materials. An example of the complete loss of a Kapton[®] H thermal blanket insulation layer, as well as degradation of other polymeric materials caused by AO erosion in LEO, is provided in Figure 1.⁷ Even materials with AO protective coatings can be susceptible to AO erosion as a result of microscopic scratches, dust particles, or other imperfections in the substrate surface which can result in defects or pin windows in the protective coating.^{8,9} These coating defects can provide pathways for AO attack, and undercutting erosion of the substrate can occur, even under directed ram AO exposure in LEO. One of the first examples of directed ram AO undercutting erosion in LEO was reported by de Groh and Banks for aluminized-Kapton insulation blankets from the Long Duration Exposure Facility (LDEF).⁸

The sensitivity of a hydrocarbon or halocarbon material to reaction with AO is quantified by the AO erosion yield, E_y , of the material. The AO E_y is the volume of a material that is removed (through oxidation) per incident oxygen atom and is measured in units of $cm^3/atom$. As AO erosion of polymers in LEO is a serious threat to spacecraft performance and durability, it is essential to know the AO E_y of polymers for spacecraft applications so that the durability of materials being considered for spacecraft design can be predicted. The most characterized AO E_y is that of polyimide Kapton[®] H, which has an erosion yield of $3.0 \times 10^{-24} cm^3/atom$ for LEO 4.5-eV AO.¹⁰⁻¹³

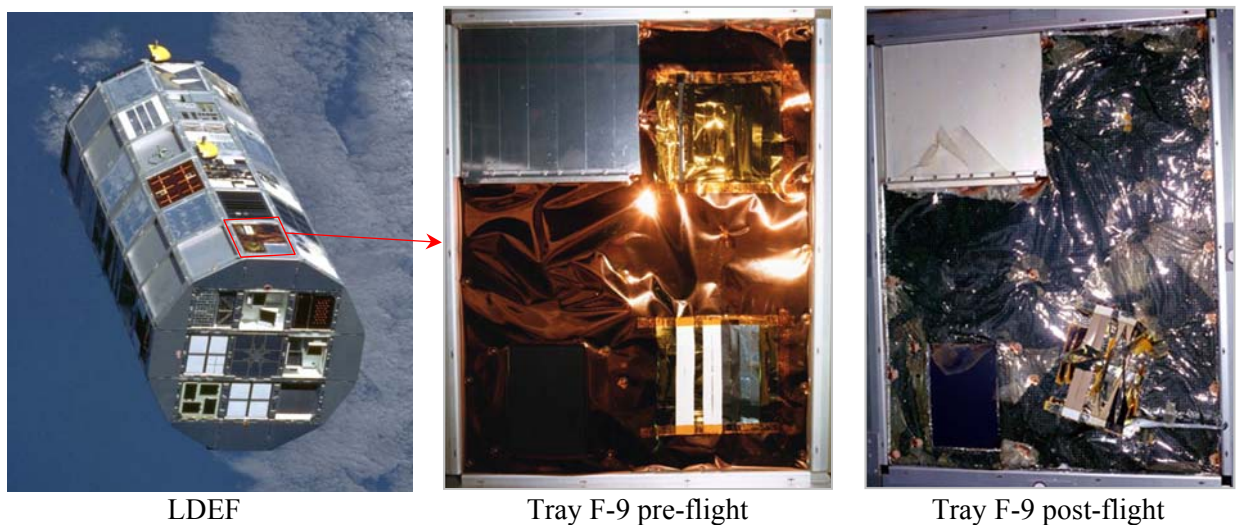


Figure 1. Atomic oxygen erosion of a Kapton[®] insulation blanket from Long Duration Exposure Facility (LDEF) experiment Tray F-9, located on the leading edge and exposed to direct-ram AO for 5.8 years.⁷

Another LEO threat to spacecraft materials is solar UV radiation, which has a typical wavelength of 0.1 to 0.4 micrometers.¹⁴ Ultraviolet radiation is energetic enough to cause the breaking of organic bonds such as C=C, C=O, and C-H as well as other functional groups.⁵ A molecule is raised to an excited state when an organic molecule absorbs a photon of UV radiation and bond dissociation can occur if the molecule acquires enough energy at the excited state. Depending on the temperature and physical properties of the materials, the dissociated radical species are reactive intermediates, with the capability of diffusing several atomic distances from their point of origin and can participate in further reactions.⁵ Solar radiation often results in bond breakage in materials as well as threats to functionality and stability of the materials. Therefore, solar radiation can possibly impact the erosion of some materials.

Because spaceflight materials exposure opportunities are rare, expensive, space-limited, and time-consuming, ground laboratory testing is often relied upon for spacecraft material environmental durability prediction. However, differences exist between ground facilities and actual space exposures, which may result in material-dependent differences in rates of reactions. Therefore, actual spaceflight AO E_y data are needed to best assess the durability of a material for spacecraft mission applicability. In addition, data from actual materials spaceflight experiments can be used to determine correlations between exposures in ground test facilities and space exposure, allowing for more accurate predictions of in-space materials performance based on ground facility testing. Materials spaceflight experiments for E_y determination have been flown on the Shuttle, the LDEF, the Russian space station Mir, and other spacecraft.¹⁵ More recently, experiments have been flown as a part of the Materials International Space Station Experiment 1-8 (MISSE 1-8) missions flown on the exterior of the International Space Station (ISS).¹⁵

To further increase our understanding of the AO erosion of spacecraft materials, NASA Glenn Research Center developed and flew a passive experiment called the MISSE 8 Polymers Experiment. This is one of a series of NASA Glenn polymer experiments flown as part of the MISSE missions.^{9,16-20} This paper provides an overview of the MISSE 8 mission, a description of the MISSE 8 Polymers Experiment with details on the polymers flown, pre-flight and post-flight characterization techniques, the AO fluence for each exposure orientation, and a summary of the AO E_y results. In addition, the MISSE 8 E_y of various Teflon fluorinated ethylene propylene (FEP) samples flown in different orientations have been compared to help determine solar exposure and associated heating effects on LEO E_y values.

Materials International Space Station Experiment (MISSE) Overview

The MISSE project is a series of spaceflight experiments flown on the exterior of the ISS to test the performance and durability of materials and devices exposed to the LEO space environment. In the original MISSE missions, individual flight experiments were flown in suitcase-like containers called Passive Experiment Containers (PECs) that provide exposure to the space environment. The PECs were closed during launch to protect the samples. Once on orbit, the PECs were placed on the exterior of the ISS during an extravehicular activity (EVA), or spacewalk, in either a ram/wake or a zenith/nadir orientation and opened exposing the experiments to the space environment for the duration of the mission. A diagram showing ram, wake, zenith, and nadir directions on the ISS is shown in Figure 2. The flight orientation highly affects the

environmental exposure. Ram facing experiments receive a high flux of directed AO and sweeping (moderate) solar exposure. Zenith facing experiments receive a low flux of grazing arrival AO and the highest solar exposure. Wake experiments receive very low AO flux and moderate solar radiation levels similar to ram experiments. Nadir experiments receive a low flux of grazing arrival AO and minimal solar radiation (albedo sunlight). All surfaces receive charged particle and cosmic radiation, which are omni-directional. It should be noted that the actual orientation of the ISS varies due to operational requirements with the majority of the time spent within ± 15 degrees of the +XVV Z nadir flight attitude (X Axis Near Velocity Vector, Z Axis Nadir/Down). Deviations from this attitude to accommodate visiting spacecraft, and other ISS operational needs, can cause variations in the orientation directions, and hence variations in environmental exposures especially for atomic oxygen exposure of zenith and nadir surfaces.

The MISSE 8 mission consisted of a PEC and a smaller passive tray called the Optical Reflector Materials Experiment III (ORMatE-III). The PEC was attached to the exterior of the ISS on the EXPRESS Logistics Carrier 2 (ELC 2) in a zenith/nadir orientation during an extravehicular activity as part of the STS-134 Shuttle mission on May 20, 2011. Because of concerns of outgas contamination from the neighboring Alpha Magnetic Spectrometer (AMS) payload, ORMatE-III was deployed in a ram/wake orientation during the STS-135 Shuttle mission on July 12, 2011, approximately two months after deploy of the MISSE 8 PEC. Once positioned on ELC 2, the PEC and ORMatE-III remained exposed to the LEO space until they were retrieved on July 9, 2013 after 2.14, and 2.00 years of space exposure, respectively, and returned to Earth in the SpaceX-3 Dragon. Figure 3 shows the location of the MISSE 8 PEC and ORMatE-III on the ISS ELC-2. Figure 4 shows on-orbit images of the PEC (Figure 4a) and ORMatE-III (Figure 4b) as imaged during the STS-135 ORMatE-III deploy mission in July 2011.

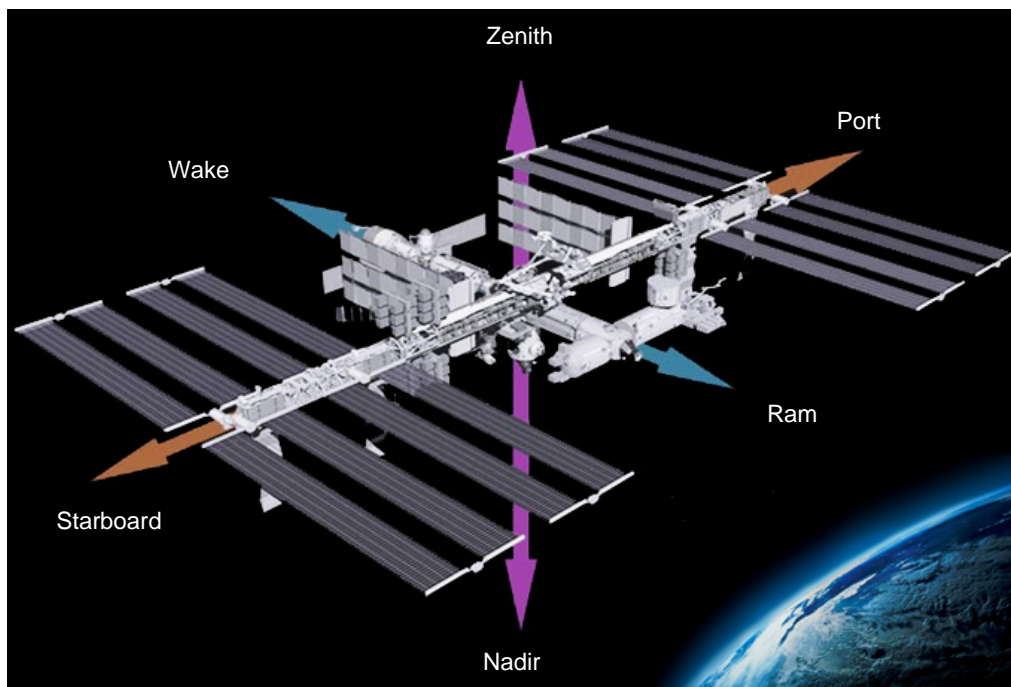


Figure 2. Diagram showing ram (flight direction), wake, zenith, and nadir directions on the International Space Station.

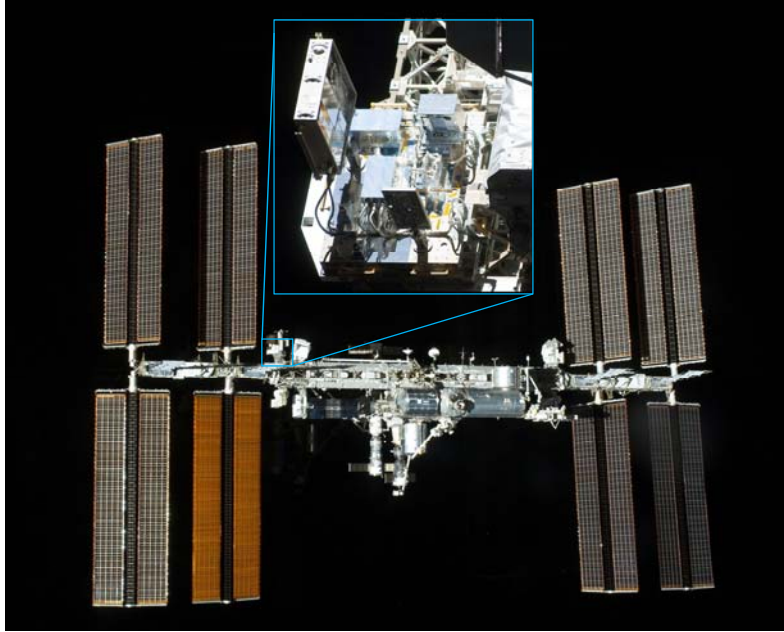
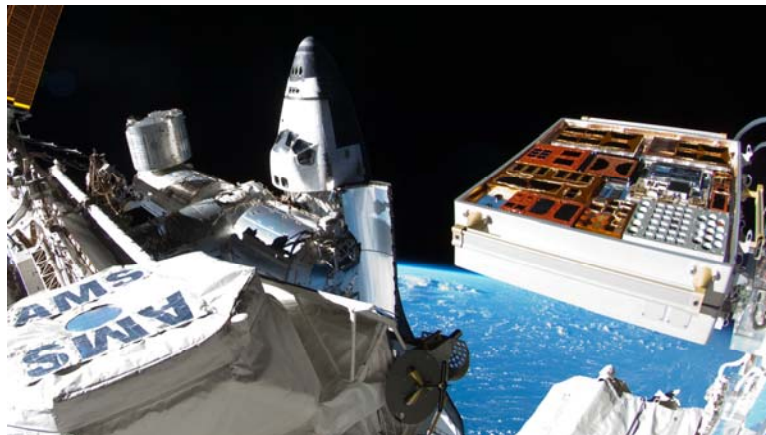
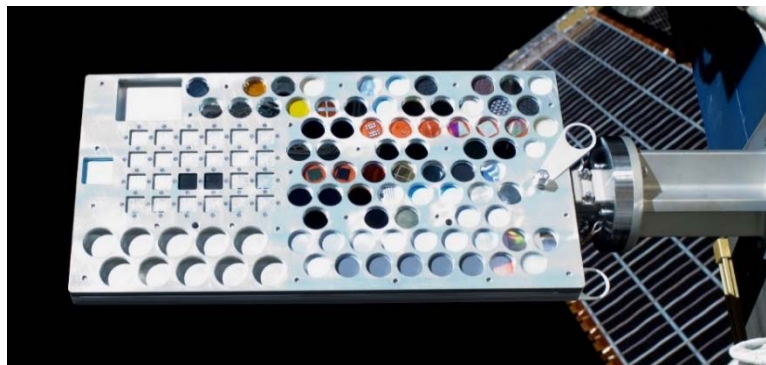


Figure 3. Location of MISSE 8 PEC and ORMatE-III on the ISS ELC-2 as imaged during the STS-135 shuttle mission in July 2011 shortly after deployment of ORMatE-III.



a.



b.

Figure 4. On-orbit images of MISSE 8 PEC and ORMatE-III as imaged during the STS-135 mission in July 2011: a). The zenith surface of the PEC is visible on the right side of the image (the AMS is visible on the left), and b). The wake surface of ORMatE-III.

MISSE 8 Polymers Experiment

The MISSE 8 Polymers Experiment is a passive experiment that includes 42 samples, which were flown in ram (8 samples), wake (11 samples) or zenith (23 samples) orientations. The primary objective of the Polymers Experiment is to determine the effect of solar exposure on the AO E_y of fluoropolymers. Pyrolytic graphite and DC 93-500 silicone samples were also included for E_y determination. The MISSE 8 Polymers Experiment also included a variety of other samples (tensile samples, composites, spacesuit fabrics, pinhole camera, docking seal sample, etc.) for environmental durability assessment that will be reported elsewhere.

Six 1-inch (2.54 cm) circular MISSE 8 Polymers Experiment samples were flown for E_y determination in the ram orientation in the ORMatE-III tray, exposing them to high AO and moderate solar radiation exposures. An on-orbit photo of the ram side of ORMatE-II is shown in Figure 5. A 1-inch (2.54 cm) circular Kapton H sample was also flown in the ram orientation for AO fluence determination. Three 1-inch (2.54 cm) circular samples were flown for E_y determination in the wake orientation in the ORMatE-III tray, exposing them to minimal AO and moderate solar radiation. An on-orbit photograph of the wake side of ORMatE-II is shown in Figure 6. A 1-inch (2.54 cm) circular Kapton H sample was also flown in the wake orientation for AO fluence determination. Three 1-inch (2.54 cm) circular and five 1-inch (2.54 cm) square samples were flown for E_y determination in the zenith orientation in the MISSE 8 PEC exposing them to grazing AO and high solar exposure. A pre-flight photograph of the zenith side of MISSE 8 is shown in Figure 7. Four circular samples were flown in an ORMatE-III like beveled tray, including a Kapton H sample for AO fluence determination. The square samples were flown in handmade thin Al foil holders which were taped in place using thermal control insulation tape. A close-up photograph of the zenith taped samples is shown in Figure 7. Flight sample holders are designated as either beveled “tray” or thin Al foil “taped” holders.

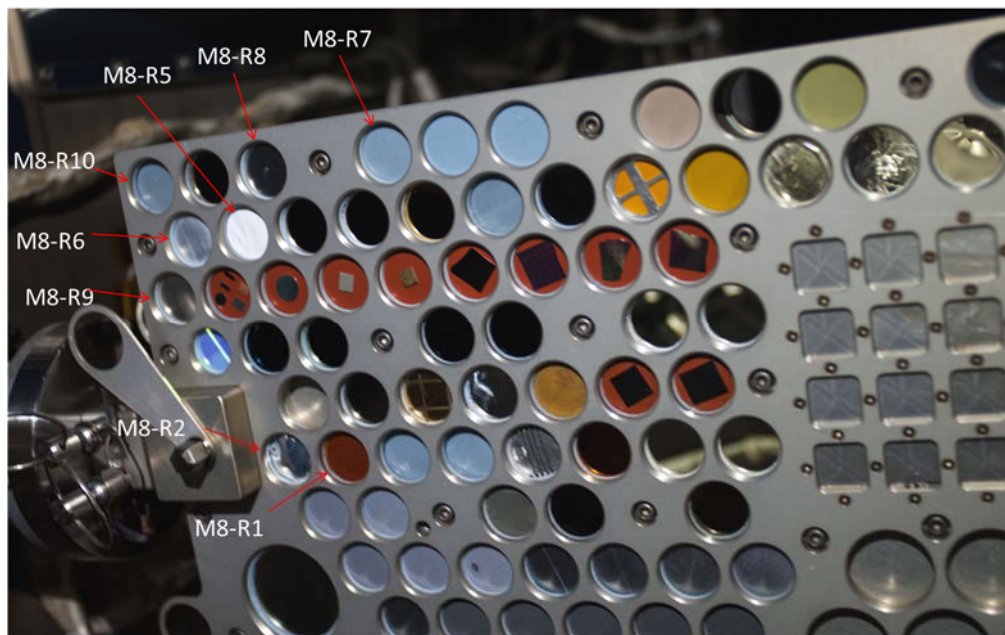


Figure 5. On-orbit image of the ram surface of ORMatE-III taken during Increment 39 on July 9, 2013 with the Polymers Experiment samples identified.

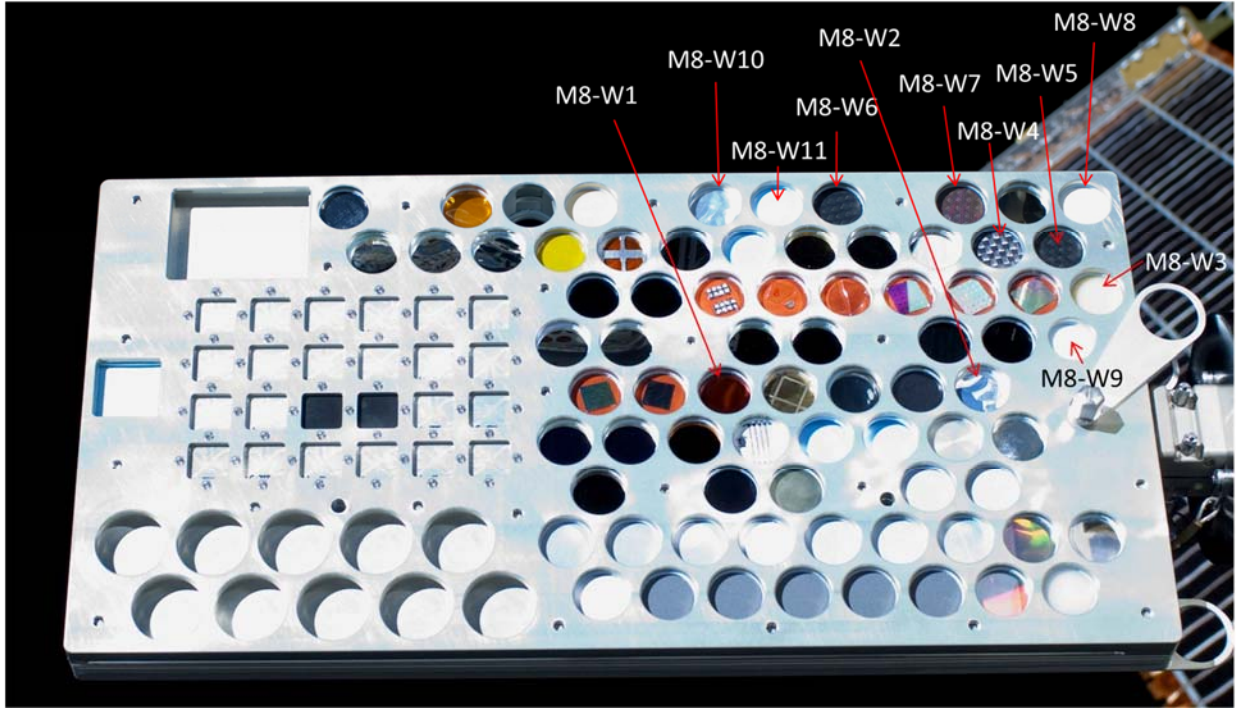


Figure 6. On-orbit image of the wake surface of ORMatE-III taken during the STS-135 Shuttle mission on July 12, 2011 with the Polymers Experiment samples identified.

Tables 1-4 provide lists of the MISSE 8 Polymers Experiment samples flown for mass-loss based E_y , along with the sample ID, film thickness and number of layers flown (to allow mass measurements to be made in the event that erosion of more than one layer would occur). The ram E_y samples are listed in Table 1, the wake E_y samples are listed in Table 2, the zenith tray E_y samples are listed in Table 3 and the zenith taped E_y samples are listed in Table 4. The zenith tray control samples were loaded into a zenith “traveler” tray. The remaining control samples were not mounted, or stored in traveler trays during the mission.

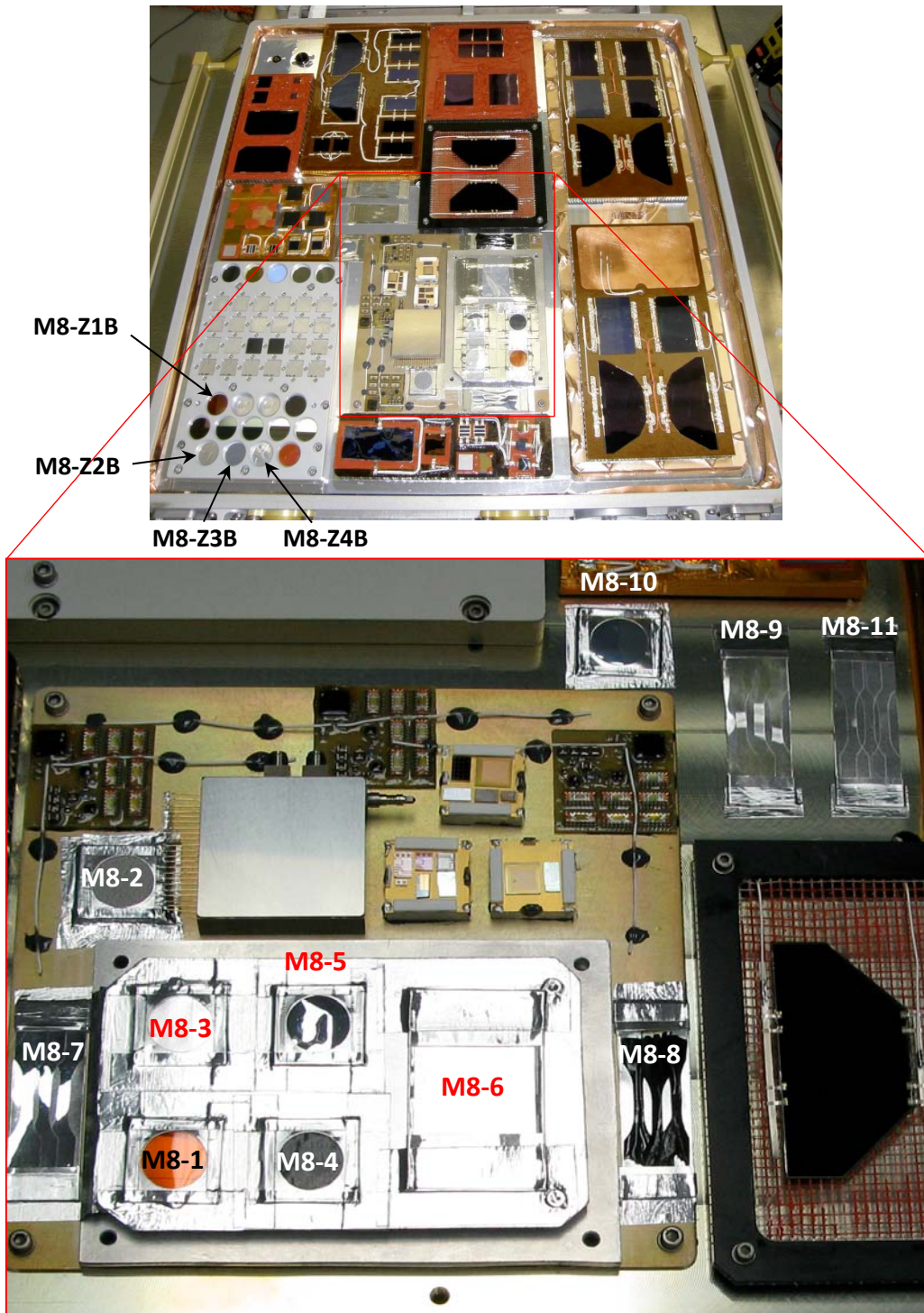


Figure 7. Pre-flight image of the zenith side of the MISSE 8 PEC with a close-up of the taped samples section and with the Polymers Experiment samples identified. (Photo credit: Naval Research Laboratory)

Table 1. MISSE 8 Polymers Experiment Ram E_y Samples.

MISSE Sample ID	Material	Trade Name (Abbreviation)	Thickness (mils)	Number of Layers
M8-R1	Polyimide (PMDA)	Kapton H (PI)	5	4
M8-R2	Aluminized-fluorinated ethylene propylene*	Aluminized-Teflon (Al-FEP)	5	1
M8-R5	Crystalline polyvinyl fluoride w/ TiO ₂ white pigment	White Tedlar (white PVF)	1	7
M8-R6	Hubble Space Telescope (9.7 yrs) aluminized-fluorinated ethylene propylene*	(HST Al-FEP)	5	1
M8-R7	Polytetrafluoroethylene	Teflon (PTFE)	2	1
M8-R9	Fluorinated ethylene propylene	Teflon (FEP)	2	1
M8-R10	DC-93-500 silicone on fused silica	DC-93-500/SiO ₂	10/64	1

* FEP layer was space facing

Table 2. MISSE 8 Polymers Experiment Wake E_y Samples.

MISSE Sample ID	Material	Trade Name (Abbreviation)	Thickness (mils)	Number of Layers
M8-W1	Polyimide (PMDA)	Kapton H (PI)	5	2
M8-W2	Aluminized-fluorinated ethylene propylene*	Aluminized-Teflon (Al-FEP)	5	1
M8-W10	Hubble Space Telescope (9.7 yrs) aluminized-fluorinated ethylene propylene*	(HST Al-FEP)	5	1
M8-W11	Fluorinated ethylene propylene	Teflon (FEP)	2	1

* FEP layer was space facing

Table 3. MISSE 8 Polymers Experiment Zenith Tray E_y Samples.

MISSE Sample ID	Material	Trade Name (Abbreviation)	Thickness (mils)	Number of Layers
M8-Z1B	Polyimide (PMDA)	Kapton H (PI)	5	3
M8-Z2B	Fluorinated ethylene propylene	Teflon (FEP)	2	1
M8-Z3B	Aluminized-fluorinated ethylene propylene*	Aluminized-Teflon (Al-FEP)	5	1
M8-Z4B	Hubble Space Telescope (9.7 yrs) aluminized-fluorinated ethylene propylene*	(HST Al-FEP)	5	1

* FEP layer was space facing

Table 4. MISSE 8 Polymers Experiment Zenith Taped E_y Samples.

MISSE Sample ID	Material	Trade Name (Abbreviation)	Thickness (mils)	Number of Layers
M8-1	Polyimide (PMDA)	Kapton H (PI)	5	1
M8-2	Pyrolytic graphite	(PG)	80	1
M8-3	Fluorinated ethylene propylene	Teflon (FEP)	2	1
M8-4	Back-surface carbon painted fluorinated ethylene propylene*	(C-FEP)	2	1
M8-5	Aluminized-fluorinated ethylene propylene*	Aluminized-Teflon (Al-FEP)	2	1
M8-10	Silvered-fluorinated ethylene propylene*	Silvered-Teflon (Ag-FEP)	2	1

* FEP layer was space facing

The zenith back-surface carbon painted FEP (C-FEP) taped sample (M8-4) was prepared by AO treating the non-exposed side of a clear FEP film to increase adherence prior to coating the surface with a layer of carbon paint. This sample was flown along with clear FEP, Al-FEP and Ag-FEP to see the effect of passive heating on the erosion of FEP. The Hubble Space Telescope (HST) Al-FEP samples (M8-R6, M8-W10 and M8-Z4B) were sectioned from multilayer insulation blankets retrieved from HST Bay 10 during the third servicing mission (SM3A) after 9.7 years of space exposure.²¹ These samples were flown for E_y characterization to determine if prior space exposure, in particular radiation induced FEP scission,²² might result in an increase in the AO E_y of Teflon FEP, a commonly used spacecraft thermal insulation material.

Erosion Yield and Atomic Oxygen Fluence Determination

A common technique for determining the E_y of materials is based on mass loss of flight samples and is calculated using dehydrated mass measurements before and after flight. The erosion yield of the sample is determined through the following equation:

$$E_y = \frac{\Delta M_s}{(A_s \rho_s F)} \quad (1)$$

Where

- E_y = erosion yield of flight sample ($cm^3/atom$)
- ΔM_s = mass loss of the flight sample (g)
- A_s = surface area of the flight sample exposed to AO (cm^2)
- ρ_s = density of flight sample (g/cm^3)
- F = fluence of AO ($atoms/cm^2$)

The AO fluence (F) can be determined through the mass loss of a Kapton H witness sample because Kapton H has a well characterized erosion yield, E_K ($3.0 \times 10^{-24} cm^3/atom$) in the LEO environment.¹⁰⁻¹³ Therefore, the AO fluence can be calculated using the following equation:

$$F = \frac{\Delta M_K}{(A_K \rho_K E_K)} \quad (2)$$

Where

- $F =$ low Earth orbit AO fluence (atoms/cm²)
 $\Delta M_K =$ mass loss of Kapton H witness sample (g)
 $A_K =$ surface area of Kapton H witness sample exposed to AO (cm²)
 $\rho_K =$ density of Kapton H witness sample (1.4273 g/cm³)
 $E_K =$ erosion yield of Kapton H witness sample (3.0×10^{-24} cm³/atom)

Thus

$$E_y = E_K \frac{\Delta M_S A_K \rho_K}{\Delta M_K A_S \rho_S} \quad (3)$$

Experimental Procedures

Mass Loss Determination

One of the critical issues with using mass loss for obtaining accurate E_y data is that dehydrated mass measurements are needed. Many polymer materials, such as Kapton, are very hygroscopic (absorbing up to 2% of their weight in moisture) and can fluctuate in mass with humidity and temperature. Therefore, for accurate mass loss measurements to be obtained, it is necessary that the samples be fully dehydrated (i.e. in a vacuum desiccator) immediately prior to measuring the mass both pre-flight and post-flight.

Samples were dehydrated in a vacuum desiccator maintained at a pressure of 8.0 - 13.3 Pa (60-100 mtorr) with a mechanical roughing pump. Typically, five flight samples and their corresponding control samples were placed in a vacuum desiccator, in a particular order, and left under vacuum for a minimum of 72 hours. Once a sample was removed for weighing, the vacuum desiccator was immediately put back under vacuum to keep the other samples under vacuum. Previous tests showed that the mass of a dehydrated sample was not adversely affected if the desiccator was opened and quickly closed again and pumped back down to approximately 20 Pa (150 mtorr) prior to that sample being weighed. This process allows multiple samples to be dehydrated together. The time at which the sample was first exposed to air was recorded along with the times at which it was weighed. A total of 3 mass readings were obtained and averaged. The total time it took to obtain the three readings, starting from the time air was let into the desiccator, was typically five minutes. The samples were weighed pre-flight using a Sartorius ME 5 Microbalance (0.000001 g sensitivity). The PG sample was measured using a Sartorius Balance R160P (0.00001 g sensitivity). Records of the following were kept: the sequence of sample weighing, the number of samples in each set, the time under vacuum prior to weighing, the temperature and humidity in the room, the time air was let into the desiccator and the time a sample was taken out of the desiccator, the time of each weighing and the mass. The same procedure and sequence was repeated with the same samples post-flight.

Density Determination

The densities of the samples were based on density gradient column measurements of polymers for the MISSE 2 Polymer Erosion and Contamination Experiment (PEACE) Polymers experiment.^{2,18,22} The density gradient columns were created in 50-mL burets with solvents of cesium chloride (CsCl, $\rho \approx 2 \text{ g/cm}^3$) and water (H₂O, $\rho = 1.0 \text{ g/cm}^3$), for less dense polymers, such as Kapton H, or carbon tetrachloride (CCl₄, $\rho = 1.594 \text{ g/cm}^3$) and bromoform (CHBr₃, $\rho = 2.899 \text{ g/cm}^3$), for more dense polymers, such as the fluoropolymers. A quadratic calibration curve was developed for each column based on the equilibrium vertical position of three to four standards of known density ($\pm 0.0001 \text{ g/cm}^3$). Subsequently, density values of samples were calculated based on the vertical positions of small (< 2 mm) pieces placed into the column and allowed to settle for 2 hours. Where possible, the same batch of material was used for MISSE 8 as was used for the Glenn MISSE 2-7 Polymers Experiments. The manufacturers' density was used for the DC 93-500 silicone.

Surface Area Determination

The exposed surface area of the ram, wake and zenith tray samples was determined by averaging four different diameter measurements of each sample tray opening obtained with a Bore Gauge ($\pm 0.001 \text{ mm}$). The exposed surface area of the taped samples was determined using AutoCAD computer design software to trace the exposed border of the sample on a sample photograph. The sample photograph was taken, along with a scale bar, with a Sony DSC-T7 digital camera on a Polaroid Land camera stand. The surface area was computed using AutoCAD based on the traced area, and measurements of the scale bar. Examples of photo-traces (pink line) of zenith taped samples Kapton H (M8-1) and C-FEP (M8-4) are shown in Figures 8a and 8b, respectively.

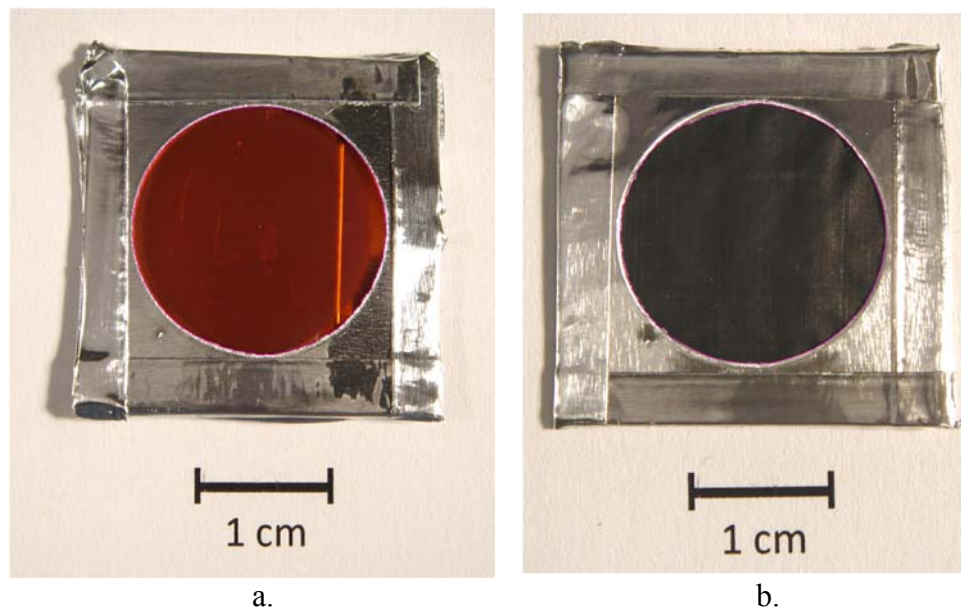


Figure 8. Example of AutoCAD photo-trace of zenith taped samples: a). Kapton H (M8-1), and b). C-FEP (M8-4).

Sample Stacking

For weighing, the four samples with more than 1 layer (M8-R1, M8-R5, M8-W1 and M8-Z1B) were divided into 2 different parts. Part A consisted of the single top space exposed layer and Part B was made up of the additional layers. Part A and Part B were weighed separately pre-flight. This way, only Part A needed to be weighed post-flight for samples with less than one layer of erosion, making the mass loss measurements more accurate.

Imaging and Optical Microscopy

Pre-flight and post-flight photographs of the samples were taken with a Sony DSC T-7 digital camera. Optical microscope (OM) images were taken using a Nikon SMZ1270 Zoom Stereomicroscope.

Results and Discussion

Atomic Oxygen Fluence and Solar Exposure

Post-flight photographs of the MISSE 8 Kapton H AO fluence witness flight and corresponding control samples are provided in Figures 9a-d. The flight orientation, sample ID, holder style, mass loss, surface area, density and computed fluence values for the four AO fluence samples are provided in Table 5. As can be seen in Figure 9a, AO eroded completely through the top layer of the four layer ram sample, and erosion texture can be seen in the 2nd layer. The AO fluence for the ram sample was determined to be 4.62×10^{21} atoms/cm². As expected, the wake surface received a low fluence of 8.80×10^{19} atoms/cm², and as seen in Figure 9b very little AO erosion is visible in the top layer of the two layer wake sample.

Surprisingly, there was a significant difference (~5X) in the AO fluence for the Kapton H sample flown in the zenith sample tray ($F = 4.04 \times 10^{19}$ atoms/cm²) and the fluence of the Kapton H sample flown in the zenith taped holder ($F = 1.96 \times 10^{20}$ atoms/cm²). A close-up image of tray and taped samples, provided in Figure 10, shows that the samples in the trays (left side of photograph) are significantly recessed in their beveled holders, whereas the taped samples which are in thin Al foil (shown in the upper right) are not significantly recessed. Because the zenith surface receives grazing AO the thin taped Al holder samples receive significantly more AO fluence than the recessed tray samples. This can be seen visually, as the “beveled tray Kapton” does not appear eroded, as shown in Figure 9c, whereas the “taped Kapton” is visibly eroded, as shown in Figure 9d. Surfaces that are 90° from the ram direction and receive “grazing AO” arrival receive a small flux, approximately 4.1% of the ram AO arrival flux, due to the spacecraft’s orbital inclination, the Earth’s atmospheric co-rotation velocity, and thermal velocities of the AO associated with their Maxwell-Boltzman velocity distribution at the high temperatures of LEO.² These results indicate that the AO flux and mission fluence for surfaces that receive grazing AO (zenith and nadir surfaces) will be highly dependent on the sample holder geometry, as the AO flux arrival varies greatly with angle of arrival. Other factors may also impact the local AO fluence, such as AO scattering from neighboring surfaces.

The nadir AO fluence was determined to be 3.63×10^{19} atoms/cm² based on mass and thickness loss measurements of three Marshall Space Flight Center Kapton HN beveled tray samples.²³ This fluence is very close to that for the zenith beveled tray ($F= 4.04 \times 10^{19}$ atoms/cm²), as would be expected as both surfaces receive grazing AO exposure.

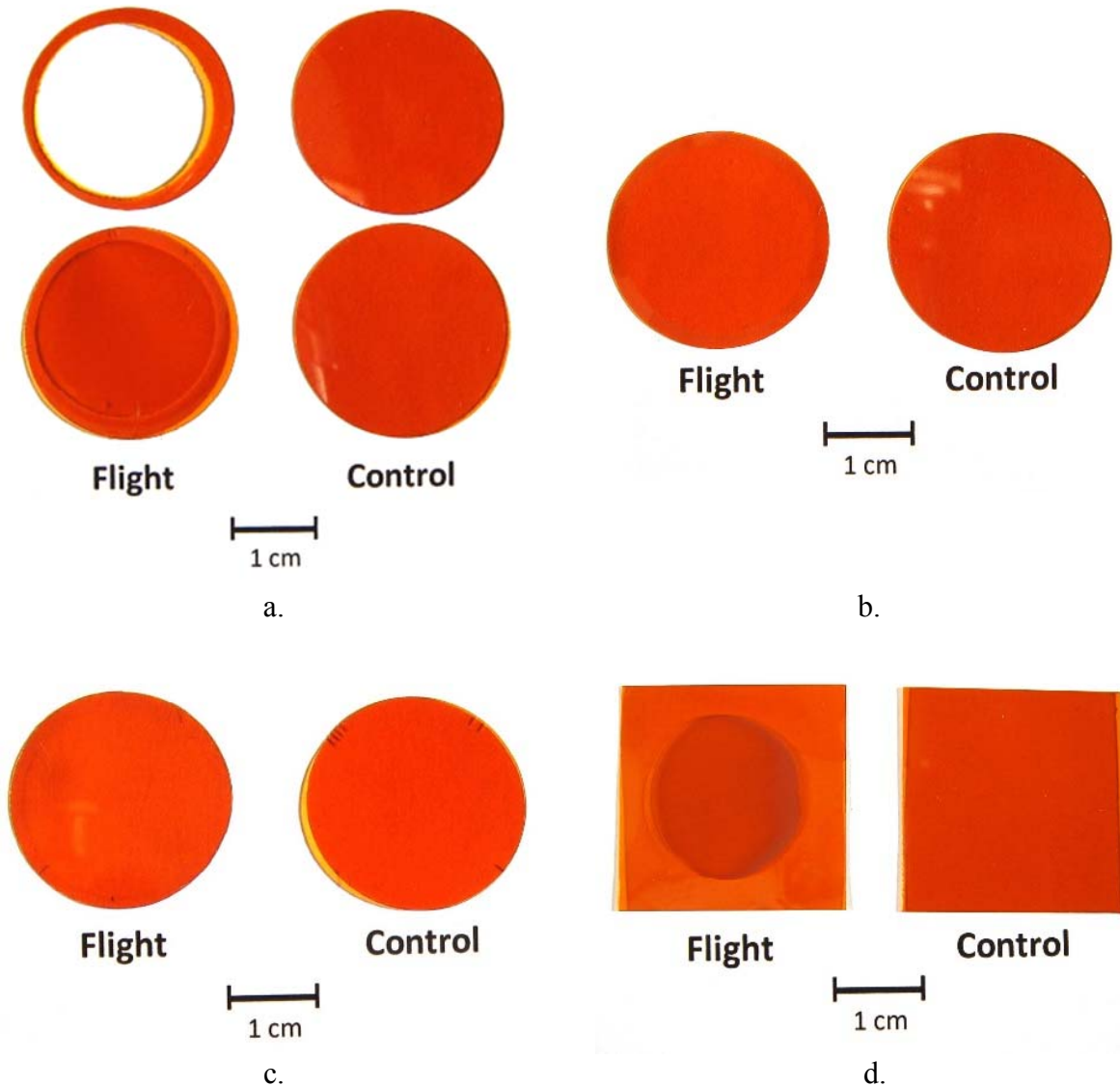


Figure 9. Post-flight photographs of the Kapton H fluence witness samples and control samples: a). Ram sample (M8-R1) with the top 2 of 4 layers imaged, b). Wake sample (M8-W1) with the top 1 of 2 layers imaged, c). Zenith beveled tray sample (M8-ZIB) with the top 1 of 3 layers imaged, and d). Zenith taped sample (M8-1).

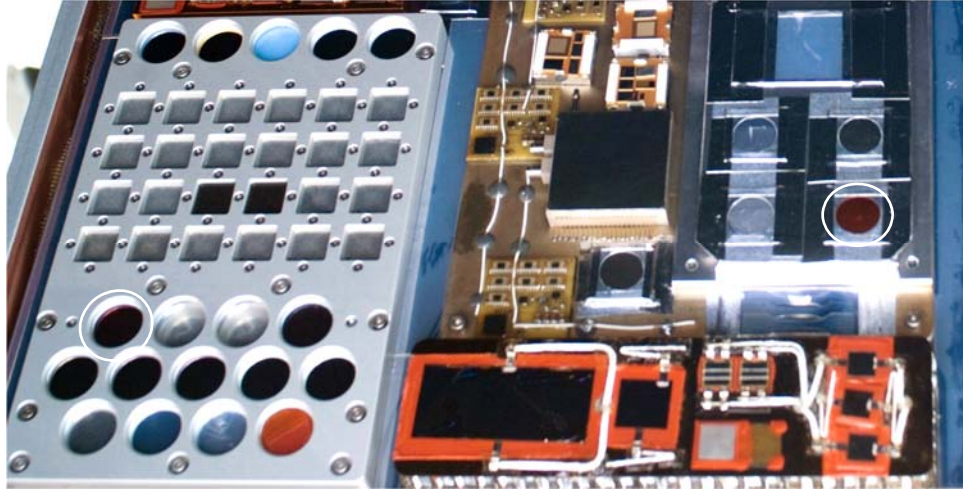


Figure 10. Close-up image of zenith beveled tray and taped samples on the MISSE 8 PEC showing a difference in extent of recession within each holder type. The Kapton H samples have been circled. (Photo credit: Naval Research Laboratory)

Table 5. MISSE 8 Kapton H Atomic Oxygen Fluence Determination.

MISSE 8 Orientation	Sample ID	Holder Style	Mass Loss (g)	Surface Area (cm ²)	Density (g/cm ³)	MISSE 8 Fluence (atom/cm ²)
Ram	M8-R1	Beveled Tray	0.079104	3.995	1.4273	4.62E+21
Wake	M8-W1	Beveled Tray	0.001523	4.041	1.4273	8.80E+19
Zenith	M8-Z1B	Beveled Tray	0.000670	3.877	1.4273	4.04E+19
Zenith	M8-1	Thin Al Foil (Taped)	0.002330	2.782	1.4273	1.96E+20

Table 6 provides the solar exposures in equivalent sun hours, or ESH, for MISSE 8. Computations of the zenith solar exposure have been conducted by the Naval Research Laboratory (NRL) and were determined to be $6,100 \pm 1,000$ ESH.²⁴ The MISSE 8 ram and wake solar exposures were approximated using the ratios of the MISSE 7 ram and wake to zenith ratios, respectively, because MISSE 8 was flown in the same location on ISS as MISSE 7 (ELC-2 Site 3). The MISSE 8 nadir solar exposure was estimated at Marshall Space Flight Center based on Teflon erosion.²³

Table 6. MISSE 8 Ram and Wake Solar Exposure Approximations.

Flight Orientation	MISSE 7 Exposure (Yrs)	MISSE 7 Solar Exposure (ESH)	MISSE 7 ESH Relative to Zenith	MISSE 8 (ESH)
Zenith	2.14	4,300 ²⁵	1	$6,100 \pm 1,000$ ²⁴
Ram	2.00	2,400 ²⁶	0.56	3,200*
Wake	2.00	2,000 ²⁶	0.47	2,700*
Nadir	2.14	<<2,000	-	800 ± 300 ²³

* Ram & wake also multiplied by the ram-wake to zenith duration ratio of 2.00/2.14 (0.93)

On-Orbit Contamination

Pre-flight model predictions indicated that there would be high levels of induced molecular contamination on MISSE 8 wake and nadir surfaces from neighboring Alpha Magnetic Spectrometer (AMS) facility materials outgassing.²⁷ Therefore, contamination studies were conducted on Teflon FEP samples flown in both wake and nadir orientations on MISSE 8. The analyzed wake sample was clear FEP (M8-W11) flown in the ORMatE-III tray. The FEP space-facing surfaces of two silver-Teflon (Ag-FEP) radiator samples from the nadir facing side of the MISSE 8 SEUXSE Power Box were also analyzed for contamination. Nadir surfaces typically do not receive direct solar exposure, and hence UV enhanced fixing of molecular contamination would not be expected to occur, which would contribute to contamination build-up. But, the wake surface does receive direct solar exposure (approximated at 2,700 ESH), and a low AO fluence (8.80×10^{19} atoms/cm²) with corresponding low erosion, therefore it would be expected that the arriving molecular contamination would be fixed, or adhered, in place in the wake direction.

The samples were analyzed for changes in surface morphology and chemistry, and for the wake samples, changes in optical properties, and compared to pristine control samples. There was no evidence of a molecular contamination layer present on the surface of the MISSE 8 wake or nadir facing Teflon FEP flight samples (within x-ray photoelectron spectroscopy (XPS) instrument detection limits, 0.1 at%). Although, the wake and nadir flight samples did contain particulate contamination in some regions. The nadir particles analyzed were primarily Zn-rich. The majority of analyzed wake particles appear to be oxidized Al with small amounts of Zn and Mg. The wake particles appear to have arrived early in the mission (or pre-flight) during a single event. Details of the MISSE 8 sample contamination analyses will be reported elsewhere.

Post-flight Observations

Ram Samples

Post-flight photographs of the ram flight samples and their corresponding control samples are provided in Figures 11a-f. Because many fluoropolymers are fairly AO durable as compared to other polymers, only minor changes in appearance were observed post-flight in the majority of the ram flight samples even with a high AO fluence of 4.62×10^{21} atoms/cm². The Al-FEP flight sample (M8-R2), which is shown in Figure 11a, appears wavy compared to the control sample, and has a small impact site in it, shown in the optical microscope image in Figure 12. The white Tedlar flight sample (white PVF, M8-R5), shown in Figure 11b, appears brighter in the exposed area. This is due to AO erosion of the polymer matrix, while leaving the AO durable inorganic TiO₂ white pigment particles on the surface. Prior studies have shown that the build-up of TiO₂ particles on the surface of white Tedlar protects the underlying material from erosion resulting a decreased E_y with fluence.^{16,20,28} This will be discussed further in the E_y section below. The Al-FEP flight sample sectioned from a multilayer insulation blanket previously flown on the exterior of the HST for 9.7 years (M8-R6), shown in Figure 11c, has the most notable change in appearance. The flight sample has a white ‘hazy’ appearance in the exposed area, as shown in Figure 13. A very slight hazy appearance is notable in the control sample when comparing the area covered by the sample holder and the area exposed to the atmosphere. The PTFE flight sample (M8-R7) is curled up, as seen in Figure 11d. The clear FEP flight sample (M8-R9) is slightly wavy as

compared to the control sample, and has a couple barely notable small hazy areas. The DC-93-500 silicone flight sample (M8-R10) has extensive surface cracking, as shown in Figure 11e and in the optical microscope image shown in Figure 14. Silicones commonly used on spacecraft do not chemically erode with AO exposure like other organic materials that have volatile oxidation products. Silicones react with AO and form an oxidized hardened silicate surface layer.²⁹ Often loss of methyl groups causes shrinkage of the surface skin and “mud-tile” crazing degradation.^{29,30} Silicones often do not lose mass, and some silicones actually gain mass during AO exposure.

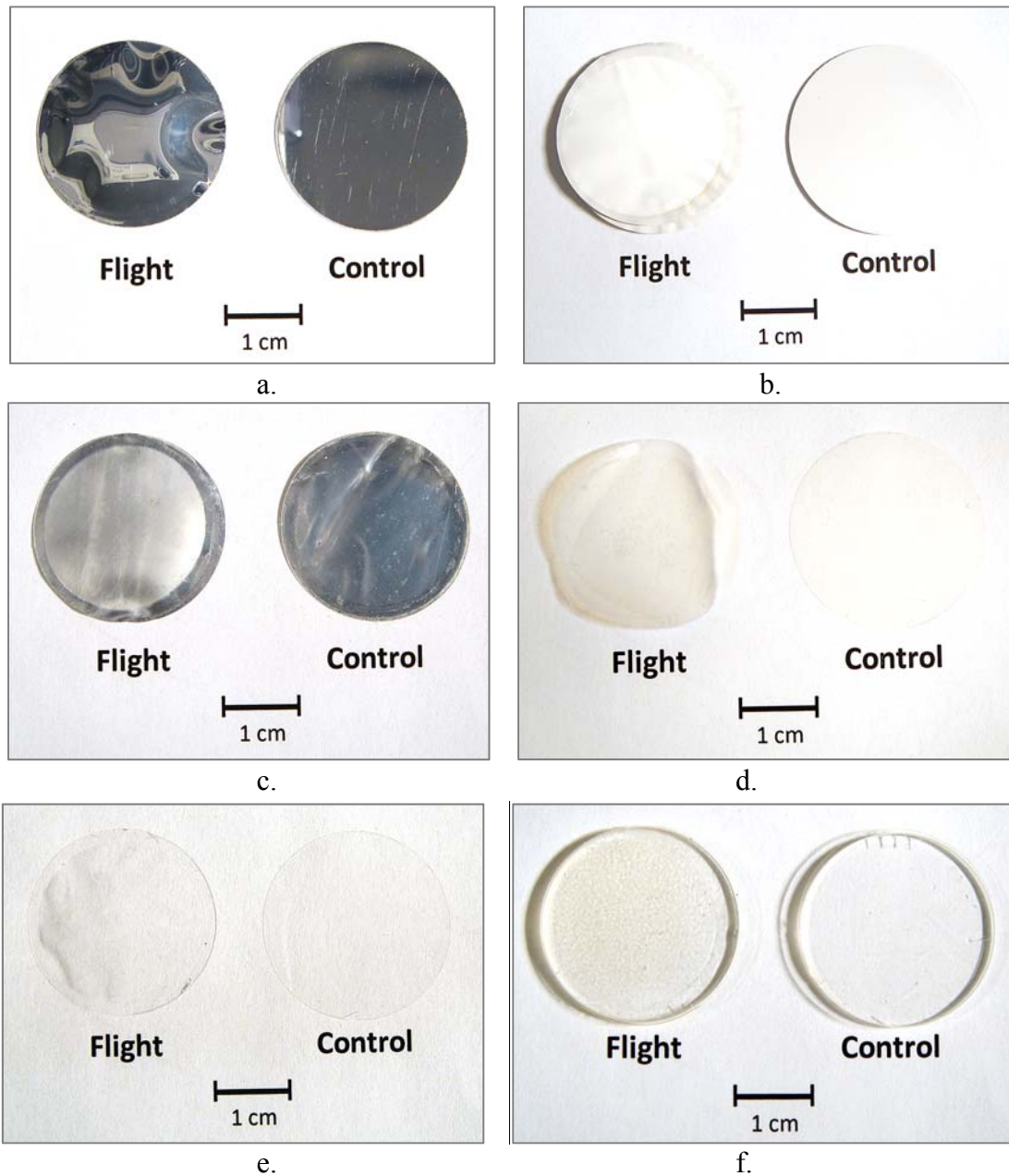


Figure 11. Post-flight photos of ram flight and corresponding control samples: a). Al-FEP (M8-R2), b). PVF white Tedlar (M8-R5) (7 layers), c). HST Al-FEP (M8-R6), d). PTFE (M8-R7), e). FEP (M8-R9), and f). DC 93-500/SiO₂ (M8-R10).



Figure 12. Optical microscope image of an impact site in the ram Al-FEP flight sample (M8-R2).

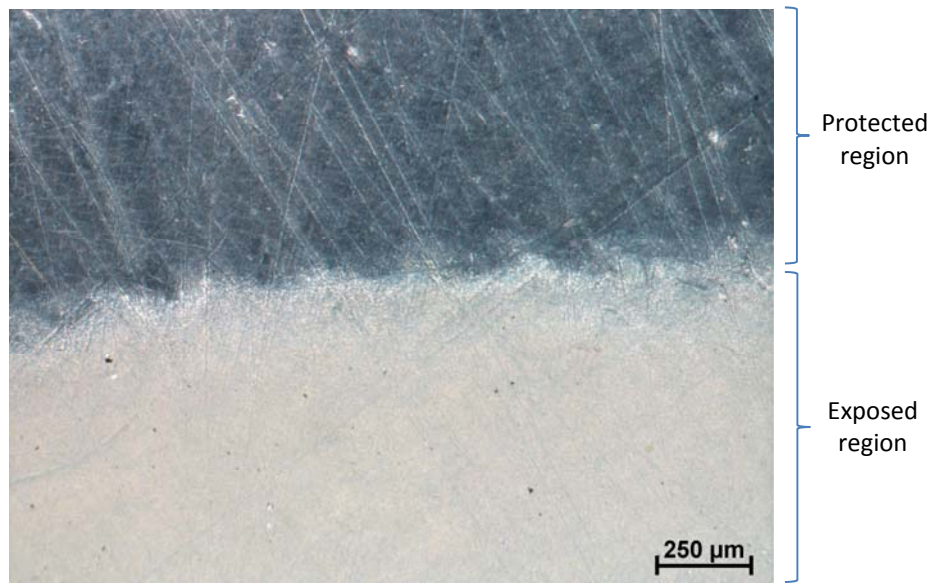


Figure 13. Optical microscope image of the ram HST Al-FEP flight sample (M8-R6) showing a hazy white exposed region (lower half of the image) and a protected, non-textured region (top half of image).

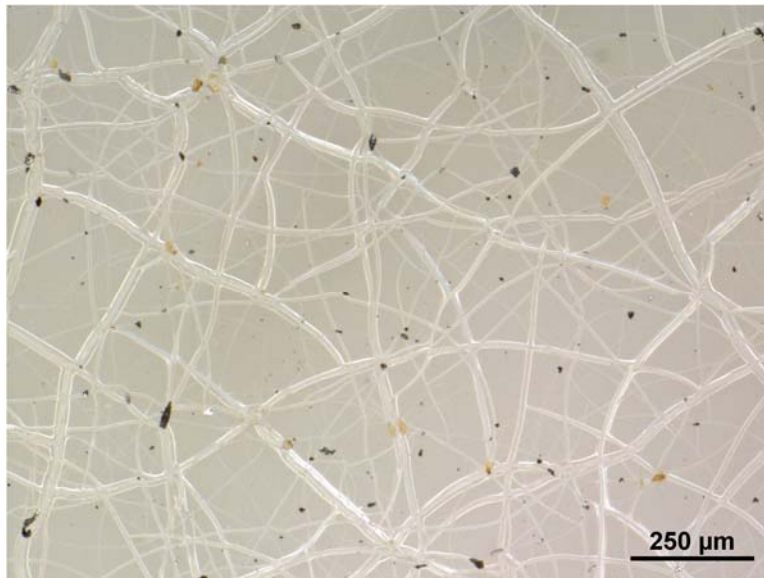


Figure 14. Optical microscope image showing surface mud-tile cracking of the ram DC 93-500 silicone flight sample (M8-R10).

Wake Samples

Post-flight photographs of the wake flight samples and their corresponding control samples are provided in Figures 15a-c. As mentioned previously, these flight samples were exposed to a low AO fluence of 8.80×10^{19} atoms/cm² and approximately 2,700 ESH. The Al-FEP flight sample (M8-W2), shown in Figure 15a, appears slightly wavy compared to the control. The Al-FEP flight sample sectioned from a multilayer insulation blanket previously flown on the exterior of the HST for 9.7 years (M8-W10), shown in Figure 15b, has a slightly hazy appearance in the exposed area. But, the control sample also appears to have a slightly hazy appearance in that area of the sample exposed to the atmosphere during storage. The clear FEP flight sample (M8-W11) is slightly wavy as compared to the control sample. It also has a few hazy regions, which appear a little darker than the rest of the sample, or the control, in the photograph in Figure 15c. These hazy areas, shown in Figure 16, are associated with the particulate contamination found through the contamination analyses.

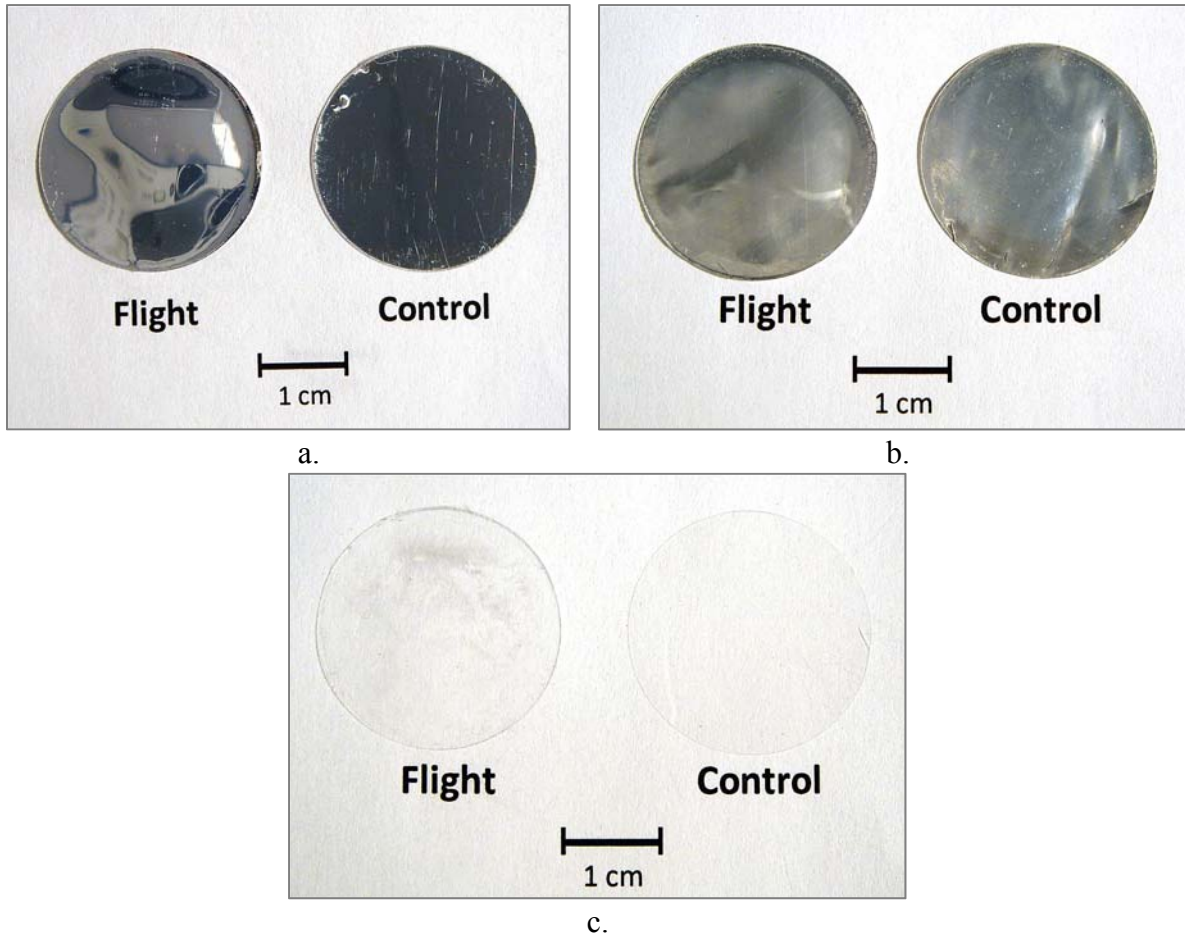


Figure 15. Post-flight photos of wake flight and corresponding control samples: a). Al-FEP (M8-W2), b). HST Al-FEP (M8-W10), and c). FEP (M8-W11).

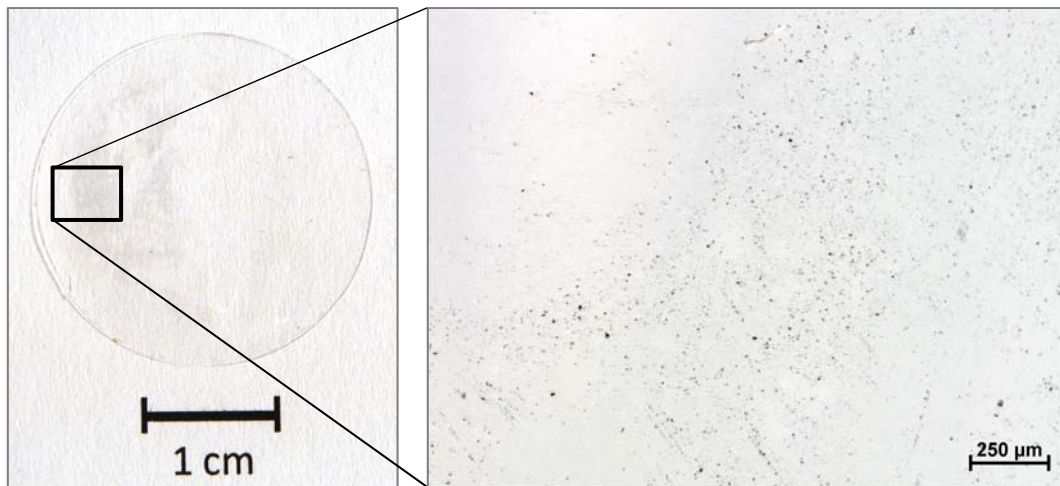


Figure 16. Post-flight photo of the wake FEP flight sample (M8-W11) with a close-up OM image of the particulate-rich hazy area.

Zenith Beveled Tray Samples

Post-flight photographs of the zenith beveled tray flight samples and their corresponding control samples are provided in Figures 17a-c. These flight samples were exposed to grazing AO exposure with a resulting low fluence (4.04×10^{19} atoms/cm²) and a high solar exposure of $6,100 \pm 1,000$ ESH. The Al-FEP flight sample (M8-Z3B), shown in Figure 17a, appears slightly wavy compared to the control. The back-surface Al coating of the control sample appears to have been scratched, which is attributed to its storage in the control tray during the mission. The Al-FEP flight sample sectioned from a multilayer insulation blanket previously flown on the exterior of the HST for 9.7 years (M8-Z4B), shown in Figure 17b, has a slightly hazy appearance in the exposed area. The control sample also appears to have a slightly hazy appearance, but the zenith flight sample discoloration is slightly more pronounced. The clear FEP flight sample (M8-Z2B) looks unchanged as shown in Figure 17c. The control sample has a slight ring that is observed at the edge of the as shown in Figure 17c. The marks on the control samples seem to indicate that the samples were tightly retained in the traveler tray.

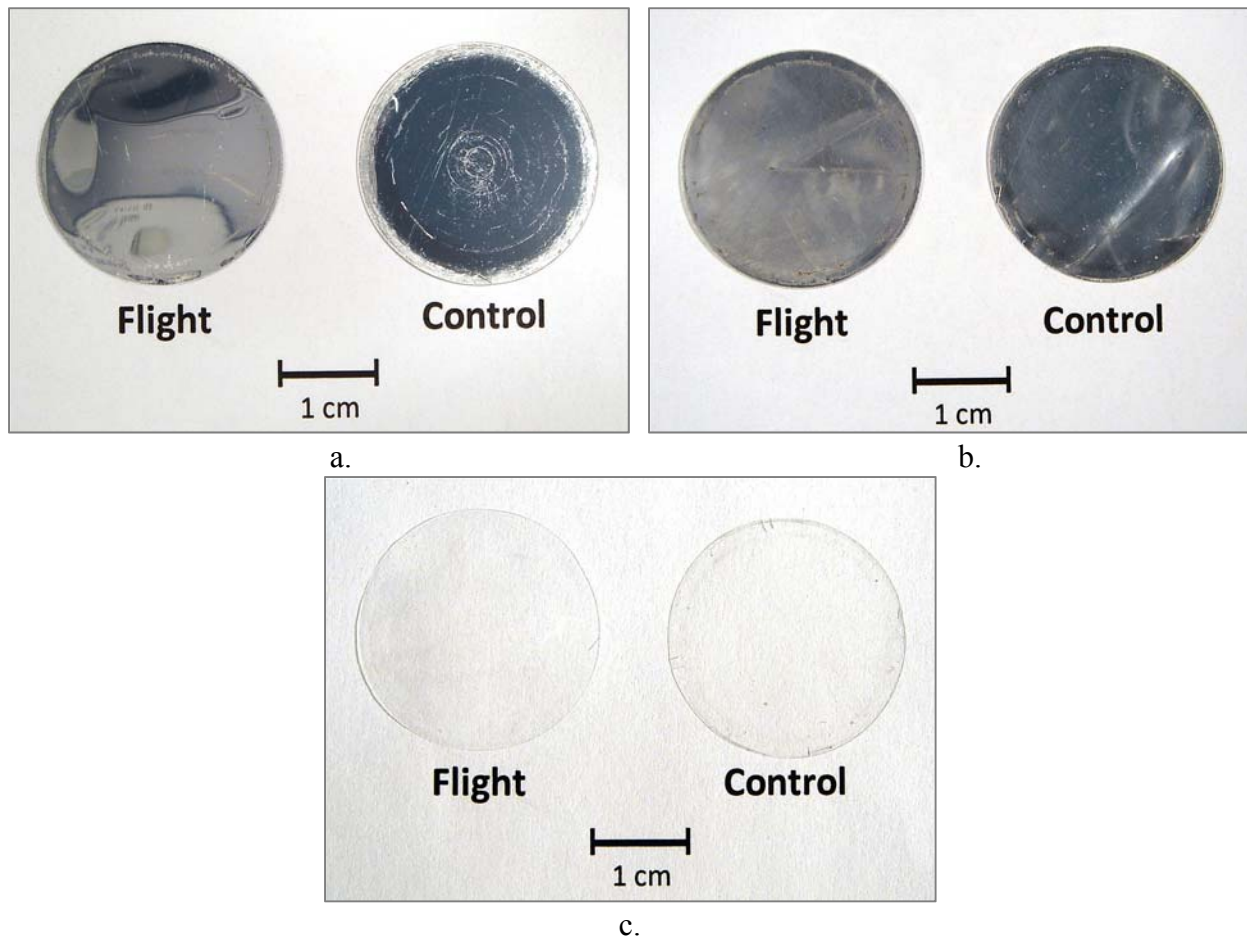


Figure 17. Post-flight photos of zenith beveled tray flight and corresponding control samples: a). Al-FEP (M8-Z3B), b). HST Al-FEP (M8-Z4B), and c). FEP (M8-Z2B).

Zenith Taped (Thin Al Foil Holder) Samples

Post-flight photographs of the zenith beveled tray flight samples and their corresponding control samples are provided in Figures 18a-f (M8-2 does not have a control sample). These flight samples were exposed to grazing AO exposure but received approximately 5Xs greater AO fluence (1.96×10^{20} atoms/cm²) than the zenith beveled samples received, along with similar high solar exposure of $6,100 \pm 1,000$ ESH.

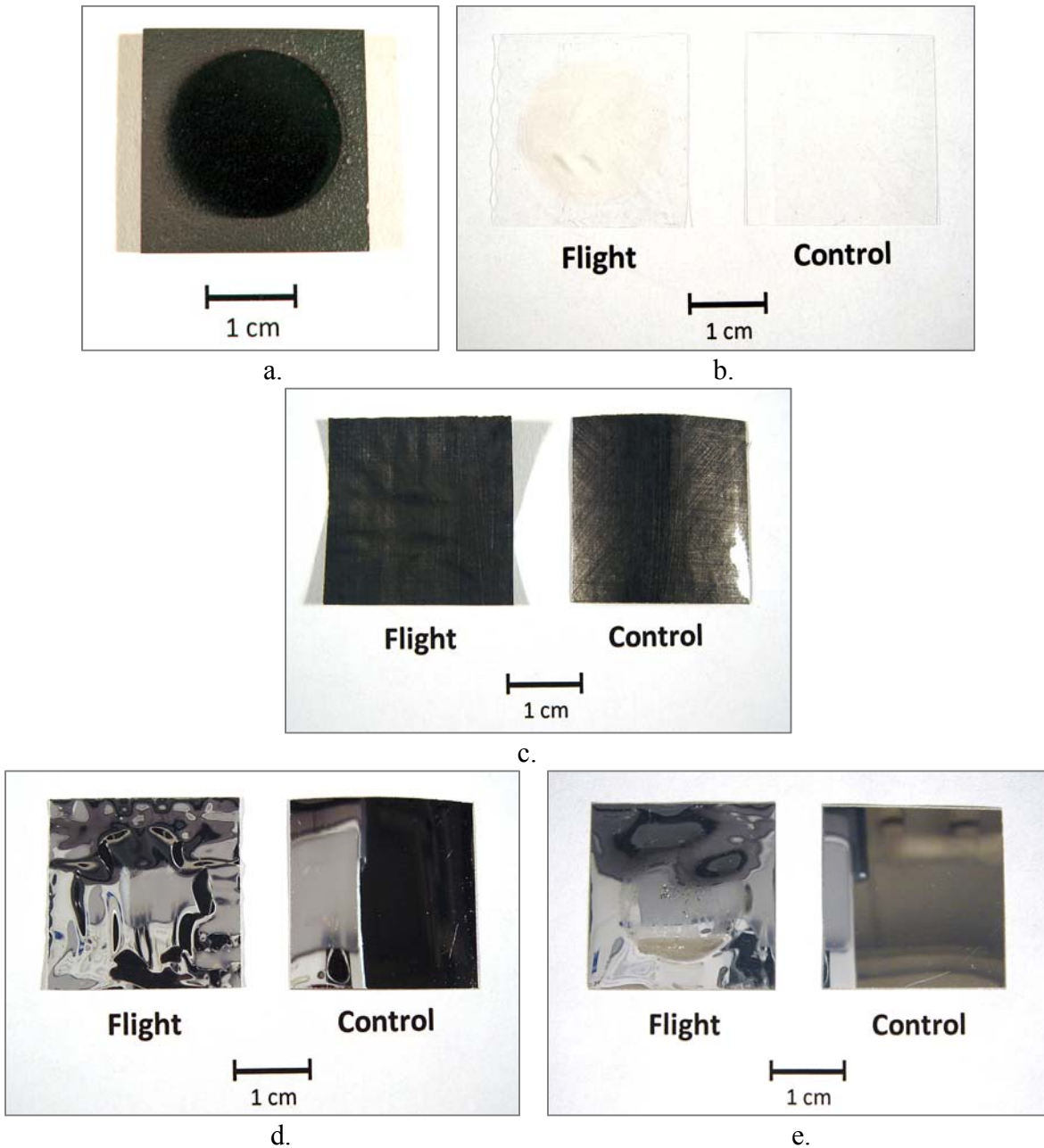


Figure 18. Post-flight photos of zenith taped (thin Al foil holder) flight and corresponding control samples: a). PG (M8-2, no control sample was available), b). FEP (M8-3), and c). C-FEP (M8-4), d). Al-FEP (M8-5), and e). Ag-FEP (M8-10).

The PG flight sample (M8-2), shown in Figure 18a, is textured and has a matt black appearance in the exposed area from AO erosion. The clear FEP flight sample (M8-3) is discolored in the exposed area with a very light brown color as shown in Figure 18b. The zenith C-FEP sample (M8-4) is wavy in the exposed area, although it is difficult to see this in Figure 18c. The Al-FEP flight sample (M8-5), shown in Figure 18d, appears very wavy compared to the control. And, the Ag-FEP flight sample (M8-10), has what appears to be extensive delamination of the back-surface metallization layers (silver and Inconel) in the exposed area, as shown in Figures 18e and Figure 19.

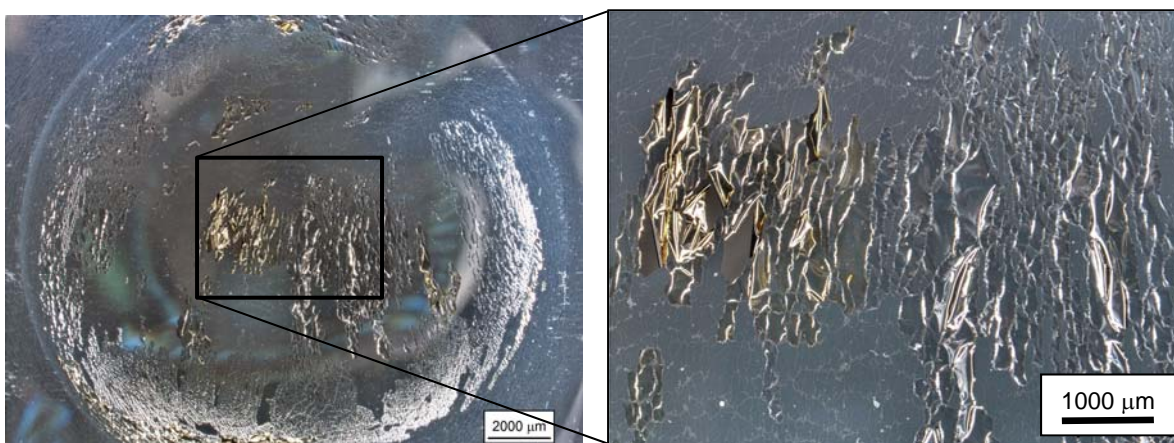


Figure 19. Optical microscope image of the Ag-FEP zenith taped flight sample (M8-10) with a close-up image of the highly delaminated central area.

Erosion Yield Values

Ram Samples

Table 7 provides the MISSE sample ID, material, film thickness, number of layers weighed post-flight, mass loss, exposed surface area, density, MISSE 8 ram AO fluence, and E_y for the 1-inch (2.54 cm) circular ram samples. The E_y values for the ram exposed fluoropolymers samples (FEP, Al-FEP, HST Al-FEP and PTFE) were an order of magnitude lower than for Kapton H. The E_y for the three ram Teflon FEP samples were all similar, with Al-FEP (M8-R2) having a slightly higher E_y ($2.39 \times 10^{-25} \text{ cm}^3/\text{atom}$) than clear FEP (M8-R9, $E_y = 2.37 \times 10^{-25} \text{ cm}^3/\text{atom}$). The previously space-exposed HST Al-FEP (M8-R6) had the highest E_y ($2.50 \times 10^{-25} \text{ cm}^3/\text{atom}$). This is only 5% higher than the E_y for the Al-FEP (M8-R2). These results are somewhat surprising, as it was thought the prior space exposure, with radiation induced polymer scission damage, would result in a significantly higher E_y than for non-previously flown Al-FEP.

Table 7. Erosion Yield Values for the MISSE 8 Ram Samples.

MISSE Sample ID	Material	Thickness (mil) (# layers weighed)	Mass Loss (g)	Bore Gauge Surface Area (cm ²)	Density (g/cm ³)	MISSE 8 AO Fluence (atoms/cm ²)	MISSE 8 E_y (cm ³ /atom)
M8-R1	Kapton H	5 (2)	0.079104	3.9953	1.4273	4.62E+21	3.00E-24*
M8-R2	Al-FEP**	5 (1)	0.009489	3.9969	2.1443	4.62E+21	2.39E-25
M8-R5	White PVF	1 (7)	0.004358	3.9945	1.6241	4.62E+21	1.45E-25
M8-R6	HST Al-FEP**	5 (1)	0.009870	3.9925	2.137	4.62E+21	2.50E-25
M8-R7	PTFE	2 (1)	0.007712	3.9956	2.1503	4.62E+21	1.94E-25
M8-R9	FEP	2 (1)	0.009399	3.9924	2.1443	4.62E+21	2.37E-25
M8-R10	DC 93-500 /SiO ₂	10/64 (1)	0.000076	3.9940	1.08	4.62E+21	3.81E-27

*Kapton H E_y based on prior LEO flight experiments

**FEP layer was space facing

The ram FEP E_y values were very similar to, but slightly higher than those measured for clear FEP flown in the ram direction for 4 years as part of MISSE 2 (2.00×10^{-25} cm³/atom).^{2,9,18} The MISSE 2 samples received an AO fluence of 8.43×10^{21} atom/cm² and a solar exposure of 6,300 ESH, which provides a similar solar exposure to AO fluence ratio as to the MISSE 8 mission. This is important because the E_y of Teflon FEP has been shown to be dependent on the solar exposure, as discussed below.^{19,20,31,32} The E_y for the PTFE was 1.94×10^{-25} cm³/atom. This is 82% lower than the E_y for the clear FEP sample. This is also consistent with the results from the MISSE 2 experiment where the PTFE sample E_y (1.42×10^{-25} cm³/atom) was 71% lower than the E_y for FEP.^{2,9,18}

The E_y for the ram facing white PVF (white Tedlar) was 1.45×10^{-25} cm³/atom. Although this is a low E_y value, it is higher than the E_y for white Tedlar flown in the ram direction for 4 years as part of MISSE 2 ($E_y = 1.01 \times 10^{-25}$ cm³/atom).^{2,9,18} This is consistent with prior spaceflight data which shows that the E_y of white Tedlar decreases with increasing AO fluence.^{16,20,28} As mentioned previously, the AO fluence for the MISSE 2 mission was 8.43×10^{21} atom/cm², almost twice that for the MISSE 8 ram samples. The decreased E_y with increased AO fluence for white Tedlar is attributed to a buildup of AO durable TiO₂ particles on the surface of the samples with increasing AO exposure. The TiO₂ protects the underlying material from erosion if undisturbed, thus decreasing the E_y with increasing AO fluence. The E_y for white Tedlar from three different MISSE missions (MISSE 2, 7 and 8) are plotted versus AO fluence in Figure 20. Further investigations on the effect of inorganic filler on the AO erosion of polymers and paints are reported by Banks.²⁸

The E_y for the DC 93-500 silicone, 3.81×10^{-27} cm³/atom, is three orders of magnitude lower than that for Kapton H due to the extremely low mass loss (0.076 mg). As mentioned previously, silicones convert to a glassy AO durable silicate layer. This silicate layer can craze with a high enough AO fluence, as was seen in the OM image shown in Figure 14.

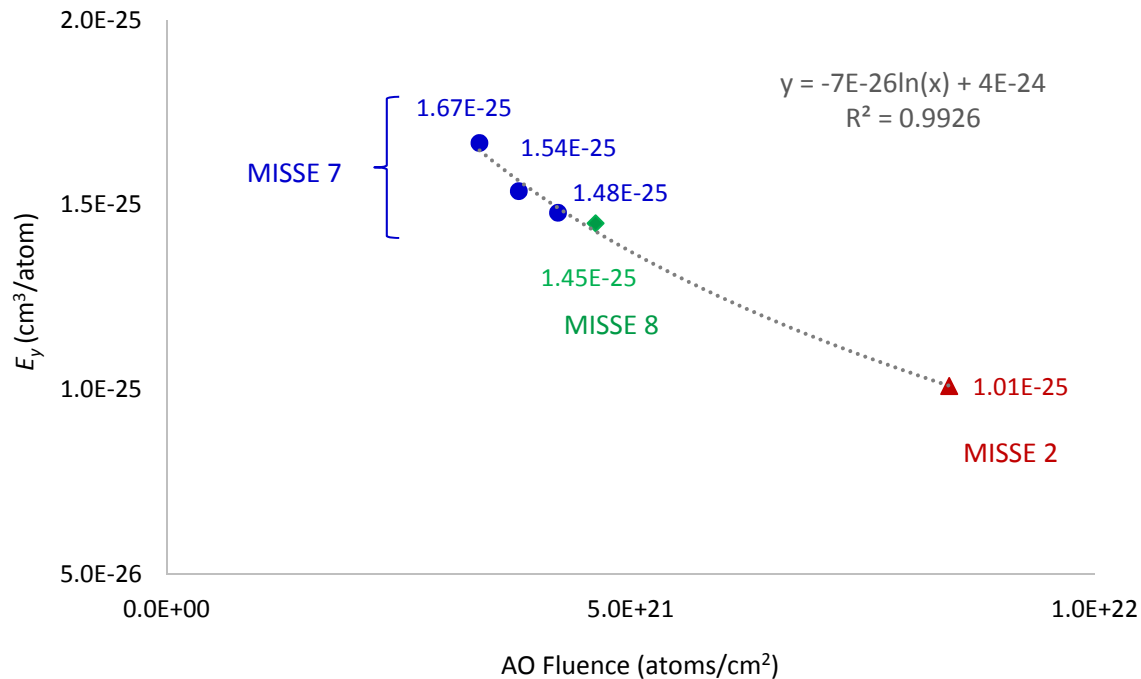


Figure 20. Erosion yield versus AO fluence for white Tedlar samples flown on MISSE 2, 7 and 8 showing decreasing E_y with increasing AO fluence.

Wake Samples

Table 8 provides the MISSE ID, material, film thickness, number of layers weighed post-flight, mass loss, exposed surface area, density, MISSE 8 wake AO fluence, and E_y for the 1-inch (2.54 cm) circular wake samples. The E_y for the three wake Teflon FEP samples were all similar, with Al-FEP (M8-W2) having a slightly higher E_y (1.10×10^{-24} cm³/atom) than clear FEP (M8-W11, $E_y = 1.09 \times 10^{-24}$ cm³/atom). The previously space-exposed HST Al-FEP (M8-W10) had the lowest E_y (1.04×10^{-24} cm³/atom). Again, these results are surprising, as it was thought the prior space exposure would result in a significantly higher E_y than for non-previously flown Al-FEP.

Table 8. Erosion Yield Values for the MISSE 8 Wake Samples.

MISSE Sample ID	Material	Thickness (mil) (# layers weighed)	Mass Loss (g)	Bore Gauge Surface Area (cm ²)	Density (g/cm ³)	MISSE 8 AO Fluence (atoms/cm ²)	MISSE 8 E_y (cm ³ /atom)
M8-W1	Kapton H	5 (1)	0.001523	4.0415	1.4273	8.80E+19	3.00E-24*
M8-W2	Al-FEP**	5 (1)	0.000839	4.0440	2.1443	8.80E+19	1.10E-24
M8-W10	HST Al-FEP**	5 (1)	0.000790	4.0437	2.137	8.80E+19	1.04E-24
M8-W11	FEP	2 (1)	0.000827	4.0410	2.1443	8.80E+19	1.08E-24

*Kapton H E_y based on prior LEO flight experiments

**FEP layer was space facing

Zenith Beveled Tray Samples

Table 9 provides the MISSE ID, material, film thickness, number of layers weighed post-flight, mass loss, exposed surface area, density, MISSE 8 zenith beveled tray AO fluence, and E_y for the 1-inch (2.54 cm) circular samples flown in the zenith facing beveled tray. The E_y for the three FEP samples were all similar, with Al-FEP (M8-Z3B) having a slightly higher E_y ($6.32 \times 10^{-24} \text{ cm}^3/\text{atom}$) than clear FEP (M8-Z2B, $E_y = 5.71 \times 10^{-24} \text{ cm}^3/\text{atom}$). The previously space-exposed HST Al-FEP (M8-Z4B) had the same E_y ($6.32 \times 10^{-24} \text{ cm}^3/\text{atom}$) as the Al-FEP. Once again, this result was not as expected, as greater erosion of previously flown FEP was anticipated.

Table 9. Erosion Yield Values for the MISSE 8 Zenith Tray Samples.

MISSE Sample ID	Material	Thickness (mil) (# layers weighed)	Mass Loss (g)	Bore Gauge Surface Area (cm ²)	Density (g/cm ³)	MISSE 8 AO Fluence (atoms/cm ²)	MISSE 8 E_y (cm ³ /atom)
M8-Z1B	Kapton H	5 (1)	0.000670	3.8771	1.4273	4.04E+19	3.00E-24*
M8-Z2B	FEP	2 (1)	0.001916	3.8772	2.1443	4.04E+19	5.71E-24
M8-Z3B	Al-FEP**	5 (1)	0.002120	3.8742	2.1443	4.04E+19	6.32E-24
M8-Z4B	HST Al-FEP**	5 (1)	0.002113	3.8774	2.137	4.04E+19	6.32E-24

*Kapton H E_y based on prior LEO flight experiments

**FEP layer was space facing

Zenith Taped (Thin Al Foil Holder) Samples

Table 10 provides the MISSE ID, material, film thickness, number of layers weighed post-flight, mass loss, exposed surface area, density, MISSE 8 zenith taped AO fluence, and E_y for the samples flown the zenith direction in thin Al foil holders. The PG sample had an E_y of $4.04 \times 10^{-24} \text{ cm}^3/\text{atom}$. Once again, this was very similar to the E_y of PG exposed to LEO ram AO for 4 years as part of the MISSE 2 mission ($E_y = 4.15 \times 10^{-24} \text{ cm}^3/\text{atom}$).^{2,9,18} Once again, the E_y for the zenith taped Al-FEP (M8-5, $E_y = 1.90 \times 10^{-24} \text{ cm}^3/\text{atom}$) was somewhat higher than for the clear FEP (M8-3, $E_y = 1.37 \times 10^{-24} \text{ cm}^3/\text{atom}$).

Table 10. Erosion Yield Values for the MISSE 8 Zenith Taped Samples.

MISSE Sample ID	Material	Thickness (mil) (# layers weighed)	Mass Loss (g)	CADD Exposed Surface Area (cm ²)	Density (g/cm ³)	MISSE 8 AO Fluence (atoms/cm ²)	MISSE 8 E_y (cm ³ /atom)
M8-1	Kapton H	5 (1)	0.002330	2.7819	1.4273	1.96E+20	3.00E-24*
M8-2	PG	80 (1)	0.000513	2.9277	2.22	1.96E+20	4.04E-25
M8-3	FEP	2 (1)	0.001573	2.7310	2.1443	1.96E+20	1.37E-24
M8-4	C-FEP**	2 (1)	0.004134	2.7264	2.1443	1.96E+20	3.61E-24
M8-5	Al-FEP**	2 (1)	0.002172	2.7213	2.1443	1.96E+20	1.90E-24
M8-10	Ag-FEP**	5 (1)	0.001565	2.7606	2.1443	1.96E+20	1.35E-24

*Kapton H E_y based on prior LEO flight experiments

**FEP layer was space facing

Two other types of FEP were flown as zenith taped samples, Ag-FEP and C-FEP. The Ag-FEP (M8-10) had a similar E_y (1.35×10^{-24} cm³/atom) as the clear FEP. But, the C-FEP had approximately 3X higher E_y (3.61×10^{-24} cm³/atom) than the clear FEP and approximately 2X higher E_y than for the Al-FEP. Maximum temperature estimates were made for Al-FEP and C-FEP flown in the zenith orientation on MISSE 8. The assumptions were: 1). samples had the same holder configuration and orientation, 2). the solar absorptance was 0.179 for 2 mil Al-FEP and 0.96 for 2 mil C-FEP, and 3). the thermal emittance was 0.66 for both Al-FEP and C-FEP. It was also assumed that radiated heat is ejected only in the space direction (due to the Al on the back of the sample, or the Al in the sample holder). Based on this constraint and these assumptions, the maximum estimated on-orbit temperature for the Al-FEP was 2 °C, while the maximum estimated on-orbit temperature was estimated to be significantly higher for the C-FEP at 170 °C. Because all other environmental conditions (AO fluence, radiation exposure, etc.) were the same between the zenith Al-FEP and C-FEP, except for the maximum on-orbit temperature, this shows that passive heating has a significant impact on the erosion of FEP in LEO. It should be noted that C-FEP flown as part of the MISSE 7 Polymers Experiment, did not have a greater E_y as compared with Al-FEP, as these MISSE 8 results indicate.²⁰ It is not clear why there is a difference in the results from these two flight experiments, but further studies are desired to confirm the results provided from the MISSE 8 experiment.

E_y Comparison of Teflon FEP Flown in Different Orientations on MISSE 8

Prior flight data have indicated that the solar exposure (sun hours with corresponding temperature effects, and possibly x-rays) plays a significant role in the erosion of some polymers, with Teflon FEP showing a strong correlation.^{19,20,31,32} For example, the E_y of Hubble Space Telescope (HST) Bay 8 Al-FEP insulation after 19 years in space, exposed to 89,300 ESH and an AO fluence of 4.65×10^{20} atom/cm², was 1.37×10^{-23} cm³/atom. This is an order of magnitude greater than the E_y of HST Bay 5 FEP ($E_y = 1.43 \times 10^{-24}$ cm³/atom) also retrieved after 19 years in space, but exposed to 24,300 ESH and a similar AO fluence (4.28×10^{20} atom/cm²).³² Thus, by flying similar polymers in different orientations on MISSE missions, the effect of solar exposure (both radiation dose and heating effects) on the E_y can be assessed.

Table 11 provides the solar exposure, AO fluence, solar exposure to AO fluence ratio, and E_y for FEP, Al-FEP and HST Al-FEP flown in the ram, wake and/or zenith orientations on MISSE 8. The E_y is plotted versus the MISSE 8 solar exposure to AO fluence ratio in Figure 21 for each type of FEP (clear, Al-FEP and HST Al-FEP) flown in each orientation. As can be seen in the graph, the E_y of FEP, Al-FEP and HST Al-FEP are all highly dependent on the flight orientation (and sample mounting), and hence on the environmental exposure. The wake exposure resulted in 4.2-4.6X higher E_y for all three FEP samples than for ram exposure. The zenith taped exposure resulted in 5.8 to 8.0X higher E_y , almost an order of magnitude, than ram exposure. And, the zenith tray exposure resulted in a greater than order of magnitude E_y (24.1-26.4X higher) than ram exposure. Also, as can be seen in the graph, there is an excellent correlation of E_y to the solar exposure to AO fluence ratio (for all three types of Teflon FEP). This clearly shows the effect of solar radiation and/or heating due to solar exposure on FEP erosion.

Table 11. Erosion Yield Comparison for Teflon FEP Flown in Different Orientations.

MISSE 8 Orientation	Solar Exposure (ESH)	AO Fluence (atoms/cm ²)	Solar/AO Ratio (xE19 ESH*cm ² /atom)	FEP E _y (cm ³ /atom)	Al-FEP E _y (cm ³ /atom)	HST Al-FEP E _y (cm ³ /atom)
Ram	3,200	4.62E+21	6.9	2.37E-25	2.39E-25	2.50E-25
Wake	2,700	8.80E+19	307	1.08E-24	1.10E-24	1.04E-24
Zenith (Taped)	6,100	1.96E+20	312	1.37E-24	1.90E-24	-
Zenith (Tray)	6,100	4.04E+19	1510	5.71E-24	6.32E-24	6.32E-24

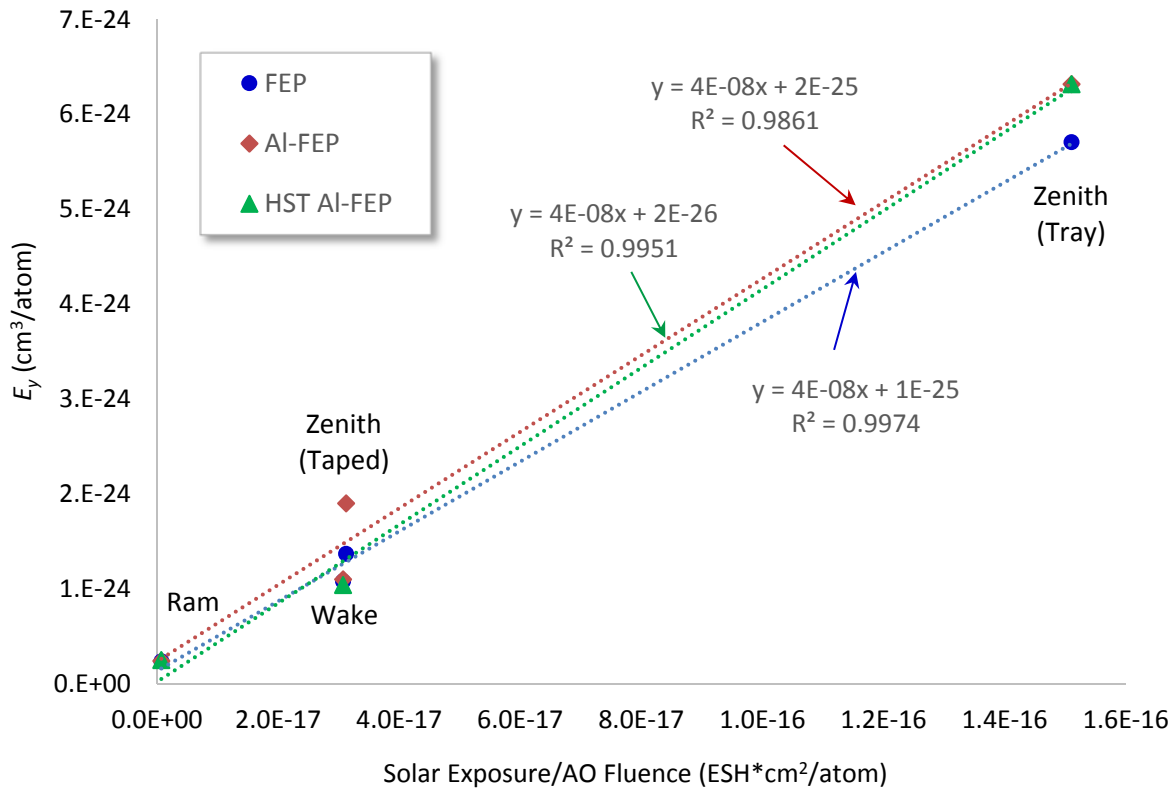


Figure 21. Erosion yield versus solar exposure to AO fluence ratio for Teflon FEP samples flown in the ram, wake and zenith orientations on MISSE 8.

Summary and Conclusions

The MISSE 8 Polymers Experiment was successfully flown and exposed to the LEO space environment on the exterior of the ISS and retrieved for post-flight analyses after 2.0-2.14 years of space exposure. A total of 42 polymer samples were flown in ram, wake and zenith orientations, each of which provided different environmental exposures. The AO fluence for the ram, wake, and zenith orientations were determined to be 4.62×10^{21} atoms/cm², 8.80×10^{19} atoms/cm², and 4.04×10^{19} atoms/cm², respectively, based on mass loss of Kapton H witness samples flown in beveled sample trays. The AO fluence for samples flown in the zenith orientation in taped thin Al

foil holders was determined to be 1.96×10^{20} atoms/cm², also based on mass loss of Kapton H. The very large difference in AO fluence (4.9X) for the two Kapton H samples flown in the zenith orientation shows that the AO exposure for surfaces receiving grazing AO in LEO is highly dependent on the sample holder geometry. The solar exposure for the zenith orientation of the MISSE 8 mission was calculated by NRL to be 6,100 ESH. The MISSE 8 ram and wake solar exposures were approximated to be 3,200 ESH and 2,700 ESH respectively. These values were determined using the ratios of MISSE 7 solar exposures, since MISSE 8 was flown in the same location as MISSE 7 on ISS ELC-2.

The LEO AO E_y values were determined for 17 samples (6 ram, 3 wake and 8 zenith samples) based on pre- and post-flight dehydrated mass. Comparing the E_y of white Tedlar from the MISSE 8 mission to white Tedlar samples flown on other MISSE missions, verified prior results that indicated that the E_y of the high ash containing white Tedlar was found to decrease with increasing AO fluence. This is attributed to a buildup of AO durable TiO₂ pigment particles on the surface of the samples with increasing AO fluence, which protects the underlying material from erosion when not disturbed. The E_y of Teflon FEP samples flown in ram, wake and zenith orientations were compared to help determine solar exposure effects on the AO erosion of Teflon. The results show that the E_y of FEP is highly dependent on the flight orientation, and therefore on the environmental exposure. The zenith and wake exposures resulted in significantly greater E_y values than ram exposure. For example, Al-FEP flown in the zenith direction in a beveled tray had an E_y that was 26X greater than for Al-FEP flown in the ram direction in a beveled tray. In addition, the E_y of FEP (FEP, Al-FEP and HST Al-FEP) was found to increase with a direct correlation to the solar exposure to AO fluence ratio clearly indicating the effect of solar radiation and/or heating due to solar exposure on FEP erosion in LEO. In addition, C-FEP flown in the zenith orientation had a significantly higher E_y than clear FEP (3X) or Al-FEP (2X). The maximum on-orbit temperature of Al-FEP was estimated to be 2 °C, while the maximum on-orbit temperature of C-FEP was estimated to be 170 °C, further providing evidence that heating has a significant impact on the erosion of FEP. The MISSE 8 Polymers Experiment provides valuable LEO flight data on the erosion of Teflon FEP, a commonly used spacecraft thermal insulation material, and other polymers for LEO spacecraft design purposes.

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