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MISSE 6 Stressed Polymers Experiment Atomic Oxygen Erosion Data

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ABSTRACT

Polymers and other oxidizable materials used on the exterior of spacecraft in the low Earth orbit (LEO) space environment can be eroded away by reaction with atomic oxygen (AO). For spacecraft design, it is important to know the LEO AO erosion yield, E_y (volume loss per incident oxygen atom), of materials susceptible to AO erosion. The Stressed Polymers Experiment was developed and flown as part of the Materials International Space Station Experiment 6 (MISSE 6) to compare the AO erosion yields of stressed and non-stressed polymers to determine if erosion is dependent upon stress while in LEO. The experiment contained 36 thin film polymer samples that were exposed to ram AO for 1.45 years. This paper provides an overview of the Stressed Polymers Experiment with details on the polymers flown, the characterization techniques used, the AO fluence, and the erosion yield results. The MISSE 6 data are compared to data for similar samples flown on previous MISSE missions to determine fluence or solar radiation effects on erosion yield.

INTRODUCTION

Spacecraft in the low Earth orbit (LEO) environment (between 200 and 2000 km above the surface of the Earth) endure extremely harsh conditions, including exposure to ultraviolet, x-ray, and charged particle radiation; micrometeoroids and debris; AO, and temperature extremes. Atomic oxygen is formed through photodissociation of diatomic oxygen by short wavelength ultraviolet radiation from the sun. Polymers and other oxidizable materials used on the exterior

of spacecraft in the LEO space environment can, in most cases, be eroded away through reaction with AO. Therefore, AO erosion poses a serious threat to spacecraft performance and durability. In order to design durable high-performance spacecraft systems, it is essential to understand the AO erosion yield (E_y) of materials being considered for spacecraft applications. The E_y is the volume loss per incident oxygen atom (cm^3/atom). Materials spaceflight experiments for E_y determination have been flown on the Shuttle, the Long Duration Exposure Facility (LDEF), the Russian space station Mir and other spacecraft. More recently, they have been a part of the Materials International Space Station Experiment (MISSE) series flown on the exterior of the International Space Station (ISS).

Upon initial cleanroom inspection, samples flown as part of MISSE 1 and 2, such as MISSE 1 Gossamer Materials Experiment samples, appeared to have experienced excessive AO erosion in bent or high stress regions. Therefore, the Stressed Polymers Experiment was developed and flown as part of the MISSE 6 with the primary objective to compare the AO erosion yields of stressed and non-stressed polymers to determine if AO erosion is dependent upon stress while in LEO.

This paper provides an introduction to the Stressed Polymers Experiment, details on the specific polymers flown, and a summary of the characterization techniques used. The AO fluence calculations are discussed along with a summary of the erosion yield results of the stressed and the non-stressed samples. The MISSE 6 flight data are compared to data for similar samples flown on previous MISSE missions to help determine fluence or solar radiation effects on LEO erosion yield.

MISSE 6 STRESSED POLYMERS EXPERIMENT

MISSE is a series of spaceflight experiments designed to test the performance and durability of materials and devices exposed to the LEO space environment. MISSE consists of 11 flight experiment trays (10 Passive Experiment Carriers (PECs) and one smaller tray being flown with MISSE 8) that are mounted to the exterior of the International Space Station (ISS). Each two-sided tray contains numerous individual flight experiments and are positioned in either a ram/wake orientation or a zenith/nadir orientation (Ref. 1). The Stressed Polymers Experiment was located on the ram side of MISSE Passive Experiment Container (PEC) 6A, which was deployed on the exterior of the ISS during the STS-123 shuttle mission on March 22, 2008. The experiment was oriented to receive directed AO exposure during the majority of the mission. The experiment remained in LEO for approximately 1.45 years, until it was retrieved during the STS-128 shuttle mission on September 1, 2009. Figure 1 shows MISSE 6A & 6B on the exterior of the Columbus Laboratory, as imaged in March 2008 during the STS-123 mission.

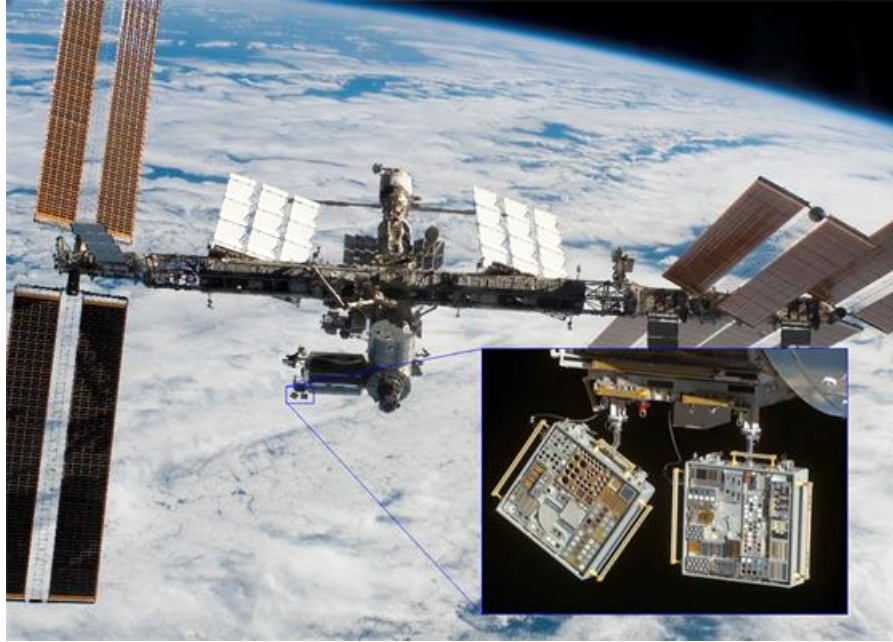


Figure 1. The International Space Station (photographed in March 2008) with a close-up photo of MISSE 6A and 6B on the Columbus Laboratory (Ref. 2).

The MISSE 6A Stressed Polymers Experiment contained 34 stacked thin film polymer samples for erosion yield determination and two DC 93-500 silicone samples for surface crazing and hardness characterization. Twenty-four samples were flown in a non-stressed configuration and 11 samples were duplicated, but flown in a stressed configuration. Six polymer materials that were flown as part of the MISSE 2 Polymer Erosion and Contamination Experiment (PEACE) and had excessively degraded after four years of LEO exposure (Refs. 3 to 5) were included for erosion yield determination. In addition, three stacked layers of Kapton[®] H of various thicknesses (12.7 μm and 127 μm) were flown, along with stacked Kapton[®] H (12.7 μm) with the layers separated with spacers, to determine if film thickness and/or spacing between layers has an effect on erosion yield. Also, included were samples of aluminized-Teflon[®] fluorinated ethylene propylene (Al-FEP), 200 °C heated Al-FEP (380 hours in air), samples of Al-FEP previously exposed to space on the Hubble Space Telescope (HST), and silvered-Teflon from the LDEF, to determine if prior space exposure affects the erosion yield of FEP. Analyses of the HST and LDEF samples are not listed in Table 1 and will not be reported in this paper.

MATERIALS

A list of the different materials exposed to AO as part of the MISSE 6 Stressed Polymers experiment is given in Table 1, along with the material abbreviation, trade name(s), material thickness and number of sample layers flown.

The samples were flown in three ram facing MISSE “W trays” that hold 15 – 1 in. square (2.54 cm) samples each. The 11 stressed samples were flown in the MISSE W2 tray (#1 stamped on tray) and the non-stressed partner samples were flown in identical tray locations in the MISSE W3 tray (#2 stamped on tray). The stressed sample Ids are designated as “S#” and the non-stressed sample Ids are “N#” (non-stressed samples flown in the “stressed tray” were designated as “N#-S”). The three layered Kapton samples were flown in the MISSE W6 Tray and the

sample Ids were W6-5, W6-9 and W6-10, as described in Table 1. The purpose of these samples is to determine the effect of thickness (5 mil vs. 0.5 mil thick layers), and the effect of having spaces between layers (i.e., using square Al “frames” between layers to provide a gap between layers). Figure 2 shows the locations of the three W trays on the Columbus Laboratory.

Table 1. MISSE 6 Stressed Polymers Experiment Flight Samples.

MISSE 6	Material	Abbrev.	Trade Name	Density (gm/cm ³)	Thickness (mils) x # of Layers	Total Thickness (mils)
S1 & N1	Polytetrafluoroethylene	PTFE	Chemfilm DF-100	2.1503	5 x 4	20
S2 & N2	Fluorinated ethylene propylene	FEP	Teflon FEP	2.1443	5 x 4	20
S3 & N3	Polyimide (BPDA)	PI	Upilex-S	1.3866	1 x 20	20
S4 & N4	Polyimide	PI	CP1	1.4193	1 x 20	20
S5 & N5	Polyimide (PMDA)	PI	Kapton CB	1.417	5 x 4	20
S6 & N6	Polyimide (PMDA)	PI	Kapton XC	1.41	5 x 4	20
S7 & N7	Polyimide (PMDA)	PI	Kapton E	1.42	2 x 10	20
S8 & N8	Polyimide (PMDA)	PI	Kapton H	1.4273	5 x 4	20
S9 & N9	Polyethylene-terephthalate	PET	Mylar A	1.3925	5 x 4	20
S10 & N10	Polyethylene	PE	PE (low oxygen)	0.918	2 x 10	20
S11 & N11	DC 93-500 Silicone on Fused Silica	DC 93-500	DC 93-500	n/a	20 x 1	20
N12	High temperature polyimide resin	PI	PMR-15	1.323	36 x 1	36
N13	Polyetherimide	PEI	Ultem 1000	1.287	10 x 2	20
N12-S	Polybenzimidazole	PBI	PBI	1.276	4 x 5	20
N14-S	Allyl diglycol carbonate	ADC	CR-39; Homalite H-911	1.317	47 x 1	47
N15-S	Polymethyl methacrylate	PMMA	Plexiglas; Lucite	1.163	2 x 10	20
W6-5	Polyimide (PMDA)	PI	Kapton H	1.4273	5 x 3	15
W6-10	Polyimide (PMDA) (no spacers)	PI	Kapton H	1.4273	0.5 x 10*	15
W6-9	Polyimide (PMDA) (with 9 Al spacers, 0.014 in. thick)	PI	Kapton H	1.4273	0.5 x 10 with spacers ⁺	10

Three samples not included in the Stressed Polymers Experiment were flown in the W2 and W3 trays: an AO pinhole camera (N13-S) flown in W3, and two passive solar cell samples (DC 93-500 silicone coated solar cell (N14) and DC 93-500/polyhedral oligomeric silsesquioxanes (POSS) coated solar cell (N15)) were flown in W2.

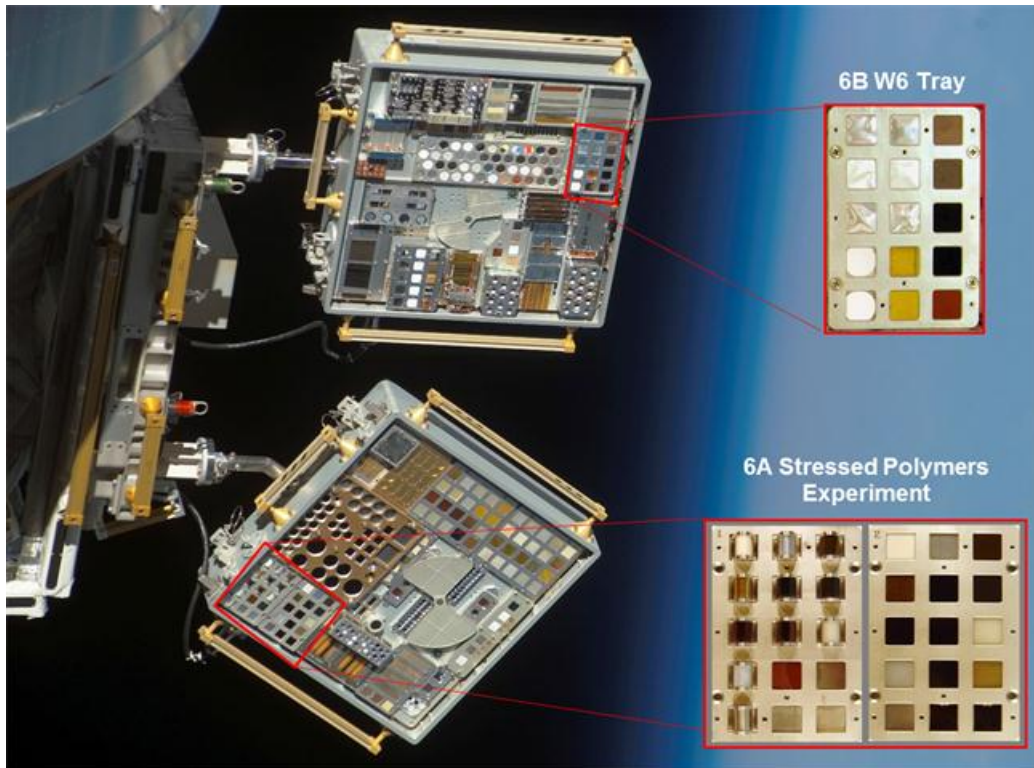


Figure 2. MISSE 6A (bottom) and 6B (top) on the Columbus Laboratory showing the locations of trays W2, W3 and W6.

Figure 3 shows a pre-flight photo of one of the stressed samples, Kapton CB (S5), in a stressed holder. The stressed holders were designed to cover the edges of the samples providing a clear exposure area. Because the stressed samples were to receive non-uniform AO flux, a ¼ in. (0.635 cm) wide area at the edge of each sample was salt-sprayed so erosion depth around the circumference of the sample using a recession depth technique could be determined, in case the AO arrival was not normal (Ref. 6). A “retaining base” was used at the bottom of the samples to keep the samples from bowing during loading and flight. A post-flight photo of the stressed Kapton CB sample is shown in Figure 3, where the retaining base is visible on one side of the sample.

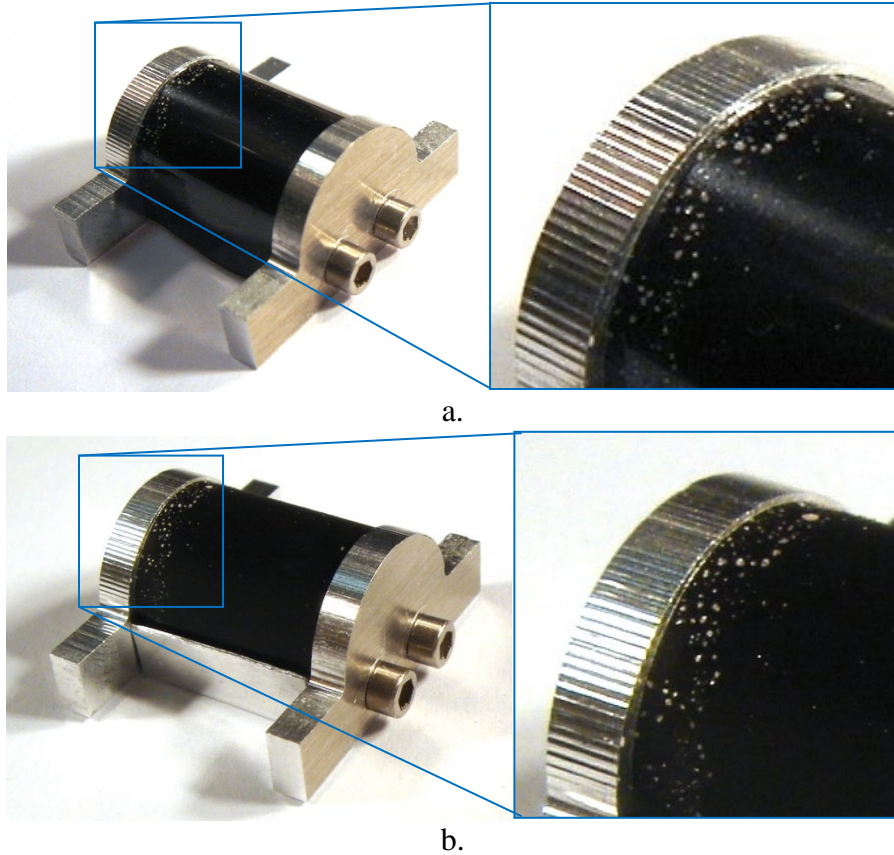


Figure 3. Kapton CB (S5) sample in a stressed holder with a close-up image showing the salt-sprayed region: a). Pre-flight photo, and b). Post-flight photo.

EXPERIMENTAL PROCEDURES

Erosion Yield Measurements

Erosion Yield Determination of Non-Stressed Samples

A common technique for determining the erosion yield (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 a flat (non-stressed) sample is calculated through the following equation:

$$E_y = \frac{DM_s}{(A_s r_s F)} \quad (1)$$

where

- E_y = Erosion yield of flight sample (cm^3/atom)
- DM_s = Mass loss of the flight sample (g)
- A_s = Surface area of the flight sample exposed to AO (cm^2)
- r_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 (3.0×10^{-24} cm³/atom) in the LEO environment (Refs. 7 to 10) Therefore, the AO fluence can be calculated using the following equation:

$$F = \frac{DM_K}{(A_K r_K E_K)} \quad (2)$$

where

- F = LEO AO fluence (atoms/cm²)
- DM_K = Mass loss of Kapton H witness sample (g)
- A_K = Surface area of Kapton H witness sample exposed to AO (cm²)
- r_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)

A non-stressed Kapton H witness sample, N8 in MISSE 6A ram sample tray W2 was flown to determine the AO fluence of the ram surfaces of MISSE 6A.

Erosion Yield of Stressed Samples

The estimate of the erosion yield of the stressed polymers was based on the volume eroded per incident atom. This was done because the flux was variable over the curved surfaces and the area of exposure was not normal to the arriving flux direction. Thus

$$E_y = \frac{DM_s}{(r_s N)} \quad (3)$$

where

- N = Number of atoms arriving at the surface of the polymer

To determine the number, N , of atoms arriving at the cylindrical polymer surface, the flux was integrated over the surface using the nearly cosine distribution of arriving atoms. Thus,

$$N = 2 F_o W R \int_0^{\pi/2} f(\theta) d\theta \quad (4)$$

where

- F_o = Ram fluence, atoms/cm²
- W = Width of the exposed area of cylindrical shaped polymer (1.52 cm)
- R = Outside radius of the polymer cylinder (0.635 cm)
- $f(\theta)$ = Fluence per angle as a function of angle θ around the polymer cylinder, atoms/cm²
- θ = Angle from normal incidence, radians

The fluence angular dependence closely follows a cosine distribution until near grazing incidence where at normal incidence the fluence is 0.041 that of the ram fluence. The angular fluence dependence is reported by Silverman in reference (Ref. 10). Slight corrections amounting to less than 2% to the integration were also performed to correct for parts of the polymer cylinders that were covered up in the grazing incidence areas.

Dehydrated Mass Loss Measurements

Because many polymers are hygroscopic and can take on moisture, which can influence mass loss and hence erosion yield values, samples were vacuum dehydrated prior to being weighed. For both pre- and post-flight mass measurements, all samples were vacuum-dehydrated at 60-100 mtorr for a minimum of 72 hours and then weighed with a Mettler M3 Balance. Records were kept of time under vacuum, sequence of weighing, and room temperature and humidity. The same sequence and procedures used for the pre-flight measurements were repeated post-flight as well as possible.

Density Measurements

The densities of the samples were based on density column measurements of polymers for the MISSE 2 PEACE Polymers experiment (Refs. 3 to 5). The density gradient columns were created in 50-mL burets with solvents of either cesium chloride (CsCl) and water (H₂O), for less dense polymers, or carbon tetrachloride (CCl₄) and bromoform (CHBr₃), for more dense polymers. Glass standards of known densities were placed in the column and allowed to settle, and then small pieces of various polymers were placed in the columns. A curve was fit to the positions and densities of the glass standards. Plotting the positions of the test polymers on the curve yielded density values for each material. Where possible the same batch of material was used for MISSE 6 as it was for MISSE 2. Manufacturers' densities were used for Kapton XC and Kapton E, as they were not flown as part of the PEACE experiment.

Surface Area Measurements

The exposed surface area of the non-stressed samples were determined by taking three different width measurements and three different length measurements of each sample tray opening. The average width was multiplied by the average length to compute the area of the square opening. But, the trays have rounded corners with a 0.062 in. (0.15748 cm) radius. Therefore 0.02129 cm² (the area of the four rounded corners) was subtracted from each square area to get the actual sample area. The exposed surface area for the N8 Kapton fluence samples was determined based on obtaining 24 measurements of the sample openings (12 vertical and 12 horizontal).

Sample Stacking

The thin film samples were stacked so that the total thickness of each sample was the same. The thickness of the stressed materials ranged from 1 mil (0.00254 cm) to 20 mils (0.0508 cm) thick. Therefore, the total thickness was determined to be 20 mils for both the stressed and non-stressed sample pairs, as seen in Table 1. Having samples 20 mils thick ensured that all the

samples would survive a mission several years longer than planned, in case the experiment was not retrieved when planned. For weighing, the samples were divided into 2 different parts: Part A, which consisted of the top space exposed layer, and Part B, which was made up of all additional layers. Part A and Part B were weighed separately post-flight. This was done so that only Part A could be weighed post-flight, if only the top layer experienced erosion during flight. An illustration of sample layer stacking is provided in Figure 4.

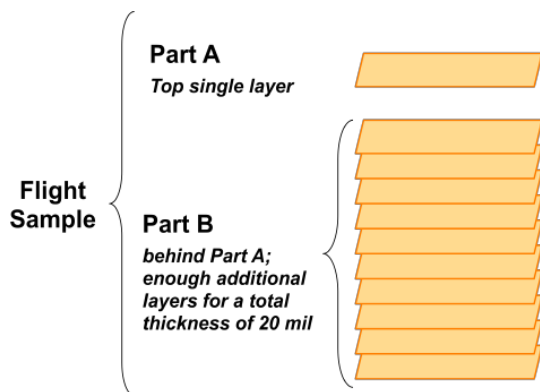


Figure 4. Illustration of the flight sample setup.

Stressed Sample Surface Strain

The strain, ϵ at the external surface of a polymer bent in a cylindrical shape is given by

$$\epsilon = \frac{t}{2R} \quad (5)$$

where:

t = The thickness of an individual sheet of the polymer, cm

R = The radius of curvature of the mid-thickness of the polymer, cm (~0.609 cm)

Thus, thick polymers had more surface strain than multiple layers of thin polymers. The strain at external surface of the stressed samples has been computed for each of the stressed samples and is reported in the MISSE 6 LEO Erosion Yields section along with the erosion yield values.

RESULTS AND DISCUSSION

Initial Inspection

Figures 5 and 6 provide pre-flight and post-flight photos of the W3 (stressed) and W2 (non-stressed) sample trays, respectively. As can be seen in Figure 2, the stressed sample tray (W3) was to the left of the non-stressed samples tray (W2). In the W3 tray, samples Upilex-S, CP1, Kapton E, PE, PBI and PMMA appeared to have multiple layers eroded through the top layer. Figure 7 provides an example of sample layer erosion. Typically, LEO ram erosion results in a change in surface appearance from shiny to matte, as shown in Figure 8. This surface change is due to the development of microscopic cones developed during directed ram exposure (Ref. 11).

In addition, substantial color changes occurred in Upilex-S, CP1, Kapton E, Kapton H, Mylar A, PMR-15, ADC and PMMA. For example, Mylar A changed from white to a dark yellow, and colorless samples ADC and PMMA turned white. Color changes can be due to thickness loss (i.e., erosion) and erosion texture, or solar radiation darkening. Likewise, in the W2 tray, color changes and erosion are observed in samples Upilex-S, CP1, Kapton E, Kapton H, Mylar A, PE and PEI. Yellowing of sample Mylar A is shown by comparing the flight and control samples in Figure 9 (see N9). A micrometeoroid or orbital debris impact occurred in one of the solar cell samples (N15) included in the W2 tray, shown in Figure 5. Upon close inspection of the samples, the majority of salt particles appear to have remained present on the samples, except where complete erosion of a surface layer has occurred. An example is provided in the pre- and post-flight photos of the Kapton CB sample in Figure 3(a) and Figure 3(b), respectively, and also in the optical micrograph of Kapton H in Figure 10.

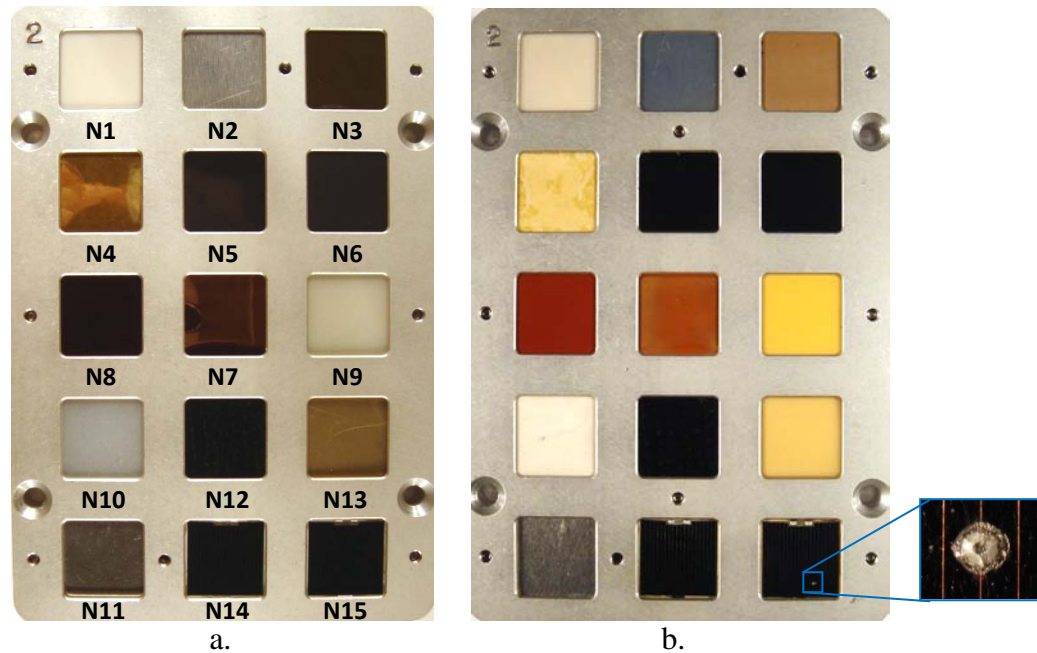


Figure 5. Non-stressed Tray (MISSE Tray W2): a). Pre-flight with sample IDs, and b). Post-flight with a close-up photo of an impact site.

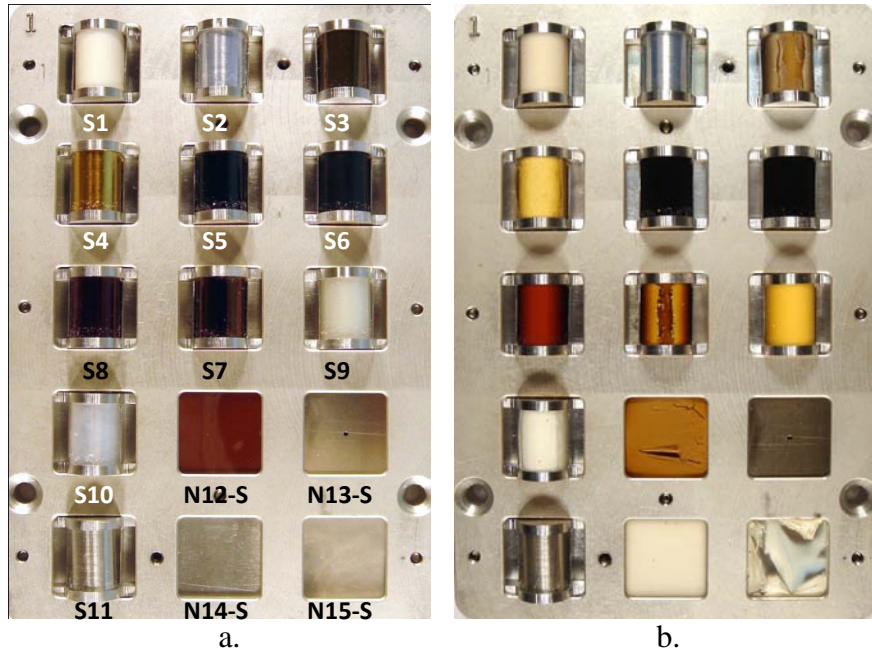


Figure 6. Stressed Tray (MISSE Tray W3): a). Pre-flight with sample IDs, and b). Post-flight.

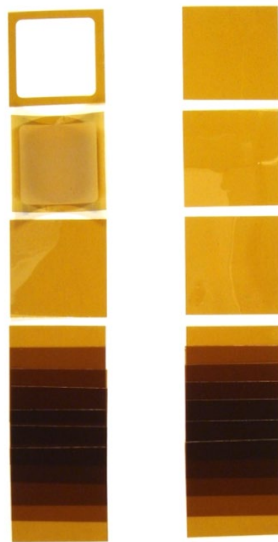


Figure 7. This photo of the flight (on left) and control (on right) samples of Upilex-S (N3) provides an example of erosion in individual layers of the stack flight samples.

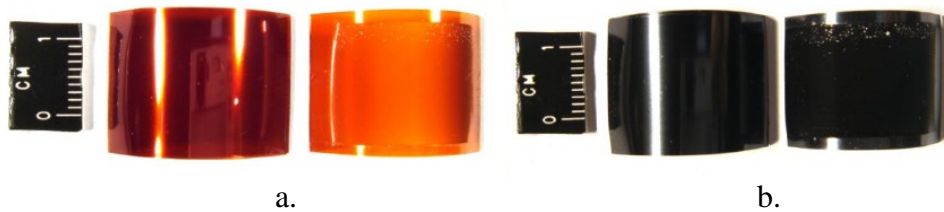


Figure 8. Flight (right) and control (left) samples showing matte erosion texture, as compared to the shiny control samples: a). Kapton H, and b). Kapton CB.

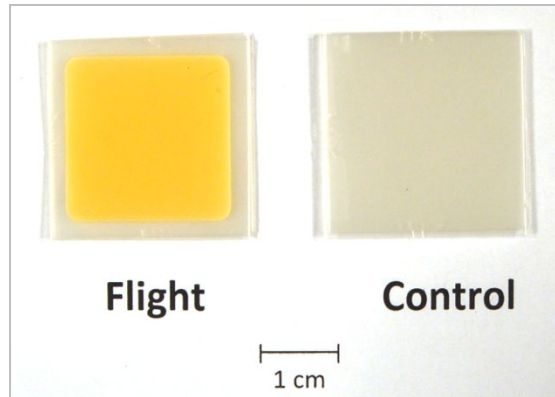


Figure 9. Flight and control samples of sample Mylar A (N9: 4 layers of 5 mil thick film).

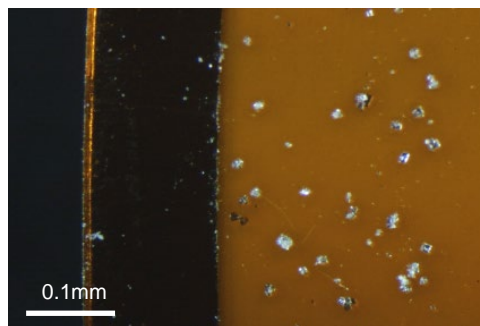


Figure 10. Optical microscope near the provided edge of Kapton H (S8) showing intact salt-particles post-flight.

MISSE 6A AO Fluence and Solar Exposure

The MISSE 6A ram AO fluence for the Stressed Polymers Experiment was computed based on the mass loss of the 1 in. (2.54 cm) square non-stressed Kapton H witness sample (N8). The data used to compute the AO fluence are provided in Table 2. This sample was positioned to be as close to the center of the two trays (W2 & W3) as possible, as seen in Figure 2. The Kapton H sample consisted of four 5 mil (0.0127 cm) thick layers for a total thickness of 20 mils (0.0508 cm). Erosion only occurred in the top layer (Part A), as shown in Figure 11, hence only pre-flight and post-flight mass of Part A was needed for fluence determination. Based on the W2 Kapton H analyses, the MISSE7B ram fluence and standard deviation was determined to be $1.97 \pm 0.05 \times 10^{21}$ atoms/cm².

Estimates of MISSE 6 solar exposures for the ram and wake surfaces were obtained using the Boeing Integrated ISS TRASYS model for solar exposure levels for the surface of the Columbus module near the location of MISSE 6. The solar exposure for the MISSE 6 ram surfaces was estimated at 2,600 equivalent sun hours (ESH) and the solar exposure for MISSE 6 wake surfaces was estimated at 1,950 ESH (Ref. 12). Because of the curved shape of the MISSE 6 stressed samples, the ESH was non-uniform across the sample surface, with the 2,600 ESH at the crown of the sample.

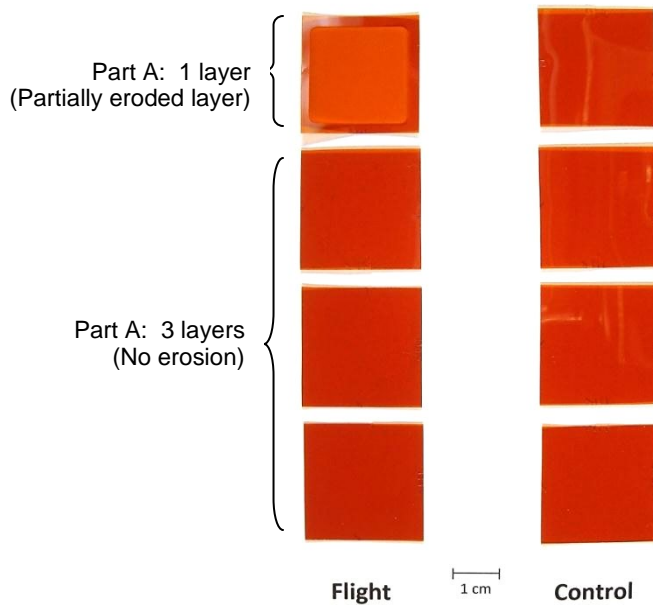


Figure 11. Post-flight photograph showing the individual sample layers of the of the Kapton H fluence witness sample (N8), along with the control sample.

Table 2. MISSE 6A Kapton H AO Fluence Data.

MISSE ID	Material	Thickness (mils) x Layers	Density (g/cm ³)	Mass Loss (g)	Surface Area (cm ²)	Kapton H LEO Ey (cm ³ /atom)	MISSE 6B Ram Fluence (atoms/cm ²)	Fluence Uncertainty, Std. Dev. (atoms/cm ²)
N8	Kapton H	5 mil x 4 layers	1.4273	0.036615	4.333	3.00E-24	1.97 E21	5.01 E19

MISSE 6 LEO Erosion Yields

Table 3 provides the LEO erosion yield data for the MISSE 6A stressed and non-stressed sample pairs from trays W3 and W2, respectively, along with the sample mass loss, strain at the external surface of the stressed samples, and the ratio of stressed to non-stressed Ey. The DC 93-500 sample was not analyzed for Ey as DC 93-500 does not erode with AO exposure but develops surface crazing (Ref. 13). Based on prior flight samples, it was expected that the Ey of the stressed samples would be greater than the non-stressed samples. As can be seen in the ratio of stressed to non-stressed Ey values in Table 3, seven of the materials (Upilex-S (S3/N3), Kapton CB (S5/N5), Kapton XC (S6/N6), Kapton E (S7/N7), Kapton H (S8/N8), Mylar A (S9/N9) and PE (S10/N10)) had ratios at or near 1.0. Three samples had stressed-to-unstressed Ey ratios beyond $\pm 10\%$ of each other, which is believed to be beyond the uncertainty of the data. Two materials, Teflon PTFE (S1/N1) and Teflon FEP (S2/N2), had stressed Ey values which were lower than the non-stressed Ey values with ratios of 0.76 and 0.83, respectively. As the stressed polymers had a lower average number of sun hours on them than the flat samples because of the variation of the angle to the sun on the stressed samples, having the stressed to non-stressed Ey ratios below 1.0 for fluoropolymers is consistent with findings that solar exposure has an impact on the Ey of fluorinated polymers. These results are confirmed in the Teflon FEP section below. The CP1 Sample (S4) was the only sample with a significantly higher stressed Ey than the non-stressed sample, with a stressed to non-stressed Ey ratio of 1.11.

Table 3. MISSE 6 Stressed Polymers Experiment Erosion Yield Results.

MISSE 6 GRC ID	Material	Non- Stressed Mass Loss (g)	Non- Stressed Ey (cm ³ /atom)	Stressed Mass loss (g)	Stressed Ey (cm ³ /atom)	Strain at External Surface*	Ratio of Stressed to Non- stressed Ey
N1 & S1	Teflon PTFE	0.002444	1.33E-25	0.000824	1.01E-25	0.0104	0.76
N2 & S2	Teflon FEP	0.003098	1.69E-25	0.001144	1.41E-25	0.0104	0.83
N3 & S3	Upilex-S	0.019478	1.65E-24	0.009011	1.71E-24	0.00208	1.04
N4 & S4	CP1	0.026214	2.16E-24	0.012964	2.41E-24	0.00208	1.11
N5 & S5	Kapton CB	0.032691	2.70E-24	0.013720	2.55E-24	0.0104	0.95
N6 & S6	Kapton XC	0.026427	2.20E-24	0.011550	2.16E-24	0.0104	0.98
N7 & S7	Kapton E	0.034299	2.83E-24	0.015315	2.84E-24	0.00417	1.00
N8 & S8	Kapton H	0.036615	3.00E-24	0.015563	2.88E-24	0.0104	0.96
N9 & S9	Mylar A	0.038276	3.22E-24	0.016061	3.04E-24	0.0104	0.94
N10 & S10	Polyethylene	0.031727	4.05E-24	0.014442	4.15E-24	0.00417	1.02

*Stressed samples surface strain

In general these results were surprising as only 1 sample indicated a higher Ey while being stressed on-orbit. And, the two fluoropolymer samples appear to have lower Ey values when stressed on-orbit. As indicated before, due to the cylindrical shape of the samples, the AO fluence is non-uniform across the surface, which complicates the analyses. Therefore, to verify these results, it would be beneficial to determine the Ey of the samples based on recession depth analyses at salt-protected areas, particularly at normal incidence where the ram fluence is known based on analyses of the non-stressed Kapton H sample (N8). It would also be of interest to simplify the geometry of the samples being exposed to AO and fly flat samples that are under tensile loading on-orbit. An experiment with flat tensile loaded samples has been proposed for flight as part of the Polymers and Composites Experiment being flown as part of the Materials International Space Station Experiment-X (MISSE-X) (Refs. 14 and 15).

An AO pinhole camera consisting of a metal orifice plate spaced away from a Kapton H film was used to provide a qualitative history of arrival AO fluence for MISSE 6 ram AO. The results indicate that, for a portion of the AO exposure, the fluence was arriving at an angle of approximately 12.8° off normal. Because the duration of time the off-normal flux was arriving is not known, the fluence computation for the stressed samples could be lower than predicted by the flat Kapton H witness samples by up to 2.5%. This would be a result of 12.8° inclined incidence of AO on the half-cylinder shaped samples. The possible consequence of this is that the erosion yields for the stressed polymers could be up to 2.5% greater than the values calculated in Table 3.

Table 4 provides the LEO erosion yield data for the additional MISSE 6A non-stressed samples flown in trays W3 and W2, along with the sample thickness, number of layers flown, density, mass loss and surface area.

Table 4. Erosion Yields for Additional Non-Stressed Samples

MISSE ID	Material	Thickness (mils)	Layers Flown	Density (g/cm ³)	Mass Loss (g)	Surface Area (cm ²)	MISSE 6 Ey (cm ³ /atom)
N11	DC 93-500 Silicone on Fused Silica	20	1	n/a	n/a	4.331	n/a
N12	PMR-15*	36	1	1.323	0.030245	4.335	2.68E-24
N13	Polyetherimide (PEI)	10	2	1.287	0.037049	4.330	3.37E-24
N12-S	Polybenzimidazole (PBI)	4	5	1.276	0.049523	4.334	4.55E-24
N14-S	Allyl diglycol carbonate (ADC)	47	1	1.317	0.093057	4.330	8.28E-24
N15-S	Polymethyl methacrylate (PMMA)	2	10	1.163	0.052134	4.314	5.28E-24
W6-5	Kapton H	5	1	1.4273	0.035514	4.364	3.00E-24
W6-10	Kapton H (no spacers)	0.5	10	1.4273	0.036512	4.371	3.08E-24
W6-9	Kapton H (with spacers)	0.5	10	1.4273	0.038498	4.368	3.25E-24

*PMR-15 had residue on the surface

MISSE 6B AO Fluence and Stacked Kapton H Samples

The MISSE 6B ram AO fluence for the W6 tray was computed based on the mass loss of the 1 in. (2.54 cm) square non-stressed Kapton H witness sample (W6-5). The data used to compute the AO fluence are provided in Table 5. The Kapton H sample consisted of three 5 mil (0.0127 cm) thick layers for a total thickness of 15 mils (0.0381 cm). Erosion only occurred in the top layer (Part A), hence only pre-flight and post-flight mass of Part A was needed for fluence determination. Based on the W2 Kapton H analyses, the MISSE 6B ram fluence was determined to be $1.90 \pm 0.05 \times 10^{21}$ atoms/cm².

Table 5. MISSE 6B Kapton H AO Fluence Data.

MISSE ID	Material	Thickness (mils) x Layers	Density (g/cm ³)	Mass Loss (g)	Surface Area (cm ²)	Kapton H LEO Ey (cm ³ /atom)	MISSE 6B Ram Fluence (atoms/cm ²)	Fluence Uncertainty, Std. Dev. (atoms/cm ²)
W6-5	Kapton H	5 mil x 3 layers	1.4273	0.035514	4.364	3.00E-24	1.90 E21	4.81 E19

Images of the stacked gossamer thin Kapton H samples flown in the W6 tray are shown in Figure 12. The Kapton H sample without the spacers between the 10–0.5 mil thick layers (W6-10) was found to have an Ey of 3.08×10^{-24} cm³/atom. Although error analyses were not conducted to determine the error in the Ey values, the data analyses were similar to those used for Ey determination of the MISSE 2 PEACE Polymers experiment, and the error for the Kapton H samples for that experiment were 0.0741×10^{-24} cm³/atom (Ref. 16). Thus based on these error values, the MISSE 6 0.5 mil thick layered Kapton H sample had a barely significant increase in Ey as compared to the 5 mil layered Kapton H fluence witness sample. The Kapton H sample with the 0.014 in. (0.0356 cm) thick Al spacers between the 10–0.5 mil layers was found to have an Ey of 3.25×10^{-24} cm³/atom, which is a significant increase in Ey. As can be seen in Figure 12, AO completely eroded the top four layers and has partially eroded the fifth layer, but

the sample with the spacers has resulted in more erosion to the fifth layer, than the sample without the spacers. This is believed to be attributed to trapping and scattering of AO between the layers in the gap between the layers. The degradation of the individual layers shown in Figure 12 also show how a chamfered tray opening, as used for the W tray, can concentrate the AO, and thus cause higher erosion at the perimeter of the samples.

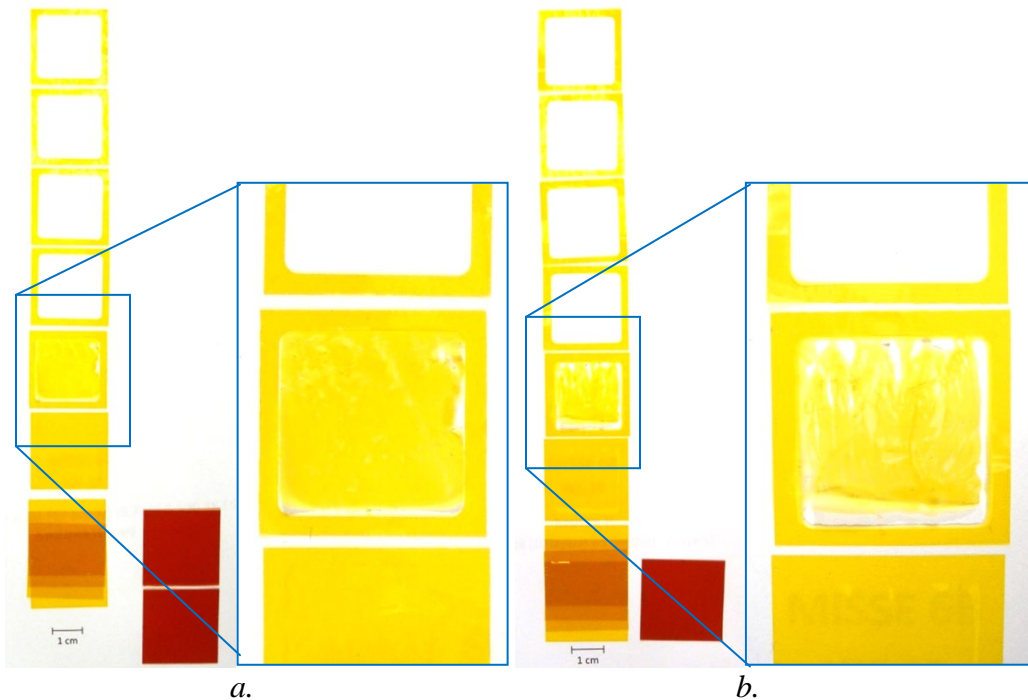


Figure 12. Post-flight photos of stacked Kapton HN samples, showing individual samples layers, a). Kapton H (10 – 0.5 mil layers + 2 – 5 mil layers) with no spacers ($E_y = 3.08 E-24 \text{ cm}^3/\text{atom}$) and b). Kapton H (10 – 0.5 mil layers + 1 – 5 mil layer) with 0.014 in. thick Al spacers ($E_y = 3.25 E-24 \text{ cm}^3/\text{atom}$).

Erosion Yield vs. LEO Fluence

A comparison of the E_y values of the MISSE 6 non-stressed erosion yields and the same material flown as part of the MISSE 2 PEACE Polymer experiment are provided in Table 6. The MISSE 2 PEACE experiment was exposed to ram AO on MISSE PEC 2 for nearly 4 years and received an AO fluence of 8.43×10^{21} atoms/cm² and solar exposure of 6,300 ESH (Refs. 3 to 5). The ratio of MISSE 2 to MISSE 6 E_y values are provided in Table 6. As stated previously, six of the MISSE 2 samples were excessively eroded and hence their E_y value is greater than the value computed for the MISSE 2 flight experiment.

Table 6. Comparison of the Ey of Polymers Flown on MISSE 2 and MISSE 6.

MISSE 6A Sample ID	Material	MISSE 6A Ey (cm ³ /atom)	MISSE 2 Ey (cm ³ /atom) [de Groh 2008]	Ratio of MISSE 2 to MISSE 6 Ey
Exposure (Yrs)		1.45	3.95	2.72
Fluence (atoms/cm²)		1.97 E21	8.43 E21	4.28
Solar Exposure (ESH)		2,600	6,300	2.42
N1	Polytetrafluoroethylene (PTFE)	1.33E-25	1.42E-25	1.07
N2	Fluorinated ethylene propylene (FEP)	1.69E-25	2.00E-25	1.18
N3	Upilex-S	1.65E-24	9.22E-25	0.56
N4	CP1	2.16E-24	1.91E-24	0.88
N5	Kapton CB	2.70E-24	N/A	-
N6	Kapton XC	2.20E-24	N/A	-
N7	Kapton E	2.83E-24	N/A	-
N9	Polyethylene terephthalate (PET)	3.22E-24	3.01E-24	0.93
N10	Polyethylene (PE)	4.05E-24	>3.74E-24	>0.92
N11	PMR-15	2.68E-24	>3.02E-24	>1.13
N13	Polyetherimide (PEI)	3.37E-24	>3.31E-24	>0.98
N12-S	Polybenzimidazole (PBI)	4.55E-24	>2.21E-24	>0.49
N14-S	Allyl diglycol carbonate (ADC)	8.28E-24	>6.80E-24	>0.82
N15-S	Polymethyl methacrylate (PMMA)	5.28E-24	>5.60E-24	>1.06

As can be seen in Table 6, the Ey of many polymers (Upilex-S, CP1, PET and possibly PE, PBI and ADC) decreases with increasing AO fluence and ESH exposure. This is believed to be due to AO protective inorganic ash from the bulk of the polymers building up on the surface, as those particles do not erode away, and can then provide some protection to the material below (Ref. 17). The samples that did not follow this trend included: PMMA, PMR-15, and the two fluoropolymers, FEP and PTFE. Note that PBI was completely eroded away on MISSE 2, and hence the MISSE 2 Ey was very low.

The MISSE 6 PMR-15 sample was found to have white residue on the surface, as shown in Figure 13, which might have protected it during flight affecting the Ey. The MISSE 2 sample did not have any residue and only had a very small area of through-thickness erosion; hence the MISSE 2 Ey is believed to be fairly accurate. Both of the MISSE 2 and MISSE 6 PMMA samples had small gossamer pieces that were lost during post-flight handling as shown in Figure 14. Also, the MISSE 2 sample was completely eroded through all layers in the center of the sample. Thus, it is not known which Ey may be more accurate. It is desired to re-fly these materials on a future MISSE experiment.

The probable reason that the ratios of MISSE 2 to MISSE 6 Ey for PTFE and FEP were greater than 1 is that the solar exposure (ESH) appears to dominate and overwhelm any protection due to ash content for fluoropolymers. This is supported by the ESH dependence discussed in the Teflon FEP section below.

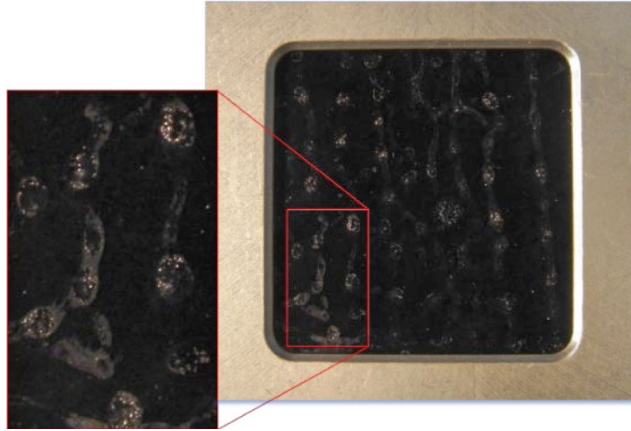


Figure 13. Post-flight image of the MISSE 6 PMR-15 sample showing white residue on the surface.

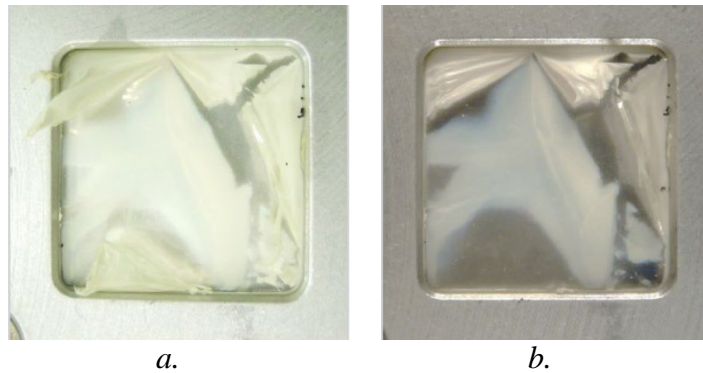


Figure 14. Post-flight images of the MISSE 6 PMMA showing loss of gossamer pieces during handling: a). Photo at LaRC after initial inspection, and b). Photo at GRC during sample analyses.

Table 7 provides Ey values for Upilex-S and CP1 from MISSE 2, 3, 4 and 6 missions. The data are plotted in the graph in Figure 15. As can be seen in the graph, the Ey of these samples decreases with increasing fluence.

Table 7. Comparison of the Ey of Polymers Flown on MISSE 2 and MISSE 6.

	Atomic Oxygen Erosion Yield, Ey (cm ³ /atom)				
	MISSE 3 E21	MISSE 4 E22	MISSE 6A W2	MISSE 2 E6	MISSE 2 E5
	Wake	Ram	Ram	Ram	Ram
AO Fluence (atoms/cm ²)	2.04E+21	2.15E+21	1.97E+21	8.51E+21	8.43E+21
Solar Exposure (ESH)	650-790 (720)	1200-1600 (1400)	2600	6000	6300
Ey for Upilex-S	2.61E-24	1.71E-24	1.65E-24	9.76E-25	9.22E-25
Ey for CP1	2.71E-24	2.26E-24	2.16E-24	1.91E-24	1.91E-24
Reference	18	18	-	19	5

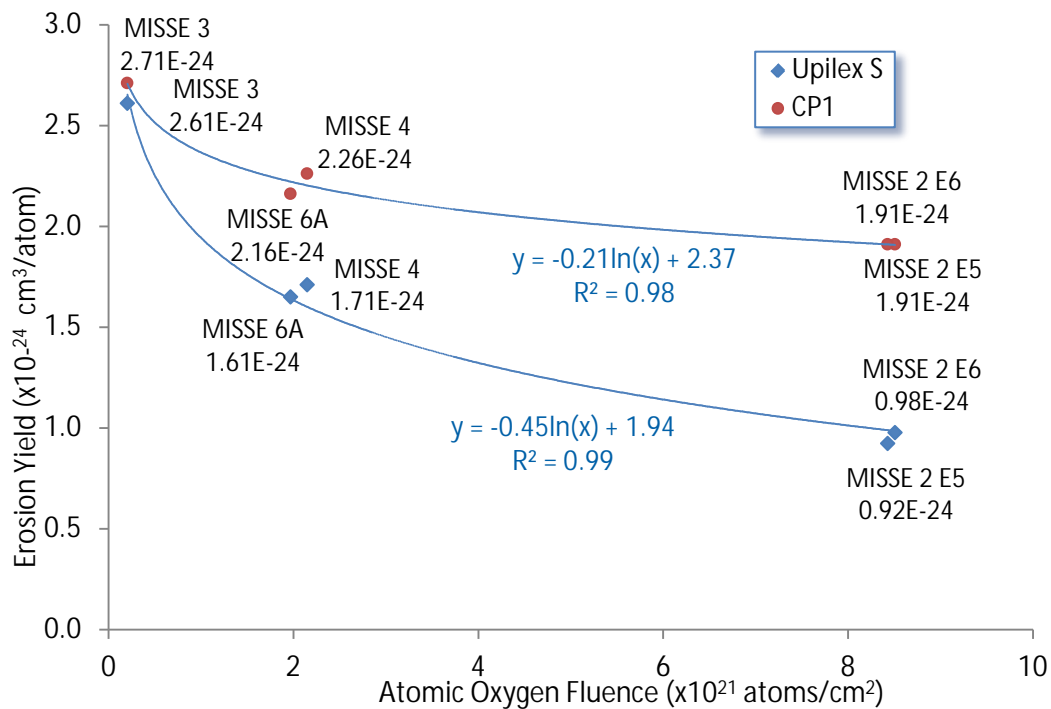


Figure 15. Erosion yield versus AO fluence for Upilex-s and CP1 samples flown on MISSE 2, 3, 4 and 6.

Teflon FEP

The Ey values of Teflon FEP from various missions including MISSE 2, MISSE 4, MISSE 6, the Long Duration Exposure Facility (LDEF) and space exposed multilayer insulation retrieved from the Hubble Space Telescope (HST) during the second servicing mission (SM2) are provided in Table 8, along with the space exposure duration, solar exposure, AO fluence and AO exposure arrival. These Ey values were plotted in numerous ways including: Ey vs. AO fluence, Ey vs. time, Ey vs. ESH and Ey vs. ESH/AO ratio. The best fit was found for Ey versus ESH, and the corresponding graph is shown in Figure 16. It should be noted that although the best fit was found for Ey vs. ESH, it is likely that temperature plays a critical role in the erosion process.

Table 8. Teflon FEP from various MISSE missions, LDEF and HST.

Material	Mission	Duration (Yrs)	Solar Exposure (ESH)	AO F (atom/cm ²)	AO Exposure	Ey (cm ³ /atom)	Reference
5 mil Ag-FEP	MISSE 4	1.04	1400	2.15E+21	Ram	1.28E-25	18
5 mil FEP	MISSE 6A	1.45	2600	1.97E+21	Ram	1.69E-25	-
5 mil Al-FEP	MISSE 2 E6	3.95	6100	8.51E+21	Ram	2.11E-25	18
5 mil FEP	MISSE 2 E5	3.95	6300	8.43E+21	Ram	2.00E-25	5
5 mil Ag-FEP	LDEF Ag-FEP	5.8	11155	8.99E+21	Ram	3.37E-25	20
5 mil Al-FEP	HST SM2	6.8	33638	3.20E+20	Sweeping AO	3.10E-24	19

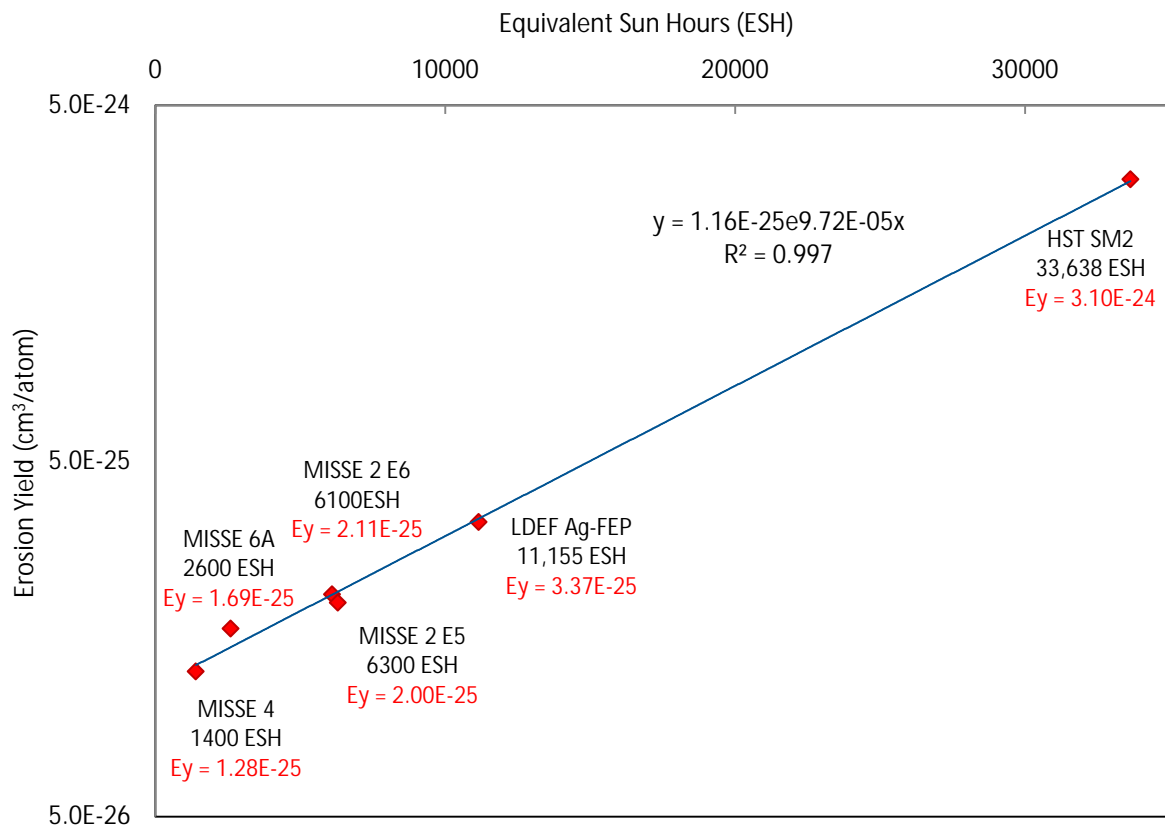


Figure 16. Erosion yield versus ESH for Teflon FEP flown on MISSE 2, 4, 6, LDEF and HST.

SUMMARY AND CONCLUSIONS

The MISSE 6A Stressed Polymers Experiment was successfully flown on the exterior of the ISS and exposed to the ram AO space environment for 1.45 years. Atomic oxygen Ey values have been determined for 10 stressed samples and 17 non-stressed samples based on dehydrated mass loss measurements. The AO fluence of the MISSE 6A tray was determined to be $1.97 \pm 0.05 \times 10^{21}$ atoms/cm² and the AO fluence of the MISSE 6B tray was determined to be $1.90 \pm 0.05 \times 10^{21}$ atoms/cm², based on Kapton H witness samples. The Ey values were found to range between 1.01×10^{-25} cm³/atom for stressed PTFE to 8.28×10^{-24} cm³/atom for ADC.

Samples of thick (5 mil) and thin (0.5 mil) stacked Kapton H layers were found to produce interesting results. The Kapton H sample with 0.5 mil thick layers (W6-10, no spacers) was found to have an Ey of 3.08×10^{-24} cm³/atom, which is slightly larger than that for the 5 mil thick Kapton H fluence witness sample, indicating that polymers with multiple thin layers have a higher Ey than for the same material flown as a thicker layer. The Kapton H sample with spacers between the 0.5 mil layers was found to have an Ey of 3.25×10^{-24} cm³/atom, which is significantly greater than the Ey for the same material with the layers stacked tightly together. This is believed to be attributed to trapping and scattering of AO between the gaps.

Surprisingly, the stressed to non-stressed erosion ratios of seven polymers were found to be near 1.0. The two fluoropolymers, Teflon PTFE (S1/N1) and Teflon FEP (S2/N2), had stressed Ey values which were lower than the non-stressed Ey values with ratios of 0.76 and 0.83, respectively. This is attributed to the lower total solar exposure for the stressed configuration. The CP1 Sample (S4) was the only sample with a significantly higher stressed Ey than the non-stressed sample, with a stressed to non-stressed Ey ratio of 1.11. An AO pinhole camera indicated that, for a portion of the AO exposure, the fluence was arriving at an angle of approximately 12.8° off normal. The possible consequence of this is that the Ey values for the stressed polymers could be up to 2.5% greater than the values reported. Desired future work includes obtaining Ey values for the stressed samples using recession depth measurements at salt locations. It would also be of interest to simplify the geometry of the samples being exposed to AO by flying flat samples that are under tensile loading on-orbit. An experiment with flat tensile loaded samples has been proposed for flight as part of the Polymers and Composites Experiment being flown as part of MISSE-X.

The MISSE 6 Ey values were compared to Ey values for similar materials flown on MISSE 2 with higher AO fluence and ESH exposure. The Ey for most samples (except the fluoropolymers (FEP and PTFE), PMR-15, PMMA, and PEI) were found to decrease with increasing AO fluence and ESH exposure. Ey for PMR-15 and PMMA were found to have been compromised. The Ey of Teflon FEP flown on various MISSE missions (2, 4 and 6), LDEF and HST were plotted in numerous ways including: Ey vs. against AO fluence, time on-orbit, ESH and ESH/AO ratio, and the best fit was found for Ey versus ESH. Increased Ey values of fluoropolymers for various missions are believed to be attributed to some combination of greater sun hours, temperature and possibly x-rays, not AO fluence.

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14. ABSTRACT Polymers and other oxidizable materials used on the exterior of spacecraft in the low Earth orbit (LEO) space environment can be eroded away by reaction with atomic oxygen (AO). For spacecraft design, it is important to know the LEO AO erosion yield, E_y (volume loss per incident oxygen atom), of materials susceptible to AO erosion. The Stressed Polymers Experiment was developed and flown as part of the Materials International Space Station Experiment 6 (MISSE 6) to compare the AO erosion yields of stressed and non-stressed polymers to determine if erosion is dependent upon stress while in LEO. The experiment contained 36 thin film polymer samples that were exposed to ram AO for 1.45 years. This paper provides an overview of the Stressed Polymers Experiment with details on the polymers flown, the characterization techniques used, the AO fluence, and the erosion yield results. The MISSE 6 data are compared to data for similar samples flown on previous MISSE missions to determine fluence or solar radiation effects on erosion yield.					
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