ABSTRACT

Forty-one different polymer samples, collectively called the Polymer Erosion and Contamination Experiment (PEACE) Polymers, were exposed to the low Earth orbit (LEO) environment on the exterior of the International Space Station (ISS) for nearly four years as part of the Materials International Space Station Experiment 2 (MISSE 2). The objective of the PEACE Polymers experiment was to determine the atomic oxygen erosion yield of a wide variety of polymeric materials after long term exposure to the space environment. The polymers range from those commonly used for spacecraft applications to more recently developed polymers. Additional polymers, not considered for spacecraft applications, were included to explore erosion yield dependence upon chemical composition. The polymers were typically in thin-film form (25 to 500 µm thick) and depending on the polymer thickness and estimated erosion yield, stacking of numerous thin film sample layers was often necessary. Several thick single layer materials, such as epoxy and pyrolytic graphite, were also included. The PEACE Polymers experiment was flown in MISSE Passive Experiment Container 2 (PEC 2) on the exterior of the ISS Quest Airlock and was exposed to ram atomic oxygen, along with solar and charged particle radiation, for the majority of the mission; hence the polymers typically developed very diffuse textures. The average atomic oxygen fluence was \(8.43 \times 10^{21} \text{ atoms/cm}^2\). This paper documents the erosion morphology of numerous MISSE 2 PEACE polymer samples. Erosion cone structures were examined for high and low erosion yield samples. Also examined were the erosion characteristics for thin film polymers eroded through several layers. Of particular interest was documentation of the erosion of a thin film polymer outer layer at cone valleys, and the corresponding erosion morphology of the underlying layer. This information is relevant to the durability of materials and components on spacecraft that are protected by thin film polymers. The MISSE 2 PEACE Polymers experiment is unique because it has the widest variety of polymers flown collectively in LEO for a long duration and was exposed to an unusually clean LEO spacecraft environment. This paper provides high fluence ram atomic oxygen erosion morphology data applicable to spacecraft durability.

Key Words: Atomic oxygen, erosion yield, erosion morphology, environmental degradation, space experiment, International Space Station, low Earth orbit

1. INTRODUCTION

Forty-one different polymer samples, collectively called the Polymer Erosion and Contamination Experiment (PEACE) Polymers, were exposed to the low Earth orbit (LEO) environment on the exterior of the International Space Station (ISS) for nearly four years as part of the Materials International Space Station Experiment 2 (MISSE 2).[1,2] The objective of the MISSE 2 PEACE Polymers experiment was to determine the atomic oxygen erosion yield, or volume loss per incident oxygen atom (cm\(^3\)/atom), of a wide variety of polymeric materials after long term exposure to the space environment. The polymers range from those commonly used for spacecraft applications to more recently developed polymers. Additional polymers, not considered for spacecraft applications, were also included to explore erosion yield dependence upon chemical composition for atomic oxygen erosion predictive tool development. The polymers were typically in thin film form (25 to 500 µm thick) and depending on the polymer thickness and estimated erosion yield, stacking of numerous thin film sample layers was often necessary.[1,2] Several thick single layer materials, such pyrolytic graphite, were also included.
The MISSE 2 PEACE Polymers experiment was exposed to ram atomic oxygen, along with solar and charged particle radiation, for the majority of the four year mission. Extensive erosion occurred in many of the samples, and the majority of the samples developed diffuse textures. This paper documents the erosion morphology of numerous MISSE 2 PEACE polymer samples. Erosion cone structures were examined for both high and low erosion yield samples. Also examined were the erosion characteristics for thin film polymers eroded through several layers. Of particular interest was documentation of the erosion of a thin film polymer outer layer at cone valleys, and the corresponding erosion morphology of the underlying layer. This information is relevant to the durability of materials and components on spacecraft that are protected by thin film polymers. Energy dispersive spectroscopy (EDS) was used to look for the presence of any surface contaminants, particularly on low erosion yield samples, and to examine the composition of non-volatile ash residue. The erosion yield of numerous samples was computed based on recession depth measurements and compared to the values obtained using mass loss. This paper provides high fluence ram atomic oxygen erosion morphology data applicable to spacecraft durability.

2. MATERIALS INTERNATIONAL SPACE STATION EXPERIMENT 2 (MISSE 2)

The MISSE program consists of suitcase-like trays, called Passive Experiment Containers (PECs), exposed to the space environment on the exterior of the International Space Station (ISS). The MISSE trays are retrieved and returned to Earth enabling post-flight experiment evaluation. The trays are positioned in either a ram/wake orientation or in a zenith/nadir orientation. The MISSE 2 PEACE Polymers experiment is a passive experiment that was flown in MISSE PEC 2, tray 1 (ram side), sample tray E5. MISSE 1 & 2 were transported to the ISS, and MISSE 2 was attached to the exterior of the Quest Airlock on August 16, 2001 during the Discovery STS-105 shuttle mission. Figure 1 is a photograph of the Quest Airlock showing the location of MISSE PEC 2. Although originally planned as a 1-year mission, retrieval of MISSE 1 & 2 was significantly delayed due to the Columbia Shuttle accident. MISSE 1 & 2 were successfully retrieved during a space walk on July 30, 2005 during Discovery’s STS-114 Return to Flight mission after 3.95 years of space exposure. While on-orbit, MISSE PEC 2 tray 1 was exposed to ram atomic oxygen, along with solar and charged particle radiation, for the majority of the four year mission. Details on the specific polymers flown, flight sample fabrication, pre- and post-flight characterization techniques, atomic oxygen fluence calculations, and a summary of the atomic oxygen erosion yield results based on mass loss measurements are reported by de Groh. [1,2]
luminescent dosimeters (TLDs) with thin shielding layers are most relevant to estimates of doses for the PEACE Polymer experiment thin polymer films. The TLD data indicated receiving approximately 26 krads(Si) through 0.005 cm aluminum for MISSE 2.[3] The average atomic oxygen fluence for the MISSE 2 PEACE Polymers experiment was determined to be 8.43 x 10^{21} atoms/cm², based on two Kapton H witness samples flown as part of the experiment.[1,2]

Black light inspection of the trays showed minimal to no contamination on the MISSE surfaces.[3] Results of x-ray photoelectron spectroscopy (XPS) contamination analysis of two MISSE 2 sapphire witness samples in tray E6 (located next to tray E5) indicated an extremely thin silica contaminant layer (1.3 and 1.4 nm on each slide, respectively).[4] A small amount of fluorine was also detected.[4] The MISSE 2 environment was found to be an unusually clean environment with very low spacecraft induced molecular contamination. This is due to low outgassing of other MISSE 2 tray 1 materials and also due to the position of MISSE 2 on ISS.

3. MISSE 2 PEACE POLYMERS EXPERIMENT

The MISSE 2 PEACE Polymers resided in sample tray E5, which holds a total of 46 1"-diameter flight samples. The PEACE Polymer samples start in the top row, 6th sample position from the left (i.e. ABS, with serial number 2-E5-6, represents a sample in MISSE PEC 2, tray E5, sample position 6). Five other samples (four DC 93-500 silicone samples and one AO scattering chamber) were also on this tray, in positions 2-E5-1 through 2-E5-5. Sample positions were chosen based on their anticipated erosion yields or by grouping samples by polymer family (such as polyimides). High erosion yield samples were located next to the silicone samples as the high erosion yield samples are less likely to be affected by silicone cross-contamination. Depending on the polymer thickness and estimated erosion yields for each polymer, stacking of several sample layers was often necessary. The total number of layers stacked for flight was decided based on the thickness needed to survive a 3-year mission (3 times the duration of the original planned mission).[1,2] Figure 2 shows pre-flight and post-flight photos of the MISSE 2 PEACE Polymers experiment.

Fig 2. MISSE 2 PEACE Polymers experiment in tray E5: a). Pre-flight photograph, and b). Post-flight photograph.

4. OPTICAL AND ELECTRON MICROSCOPY

An Olympus SZH stereo-zoom microscope operated with a Canon EOS D30 digital camera was used to document various features at magnifications on the order of 10 to 100×. Scanning electron microscope images were obtained using Hitachi S-4700 field emission scanning electron microscopes (FESEM) operated at an accelerating voltage from 2-15 kV, but typically at 6 kV. Energy dispersive spectroscopy (EDS) was conducted using either EDAX CDU Leap Detector or IXRF Detector systems. All samples, except pyrolytic graphite, were sputter-coated with thin gold-palladium (Au-Pd) films to make them conductive for imaging.
5. RESULTS & DISCUSSION

The MISSE 2 PEACE flight samples that were analyzed included: polyimide Kapton H (2-E5-30) flown as an atomic oxygen fluence witness sample, polyvinyl fluoride (PVF) also known as clear Tedlar (2-E5-10), crystalline PVF w/white pigment also known as white Tedlar (2-E5-11), pyrolytic graphite (PG) (2-E5-25), chlorotrifluoroethylene (CTFE) also known as Kel-F (2-E5-39), fluorinated ethylene propylene (FEP) also known as Teflon FEP (2-E5-42), polytetrafluoroethylene (PTFE) also known as Teflon PTFE (2-E5-43), and perfluoroalkoxy copolymer resin (PFA) also known as Teflon PFA (2-E5-44). In addition, aluminized-Teflon FEP (Al-FEP) from MISSE 2 sample tray E6, flown adjacent to E5, was also examined. Results for the individual samples are provided below.

5.1 Polyimide Kapton H

One of two Kapton H witness samples that was flown consisted of a stack of three layers of Kapton H films each being 5 mil (127 µm) thick. Post-flight inspection found: the top layer to be completely eroded away (leaving a ring in the protected experiment tray holder area); the second layer was very diffuse, gossamer thin, and eroded at an edge; and, the third layer was textured. Figure 3 includes a post-flight photograph of the flight sample individual layers, next to a control sample. Also included in the figure is a photo of the sample in tray E5 and information about sectioning of the sample for FESEM imaging.

The fact that the second layer was still intact, and yet the third layer appeared to be textured was interesting, and indicates that for thin film polymers the underlying layers may be susceptible to atomic oxygen erosion even when there is a layer above it. Because directed ram atomic oxygen erosion typically causes cone morphologies to develop in materials with gaseous oxidation products, it was hypothesized that the second layer had holes at “cone valleys” and that the third layer was exposed to atomic oxygen arrival at the locations of the holes in the layer above (in this case, the second layer).[5] A visual example of this is shown in the diagram in Figure 4.[5]
To determine if this was true, samples were sectioned from the second and third layers and examined with FESEM. Three samples were examined, as shown in Figure 3: a section of the second layer mounted with the space-exposed surface up (to examine the cone texture), a section of second layer mounted with the backside up (to look for holes at cone valleys), and a section of the third layer mounted with the space-exposed surface up (to examine the texture that developed “below the hole”).

FESEM imaging revealed that the diffuse, space-exposed, second layer of Kapton H contained well developed cone structures, as had been expected. Examples are provided for low (200 X) and higher (1kX) magnification in Figure 5. A couple other observations were made; the first was that when examined at low magnification, the surface had an overall waviness to it, as shown in Figure 5a. This will be discussed below. The second observation was that the tops of the cones contained a substantial amount of fine debris, or ash, as shown in Figure 5b. Backscattered electron (BSE) images, which show higher density elements to be brighter than lower density elements, were obtained. An example of a BSE image is provided in Figure 6, where the sample was imaged at a 0° tilt angle. In this image higher density elements are present on the tips of the cones. This high density ash protects the Kapton H from erosion, and it is believed that the ash content plays a significant role in the erosion morphology development.

Fig 4. Schematic diagram showing atomic oxygen texturing occurring in two layers of a flight stack of polymer samples. [5]

Fig 5. FESEM images showing the erosion morphology of the space-facing side of the second layer of Kapton H with well developed cone structures: a). Low magnification image (200X, 45° tilt), and b). Higher magnification image (1kX, 45° tilt).

Fig 6. Backscattered electron image of the space-facing second layer of Kapton H showing high density elements on the cone tips (1kX, 0° tilt).
The delicate looking cone tip debris was analyzed with EDS at an accelerating voltage of 15 kV to determine the composition of the protective ash. The results are provided in Figures 7. Figure 7a is the spectrum obtained at the top of a cone shown in the BSE image in 7b (location EDS-B), where the protective ash is not present; hence it is the composition of the cone itself. The composition is primarily C and O, as expected for Kapton H polyimide, and the conductive film elements are also present. Figure 7b is the spectrum obtained with the beam concentrated on ash, at location EDS-C. In addition to C, O, Au and Pd the ash is composed of Si and Zn, and possibly very small amounts of Fe and Cu. Figure 7c provides a close-up BSE image of the ash on top of a cone. The corresponding spectrum is for the bright spot identified as EDS-D. This bright particle within the ash has strong Zn and Si peaks, along with Al peaks.

Images of the back-side of the second layer of the Kapton H flight sample are shown in Figures 8 and 9. As predicted, holes were present in the Kapton H layer at cone valleys. These holes are easily seen in all the images. The holes appear to be circular in shape, but become irregularly shaped when several holes are joined. This can be seen in Figure 8b. When the density of the holes becomes high enough, the holes eventually join together and can form “free” regions of cones, producing tiny cone clusters. One of these isolated cone clusters is shown in Figure 8c where it is lifting out of the back-surface plane and the cones are visible. It should be noted that this Kapton H layer was very fragile, and hence it is very likely that this cone section separated during handling and sample mounting. The images shown in Figure 8a and 8b are from the center of the sample. Images were obtained near the protected edge where the sample tray held the sample in place, to see if the density of holes was greater than in the center of the sample. Figure 8d is an image taken near the edge. It was taken at the same magnification (1kX) as the image in Figure 8a. It clearly shows that there is a higher density of holes, and hence greater erosion, at the protected edge than in the center of the sample. This may be due to a higher concentration of atomic oxygen at the edge due to
focusing by the sample holder. Greater erosion at the sample edge of the MISSE 2 PEACE Polymer samples was observed visually, and measured with profilometry as reported in [5]. A loose cone range is also visible in Figure 8b. Figure 9 illustrates more clearly that the holes are at the base of the erosion cones.

Fig 8. Images of the back surface of the second Kapton H layer: a). Image obtained from the center of the sample (1kX, 45° tilt), b). Image from the center of the sample at higher magnification showing connecting holes (5kX, 45° tilt), c). An isolated cone clusters that has lifted out of the back-surface plane, and the cones are visible (1.5kX, 45° tilt), and d). Image taken near the protected edge showing a higher hole density than the image in 8a (1kX, 45° tilt).

Fig 9. Images of cone morphologies observed from the back surface of the second Kapton H layer: a). An isolated cone cluster (1kX, 45° tilt), and b). A crack in the film where the cone structure is visible (1kX, 45° tilt).

Images of the space-exposed third layer of Kapton H are shown in Figure 10. As can be seen, erosion has occurred in this layer of Kapton, even though it was below a seemingly intact layer. The erosion appears as shallow rounded valleys. The rounding of the valleys is probably due to the fact that the Kapton H layers had some gap between them, which allows the divergence and scattering of incoming atomic oxygen to produce less well defined erosion. Upon closer examination, very fine erosion texture can be seen along the walls of the shallow valleys, as shown in Figure 10b. If one compares the density of the valleys in Figure 10b with the density of holes in Figure 8a for the second layer, it is apparent the hole density in layer two and the erosion valleys in layer three are similar. Verifying that erosion has occurred in the third layer of Kapton H, below a seemingly intact second layer provides evidence that one should not use recession depth measurements for erosion yield determination for thin film polymers, where erosion has affected more than one layer.
Fig 10. Images of the space-exposed third layer of Kapton H showing rounded erosion valleys: a). Image obtained from the center of the sample (1kX, 45° tilt), b). Close-up image (2.5kX, 45° tilt) with an individual erosion valley enlarged.

Another interesting observation from examining this multilayer thin film sample is that it was apparent that the second layer eroded somewhat non-uniformly. As an example, one can see waviness in the overall surface of the space-facing Kapton second layer, as shown in the low magnification image in Figure 11. This waviness is attributed to non-uniform erosion of the first layer, which became completely eroded away while in space. There can be numerous factors that can increase, or decrease, non-uniform erosion such as protective particles, scattering effects, non-uniformity of film thickness, and gaps between thin film layers (which can produce a smoothing effect). As a side note, this image includes the impact area, shown in Figure 3 above.

Fig 11. Low magnification image of the space-facing second layer of Kapton H showing surface waviness (50X, 45° tilt).

5.2 Polyvinyl Fluoride (PVF), Clear Tedlar

Polyvinyl fluoride (PVF), also commonly known as Tedlar® was analyzed. The clear Tedlar film (TTR10SG3) was 1 mil (25.4 μm) thick and a total of 13 layers were stacked together for flight. Post-flight, the top 10 layers were completely eroded away, the 11th layer was textured and eroded, particularly along the edge, and the bottom 2 layers (layers 12 & 13) appeared to be slightly discolored. The MISSE 2 LEO erosion yield for PVF was determined to be $3.19 \times 10^{-24} \text{ cm}^3/\text{atom}$. Figure 12 is a post-flight photograph of the flight sample individual layers, next to a control sample. The top exposed layer is on the left side of the figure and the bottom layer is on the right. A piece of the 11th layer was sectioned and examined with the FESEM.
Examination of the eroded, but intact 11th layer of the Tedlar sample stack was very interesting. The first observation was that the sample layer was non-uniformly eroded or textured, as shown in Figure 13a. Large areas were present with non-uniform texture. Upon closer examination, it became apparent that cone clusters from the (prior) upper surface layers were present and either sitting protecting the underlying layer from erosion, or were littered on the surface (possibly shifted during shuttle retrieval and handling). Figure 13b shows an example of a single loose cone cluster, which likely came from the protected area seen in the upper left corner of the image. Figure 13c shows an area littered with many loose cone clusters.

These cone clusters appear to develop as upper layers eventually become non-uniformly eroded. Eventually, the non-uniform erosion can result in areas where loose cone clusters from the upper layer remain intact and protect the area below it from eroding. This can be seen in Figures 14a-14c. In Figure 14a, the mountain ranges with cone cluster tops have lines horizontally through the center of each, similar to strata in real mountain ranges. This line is actually the boundary between the 10th layer and the 11th layer. Hence, a section of the 10th layer is still sitting on top of the 11th layer, protecting it. Two flat top mountains (plateaus) are shown, these are areas where the cone clusters from the 10th layer protected these regions during flight, but are no longer present (probably shifted during retrieval or handling). Figure 14b shows a shifted erosion peak, where the atomic oxygen erosion texture matches nicely to the protected mesa below. Figure 14c shows a “mountain range” with the erosion peaks from layer 10 all still intact, but the boundary between the 10th and 11th layer is visible. Atomic oxygen erosion cone propagation in multi-layered polymer films can result in the generation of weakly attached free particles, that could result in particulate contamination on-orbit (e.g. when exposed to plume impingement or MMOD impacts).
Fig 14. Images of the 11th layer of clear Tedlar: a). “Mountain ranges” with cone cluster tops have lines horizontally through the center of each indicating the boundary between the 10th and 11th layers (2.5kX, 45° tilt), b). 10th layer cone cluster that had protected the 11th layer below from erosion, but is now shifted (4kX, 0° tilt), and c). A mountain range with the erosion peaks from layer 10 all still intact and the boundary between the 10th and 11th layer is visible (3kX, 45° tilt).

5.3 **Crystalline Polyvinyl Fluoride (PVF) w/ White Pigment, White Tedlar**

Crystalline Polyvinyl Fluoride (PVF) w/ white pigment, also commonly known as white Tedlar, was flown. The white Tedlar film was 1 mil (25.4 µm) thick, and a total of 13 layers were stacked together for flight. Post-flight, surprisingly, all 13 layers were intact. The top layer appeared to be textured, or more accurately, appeared to have a white powdery looking surface. Figure 15 is a post-flight photo of the top flight sample layer. The flight sample had an impact site in the top layer. The impact caused a very large area to be affected, as shown in Figure 15, where the powdery texture appears to have been “blown-off” during the impact. The MISSE 2 LEO erosion yield white Tedlar was determined to be only 1.01 x 10⁻²⁵ cm³/atom.[1,2]

Fig 15. Photograph of the top layer of the white Tedlar flight sample with a close-up image of the impact area. The very small impact crater (≈0.06 mm) is pointed by the arrow.

Even though this sample was coated with a thin conductive Au-Pd film, the sample charged excessively during imaging, and good quality images were difficult to obtain. Figure 16 shows one image, taken at a 39° tilt, which shows that a very porous texture develops with atomic oxygen exposure. This porous texture is the result of the polymer being mixed with an atomic oxygen durable pigment, titanium dioxide (TiO₂). With atomic oxygen exposure, a fine TiO₂ powder was found to remain on the surface, as the surrounding polymer eroded away. In space, under direct ram atomic oxygen exposure, and with little disturbance (the exception being small impacts), the powder gradually forms an increasingly protective layer reducing the rate of erosion. Hence, white Tedlar has a substantially lower erosion yield in space (1.01 x 10⁻²⁵ cm³/atom) than clear Tedlar (3.19 x 10⁻²⁴ cm³/atom).[1,2]
Interestingly, a study conducted by Stambler, et al. found that the erosion yield of white Tedlar (relative to Kapton H) in a RF plasma asher was an order of magnitude greater ($3.7 \times 10^{-24}$ cm$^3$/atom) than it was in space.[6] In the asher, where the atomic oxygen arrival is isotropic and at thermal energy, the thermal energy atomic oxygen is effective in eroding the Tedlar matrix due to that fact that a higher fluence of atoms is needed to produce an equivalent erosion in Kapton H (the witness) exposed to hyperthermal atomic oxygen in LEO. In LEO, the incoming hyperthermal atomic oxygen has a much higher probability of reaction upon initial impact with polymers. Upon scattering off non reactive pigment particles, the AO becomes thermally accommodated resulting in orders of magnitude lower reaction probability for oxidizing the polymer under the protective particles. Hence, after scattering and thermally accommodating in LEO, the energy is the same as in an asher, but the total fluence differs as the asher needs a higher fluence to replicate the equivalent erosion in unprotected Kapton H in LEO. This causes greater undercutting below the TiO$_2$ pigment particles for the same effective fluence as in LEO ram exposure.

5.4 Pyrolytic Graphite (PG)

The only non-polymer flown as part of the MISSE PEACE Polymers experiment was pyrolytic graphite (PG). The PG was 80 mil (0.203 cm) thick, and therefore only 1 layer was flown. The directed ram LEO atomic oxygen exposure resulted in the development of a black velvet-looking texture, as shown in Figure 17. The MISSE 2 LEO erosion yield for PG was determined to be $4.15 \times 10^{-25}$ cm$^3$/atom.[1,2]

As expected, based on the very diffuse, black, surface appearance, the high fluence LEO direct ram atomic oxygen exposure resulted in a fine microscopic high density cone texture, such as shown in Figure 18. The PG was found to display some other interesting features. For example, when examining the sample at lower magnifications, such as at 250X shown in Figure 19a, there are “lines” or rills that appear to be more resistant to atomic oxygen erosion. When examining the protected edge of the sample, such as shown in Figure 19b, it can be seen that these more atomic oxygen resistant lines appear to correspond to the structures that may be grain boundaries. Perhaps impurities reside at these boundaries which impact the erosion rate. Upon close inspection of the erosion cones, a small amount of very fine ash appears to be present on the tips of the cones, as shown in the images in Figure 20.
Fig 18. FESEM surface morphology images of pyrolytic graphite: a). Texture viewed normal to surface (1kX, 0° tilt), b). Cone texture seen at a titled angle (1kX, 45° tilt), and c). Close-up of cone texture (2.5kX, 45° tilt).

Fig 19. Low magnification images of pyrolytic graphite a). Erosion resistant rills are visible (250X, 45° tilt), and b). Protected edge area where more resistant areas appear to line up with grain boundaries (250X, 45° tilt).

Fig 20. High magnification images of pyrolytic graphite a). Erosion cones with fine ash on the tips (5kX, 45° tilt), and b). Image of several cones, with a close-up showing the gossamer fine ash (9kX, 45° tilt).

Because the PG was a single thick layer, it provided a good material to compare the erosion yield determined using recession depth measurements with the erosion yield determined using mass loss measurements. Fortunately, a good size protected butte, or plateau, where the protected material was no longer present was found, as shown in Figure 21. To obtain the erosion (or recession) depth, one needs to measure from the top of the protected butte to the center of the erosion cones. Because it is not possible to see the bottom of the cones, the center of the cones needed to be guessed at, and this can introduce error. Two recession depth measurements were obtained from the butte at two locations: 24.66 μm and 25.19 μm. Hence, the average depth was determined to be 24.93 μm. Because the image was obtained with the sample tilted at a 45° angle, the actual depth of erosion was equal to 24.93 μm/sin(45°), or 35.25 μm. After converting this to cm (0.003525 cm) and dividing by the atomic oxygen fluence (8.43 x 10^{21} atoms/cm²), the erosion yield of the PG based on recession depth was determined to be 4.18 x 10^{-25} cm³/atom. This is in excellent agreement with the erosion yield determined by mass loss (4.15 x 10^{-25} cm³/atom).
Fig 21. Recession depth measurements at a protected butte on the surface of PG: 24.66 µm and 25.19 µm (1.3kX, 45° tilt).

5.5 Chlorotrifluoroethylene (CTFE), Kel-F or Neoflon

A chlorine containing fluoropolymer was flown, chlorotrifluoroethylene (CTFE), is also commonly known as Kel-F. This particular film was Neoflon M-300. The CTFE film was 5 mil (127 µm) thick, and only 1 layer was flown. The directed ram LEO atomic oxygen texture changed the essentially clear film into a hazy white material, as shown in Figure 22. The MISSE 2 LEO erosion yield for CTFE was determined to be $8.31 \times 10^{-25}$ cm$^3$/atom.[1,2]

Fig. 22 Photograph of MISSE 2 CTFE flight and control samples (1 layer, 127 µm thick).

The first observation for this sample was that it was very brittle. It cracked when the sample was cut with scissors to section a piece for FESEM examination. Upon FESEM examination, this sample, similar to the PG had a well developed cone morphology. Although the cones were found to be larger than the PG, this was expected because the erosion yield was twice as great as PG. With a quick comparison of the cone density shown in Figure 18a for PG with the cone density for CTFE shown in Figure 23a, both taken at the same (1kX) magnification, it appears that there may be twice the number cones for PG than for CTFE. Another observation for the CTFE is that there appears to be greater erosion at the edge where the sample holder held it in place for flight, as shown in Figure 24, which may be due to a high atomic oxygen flux due to scattering off the chamfered sample holder edge. Also, the CTFE cones have a bit of a melted look to them, as visible in the higher magnification images shown in Figure 25.
Fig 23. FESEM images of the surface morphology of MISSE 2 CTFE: a). Texture viewed normal to surface (1kX, 0° tilt), and b). Cone texture seen at a tilted angle (1kX, 45° tilt).

Fig 24. Low magnification image of CTFE showing enhanced erosion at the protected/exposed border (250X, 0° tilt).

Fig 25. Surface morphology images of CTFE showing a “melted” appearance: a). Low magnification image of cone texture (1kX, 45° tilt), b). Closer-up image of cone texture (2kX, 45° tilt), and c). High magnification image of cones (5kX, 45° tilt).

This sample was examined with EDS. A typical spectrum for a large surface area is shown in Figure 26, along with the corresponding analyzed area. The main components are: F, Cl, C, O, and there is also a small peak that is either Na or Zn. The conductive film elements, Au & Pd are also present. Two protective particles, at the tops of cones, were also analyzed, and both were found to have the same spectrums, which consisted of Zn, Al, Si and K in addition to F, Cl, C, O, Au & Pd, as shown in Figure 27.
5.6 **Fluorinated Ethylene Propylene (FEP), Teflon FEP**

Clear fluorinated ethylene propylene (FEP), also known as Teflon® FEP (200A) was flown. The clear FEP film was 2 mil (50.8 µm) thick, and only 1 layer was flown. The directed ram LEO atomic oxygen did not appear to texture the FEP, (see Figure 28) as one would expect based on prior flight data, such as from the Long Duration Exposure Facility (LDEF). Although the sample did appear to perhaps shrink as evident by its waviness as compared to the control sample. The MISSE 2 PEACE LEO erosion yield for FEP was determined to be $2.00 \times 10^{-25}$ cm³/atom.[1,2]

The first observation when examining the FEP with the FESEM was that there was a crack along the protected/exposed border, as shown in Figure 29. The sample holder is chamfered in this area and can provided additional reflected radiation. Perhaps the reflected solar radiation can increase the degree of embrittlement through increased dose or heating effects. But, the most surprising observation was that there were no erosion cones on the FEP. Silvered-Teflon FEP was flown on the Long Duration Exposure Facility (LDEF), and the diffuse leading edge surfaces had well developed erosion cones (see section 5.10 below). Figure 30 shows two images of the MISSE 2
PEACE FEP, taken at 5kX and 10kX magnifications. The only “cones” present are those left due to the presence of protective debris. The only texture visible in “non-debris areas” is the presence of very small bright bumps, as seen at 20 kX in Figure 31b. Figure 31a shows a 20kX image in the protected area, where the bright bumps are not present. It should be noted that the electron beam caused surface cracking to occur when imaged at 10 kX or above. An example is shown in Figure 31c which was imaged at 50kX.

Fig 29. Low magnification FESEM image of FEP at the protected/exposed border showing materials cracking (180X, 0° tilt).

a.  

b.

Fig 30. Surface morphology images of FEP showing that the only cones present are those associated with protective ash: a). Smooth background morphology shown at 1,000X (1kX, 0° tilt), and b). High magnification image showing tiny bright bumps (10kX, 45° tilt).

a.  

b.

c.

Fig 31. High magnification images of the surface morphology of FEP: a). Protected area (20kX, 0° tilt), b). Exposed area showing tiny bright bumps (20kX, 45° tilt), and c). Very high magnification image showing electron beam induced surface cracking (50kX, 45° tilt).

EDS spectrums were obtained for both exposed and protected areas of FEP, to verify the chemistry and to look for any thin film of contamination, such as silicone contamination, which could affect the erosion process. The spectrum for the protected area (imaged at 10kX) is showed in Figure 32, and the only elements present were C and Fl, as expected (along with the conductive coating elements: Au & Pd). The spectrum for the exposed area (imaged at 10kX) is shown in Figure 33, and is essentially the same as for the protected material. There is no evidence of
contamination. Because FEP is such a low erosion yield material, if contamination was occurring on-orbit, one would expect it to be shown on FEP, as a high erosion yield material may shed the in-coming contaminant quicker than it can accumulate. These EDS analyses are consistent with those reported in [3] and [4] on the cleanliness of this flight experiment on orbit.

![Figure 32](image1.png)

**Fig 32.** Energy dispersive spectroscopy spectrum for protected FEP surface and corresponding analyzed area.

![Figure 33](image2.png)

**Fig 33.** Energy dispersive spectroscopy spectrum for exposed FEP surface and corresponding analyzed area. The spectrum shows no evidence of contamination.

When examining the protected edge of the sample (shown in Figure 34a), a protected butte was found as shown in Figure 34b. Because the butte was close to the protected edge, as seen in Figure 34a, and appeared to be the full erosion depth in height, it was used to compute the erosion yield based on recession depth. One recession depth measurement was obtained, and was 13.08 µm, as shown in Figure 34b. Because the image was obtained with the sample tilted at a 45° angle, the actual depth of erosion was equal to 13.08 µm/sin(45°), or 18.50 µm. After converting this to cm (0.00185 cm) and dividing by the atomic oxygen fluence (8.43 x 1021 atoms/cm²), the erosion yield of the FEP based on recession depth was determined to be 2.19 x 10⁻²⁵ cm³/atom. This is in good agreement with the erosion yield determined by mass loss (2.00 x 10⁻²⁵ cm³/atom).
a. Fig 34. Images near protected edge area of FEP: a). Low magnification image showing erosion step and protected butte (500X, 45° tilt), and b). Close-up of protected butte and corresponding recession depth measurement: 13.08 µm (4kX, 45° tilt).

One other observation that is worth noting is that the butte shown in Figure 35 appears to have been protected during flight, but upon close inspection there is actually a very fine texture on the surface. This indicates that the protective particle was removed sometime during flight and that erosion has occurred. If one compares the height of this butte to the one in Figure 34b (taken at 4kX), it can be seen that the butte in Figure 35 (taken at 5kX) does not have the same recession step-height. The lesson here is that care must be taken when using protected buttes for recession depth measurements. It is important to be certain that it is a “full erosion depth” butte. The potential for making an error by obtaining the recession depth from a partially eroded butte, is another reason why mass loss measurements can be more advantageous: they average out the recession depth for the entire surface.

b.

Fig 35. Butte on the surface of FEP, which under close examination has a textured surface and hence was exposed to atomic oxygen during the mission (5kX, 0° tilt).

5.7 Polytetrafluoroethylene (PTFE), Teflon PTFE

Another fluoropolymer that was flown was polytetrafluoroethylene (PTFE), also referred to as Teflon PTFE. This particular film was Chemfilm DF 100. The PTFE film was 2 mil (50.8 µm) thick, and only 1 layer was flown. The directed ram LEO atomic oxygen appeared to cause only very slight texturing, and like the FEP this sample was wavy as compared to the control sample, as shown in Figure 36. The MISSE 2 LEO erosion yield for PTFE was determined to be $1.42 \times 10^{-25}$ cm$^3$/atom.[1,2]

Fig 36. Photograph of MISSE 2 PTFE flight and control samples (1 layer, 50.8 µm thick).
Upon macro examination, a large area of the protected/exposed edge of the sample had a large through-thickness “split” in the material. It was not apparent if this split was due to excessive erosion or if it was embrittled (hence a crack). The sample was sectioned carefully and mounted on a FESEM holder so that the protected/exposed edge could be examined in the FESEM. Figure 37 shows a view of the edge, which was not eroded through and was obviously embrittled with brittle fracture cracks.

Fig 37. FESEM image of a brittle fracture crack in PTFE near the protected border (1kX, 0° tilt).

Similar to the FEP, the MISSE 2 PEACE PTFE did not develop cones during erosion, except at locations of protective debris, as shown in Figure 38. With a 0° tilt, the surface appears to have small bright bumps, again similar to the FEP. At higher magnification, an interesting morphology is apparent along with the bumps, as shown in Figure 39. This sample was found to contain large debris fields, as shown in Figure 40, with numerous protective particles, such as shown in Figures 41a-41c.

Fig 38. Surface morphology images of PTFE showing that the only cones present are those associated with protective ash: a). Relatively smooth background morphology shown at 5,000X (5kX, 0° tilt), and b). High magnification image showing micro-texture (10kX, 45° tilt).

Fig 39. High magnification images of the surface morphology of space exposed PTFE: a). Small bright bumps are observed (5kX, 45° tilt), and b). An interesting surface structure is visible at very high magnification (20kX, 45° tilt).
Fig 40. View of a large debris field on the surface of PTFE (500X, 45° tilt).

Fig 41. Atomic oxygen durable particles or ash protecting the underlying PTFE from erosion: a). Large particle on a plateau (4.5kX, 45° tilt), b). Particle sitting on the top of cone tip ash (6kX, 45° tilt), and c). Debris on top of a butte (5kX, 45° tilt).

Once again for this sample, a protected butte was found as shown in Figure 42. The top of the butte is smooth with some processing lines on it, indicating it was protected during space exposure. Therefore, this plateau was used to compute the erosion yield based on recession depth. Two recession depth measurements were obtained, 7.90 µm and 8.81 µm, and the average was 8.36 µm. Because the image was obtained with the sample tilted at a 45° angle, the actual depth of erosion was equal to 8.36 µm/sin(45°), or 11.589 µm which predicts an erosion yield of 1.40 x 10^{-25} cm³/atom. This is in good agreement with the erosion yield determined by mass loss (1.42 x 10^{-25} cm³/atom).

Fig 42. Recession depth measurements at a protected plateau on the surface of PTFE: 7.90 µm and 8.81 µm (2.5kX, 45° tilt).
5.8 Perfluoroalkoxy copolymer resin (PFA), Teflon PFA

Perfluoroalkoxy copolymer resin (PFA), also referred to as Teflon PFA, was flown. This particular film was Teflon PFA 200 CLP. The PFA film was 2 mil (50.8 µm) thick, and 4 layers were stacked together for flight. All four layers were intact, as shown in Figure 43, and the directed ram LEO atomic oxygen appeared to cause only very slight texturing of the top layer. The MISSE 2 LEO erosion yield for PFA was determined to be $1.73 \times 10^{-25}$ cm$^3$/atom.[1,2]

Similar to the FEP and the PTFE, the MISSE 2 PFA did not develop cones during erosion, except at locations of protective debris, as shown in Figures 44a-44c. Figure 44b is an image taken at 5 kX that shows erosion around a protective particle, but with an otherwise smooth surface. Note that these features are leaning slightly in 44a. This “non-perpendicular” tilt of erosion features was observed in most of the examined samples, and is attributed to the fact that MISSE 2 was found to have been tilted with respect to the ram atomic oxygen, by approximately 8 degrees.[5] The image in 44b was scan rotated (electronically rotated) to eliminate this tilt. Figure 44c, taken at 10kX shows small bright bumps. With a 0° sample tilt, and high magnification, the surface appears to have bright bumps, again similar to the FEP and PTFE. Figure 45 shows high magnification images of both protected and exposed PFA. At very high magnification (50kX), again, like the PTFE, an interesting morphology is apparent along with the bumps, as shown in Figure 45c. Although the sample was sensitive to the electron beam and cracked at high magnification imaging. The FEP appeared to have a similar polymer texture as the PTFE and PFA at 50kX, but because the FEP surface became easily damaged & cracked under high magnification imaging, it was difficult to tell if the observed features were induced or changed by the imaging electron beam.

Fig 44. FESEM surface morphology images of PFA: a). Image showing cones associated with protective particles (2.0kX, 45° tilt), b). Close-up of butte with protective particle and smooth background (5kX, 45° tilt), and c). High magnification image showing micro-texture (10kX, 45° tilt).
Fig 45. High magnification images of the surface morphology of PFA: a). Protected area (20kX, 0° tilt), b). Exposed area showing little bright bumps (20kX, 45° tilt), and c). Very high magnification image showing bumps and surface structure similar to PTFE in Figure 39b (50kX, 45° tilt).

EDS spectrums were obtained for both exposed and protected areas of PFA, to verify the chemistry and, once again to look for any thin film of contamination, such as silicone contamination. The spectrum for the exposed area (imaged at 10 kX) is shown in Figure 46, and was the same for a 2 kX analysis area. There is no evidence of contamination. The only elements present are C, F and the conductive film elements (Au & Pd). Again, because PFA is a low erosion yield material, if contamination was occurring on-orbit, one would expect it to be shown on the PFA.

Fig 46. Energy dispersive spectroscopy spectrum for exposed PFA surface and corresponding analyzed area. The spectrum shows no evidence of contamination.

5.9 Aluminized-FEP (Al-FEP)

Because the clear FEP sample did not show the presence of any cones, it was decided to examine another FEP sample flown on MISSE 2 tray 1. The FEP film was 5 mil (127 µm) thick and was vapor deposited with ≈1000 Å of aluminum (VDA) on the back surface. Only 1 layer was flown, with the FEP space-facing. This sample was flown as part of the Polymer Film Thermal Control (PFTC) and Gossamer Materials experiments, and resided in MISSE PEC 2, tray 1, sample tray E6. Sample tray E6 was flown adjacent to E5, and hence received essentially the same LEO exposure as E5. The atomic oxygen fluence for sample tray E6 was determined based on the mass loss of a single Kapton H witness sample, flown as part of the PFTC and Gossamer Materials experiments. The atomic oxygen fluence was determined to 8.51 x 10^{21} atoms/cm².[4] This is in good agreement with the fluence determined for the PEACE Polymers experiment tray. The solar exposure for sample tray E5, near the aluminized sample, was approximately 6,050 ESH.[3] The MISSE 2 LEO erosion yield for Al-FEP was determined to be 2.11 x 10^{-25} cm³/atom.[4] This fluence is slightly higher than the fluence determined for the clear FEP on tray E5, which was 2.00 x 10^{-25} cm³/atom.

When viewed with a 0° tilt angle (looking straight down on the sample), the Al-FEP sample was found to have bright bumps, similar to the FEP, as shown in Figure 47a. However, the bumps shown in the FEP samples (Figure 31b) are much smaller. At a 45° tilt, the Al-FEP was found to have very small erosion cones, as shown in Figure
47b. Comparing this image to that taken at the same tilt angle and magnification for FEP in Fig 44c above, it
appears that the metallized Teflon has small cones, while the clear FEP does not. Once again, this sample was
examined with EDS, and the area shown in 47a, but imaged at 5kX, was found to only contain F, C, Au and Pd, as
shown in Figure 48. A protected area was also imaged and EDS analyzed, and the spectrum was nearly identical to
that of the exposed area.

Fig 47. High magnification images of the surface morphology of MISSE 2 E6 Al-FEP: a). Area showing larger
bright bumps than for clear FEP: a). Tilted image shows very small cones (10kX, 45° tilt).

Fig 48. Energy dispersive spectroscopy spectrum for exposed FEP of the area shown in Figure 47a. The spectrum
shows no evidence of contamination.

Once again for this sample, a protected butte with a smooth top was found as shown in Figure 49 (imaged with scan
rotation of 11.4 degrees). The butte was used to compute the erosion yield based on recession depth. Two recession
depth measurements were obtained, 13.25 µm and 13.85 µm, and the average was 13.55µm. Because the image
was obtained with the sample tilted at a 45° angle, the actual depth of erosion was equal to 13.55 µm/sin (45°), or
19.16 µm which indicates an erosion yield of the Al-FEP based on recession depth of 2.25 x 10⁻²⁵ cm³/atom. This is
in good agreement with the erosion yield determined by mass loss (2.11 x 10⁻²⁵ cm³/atom).

Fig 49. Recession depth measurements at a smooth surface butte on Al-FEP: 13.25 µm and 13.85 µm (4kX, 45°
tilt).
As mentioned, although eroded, the MISSE 2 clear FEP did not develop erosion cones, while the MISSE 2 Al-FEP did develop small cones, and the erosion yield for the Al-FEP (2.11 x 10^{-25} \text{ cm}^3/\text{atom}) was found to be slightly greater than clear FEP (2.00 x 10^{-25} \text{ cm}^3/\text{atom}), based on mass loss measurements. It is hypothesized that metallized FEP may have a slightly higher erosion rate and shows slight development of cones, as compared with clear FEP, because as a second surface reflector the solar radiation can reflect off the metal coating and travel back through the FEP layer increasing both radiation and heating effects. Clear FEP and Al-FEP were tested together in an energetic end Hall atomic oxygen beam system which impinges a predominantly O_{2}^{+} beam at 70 eV onto samples. Using this system, the Al-FEP was found to have an erosion yield that was 15% greater than the clear FEP. Further analyses of the texture of these samples needs to be conducted.

### 5.10 LDEF Ag-FEP vs. MISSE clear FEP and MISSE Al- FEP

As mentioned previously, Ag-FEP on the leading edge of LDEF was found to be hazy and had developed a ram atomic oxygen cone texture as it eroded. Images of Ag-FEP from LDEF tray E10 (from row 10, which was next to the direct ram facing surface (row 9)) are shown in Figures 50a-50c. For comparison, images of MISSE 2 Al-FEP taken at the same magnifications are shown in Figures 51a-51c. The erosion yield for LDEF Ag-FEP (average for rows 7, 8, 10 and 11; based on mass comparison of flight and control samples) was 3.4 ± 1.3 x 10^{-25} \text{ cm}^3/\text{atom}.[7]

Images of protected buttes for MISSE 2 clear FEP (4kX magnification), MISSE 2 Al-FEP (4kX magnification) and LDEF E10 Ag-FEP (2kX magnification) are shown in Figure 52a-52c, respectively. Coincidentally, the Ag-FEP on LDEF row 10 (E10) was exposed to the same atomic oxygen fluence, 8.43 x 10^{21} \text{ atoms/cm}^2, as the MISSE 2 FEP on E5, and essentially the same fluence as the MISSE 2 Al-FEP on E6 (8.51 x 10^{21} \text{ atoms/cm}^2).[7] But, the LDEF Ag-FEP was exposed to a higher solar exposure than the MISSE Teflon samples. LDEF row 10 received 10,700 ESH [7], while the MISSE E5 tray received ≅6,300 ESH and E6 received ≅6,050 ESH.
In summary, LDEF Ag-FEP (E10) had significantly more erosion ($E_y = 3.4 \times 10^{-25} \text{ cm}^3/\text{atom}$) and substantially greater developed texture (larger cones) than MISSE Al-FEP ($E_y = 2.11 \times 10^{-25} \text{ cm}^3/\text{atom}$), or MISSE clear FEP ($E_y = 2.00 \times 10^{-25} \text{ cm}^3/\text{atom}$), with similar atomic oxygen fluence exposure. It is hypothesized that this may be primarily due to the difference in solar exposure between the two missions:

- MISSE FEP: $8.43 \times 10^{21} \text{ atom/cm}^2$ & 6,300 ESH ($E_y = 2.00 \times 10^{-25} \text{ cm}^3/\text{atom}$)
- MISSE Al-FEP: $8.51 \times 10^{21} \text{ atom/cm}^2$ & 6,050 ESH ($E_y = 2.11 \times 10^{-25} \text{ cm}^3/\text{atom}$)
- LDEF Ag-FEP: $8.43 \times 10^{21} \text{ atom/cm}^2$ & 10,700 ESH ($E_y = 3.4 \times 10^{-25} \text{ cm}^3/\text{atom}$)

Interestingly, the LDEF FEP had 1.7 times the erosion yield of MISSE clear FEP (1.6 times the erosion yield for Al-FEP) and the LDEF FEP had 1.7 times the solar exposure as MISSE clear FEP (1.8 times the erosion yield for Al-FEP). It should be noted that heating is believed to also play a role in erosion. A thermocouple on MISSE 2 tray 1 measured an on-orbit temperature range of -44.7°C to +31.6°C [3], while the structure of LDEF for row 9 (next to row 10) has been calculated to have been +25°C to +38°C during flight. Therefore, it appears that the average temperature of LDEF was higher (25°C) than MISSE 2 (-7°C). In addition, the average number of suns for the LDEF Mission on row 10 (10,700 ESH/50,568 mission hours = 0.212) was 16% higher than for the MISSE 2 E5 tray (6,300 ESH/34,680 mission hours = 0.182). Also, the beginning of life absorptance to emittance ratios (LDEF Ag-FEP = 0.10, MISSE Al-FEP = 0.12, and MISSE clear FEP possibly = 0.002-0.003) indicate that Ag-FEP would run cooler than Al-FEP, but hotter than clear FEP. [9] Certainly the temperature differences could help explain the different in texture between the MISSE Al-FEP (hotter) and non-aluminized MISSE FEP (cooler). Therefore, the effect of the metallization may contribute to the presence of texture due to increased temperature and also possibly increased radiation exposure. Both radiation effects, and temperature effects, on the presence or absence of texture deserve further investigation.

6. SUMMARY & CONCLUSIONS

The MISSE 2 PEACE Polymers experiment is unique because it has the widest variety of polymers flown collectively in LEO for a long duration (3.95 years), and was exposed to an unusually clean LEO spacecraft environment. Examination of numerous MISSE 2 PEACE Polymer experiment flight samples, after high fluence LEO ram atomic oxygen exposure, by FESEM and EDS was found to provide a wealth of knowledge on the degradation of thin film polymers in the LEO space environment. These findings include the following:

- EDS analyses confirmed the prior conclusion that the MISSE 2 flight experiment was exposed to a very clean space exposure environment, as no sources of contamination, such as silicone, were observed. Therefore, the Ey data reported for the MISSE 2 PEACE Polymers was not affected by contamination, unlike numerous other flight experiments.
- Erosion can occur in underlying materials below thin film polymers, even when the thin film is still structurally intact. This was verified by examining Kapton H and documenting both holes at “cone-valleys” and erosion texture in an underlying Kapton layer at the corresponding hole locations. Therefore, a spacecraft may have damage to underlying layers on-orbit, even if the Ey predicts that the “outer layer” will be intact.
Atomic oxygen erosion cone propagation in multi-layered polymer films can result in the generation of weakly attached free particles, that could result in particulate contamination on-orbit (e.g. when exposed to plume impingement, MMOD impacts, etc.).

FESEM analyses confirmed the prior conclusion that mass loss was the best technique for obtaining the Ey of the MISSE 2 PEACE Polymers. Hence, mass loss is the recommended technique for Ey determination of stacked thin film polymers where the erosion can extend beyond the top layer.

Non-volatile oxide ash debris is present on the tops of the cones of many samples. This ash helps protect the underlying material from erosion, and is believed to play a significant role in the erosion morphology development. Future studies of the effect of ash content on erosion morphology are desired.

Care should be used when looking for protected buttes for recession depth measurement, as often, buttes may be present, but are not the full erosion depth in height. The lesson learned is that one needs to be careful to use a full height butte for recession depth measurements.

White Tedlar was found to develop a fine loose powdery surface, which under directed ram atomic oxygen exposure in LEO provided protection to the underlying material from atomic oxygen erosion.

Grain boundaries of PG were found to be more atomic oxygen durable than the grain matrix.

Samples with erosion occurring only in the top (or a single flown) layer, such as pyrolytic graphite, Teflon FEP and PTFE were used to determine the Ey based on recession depth measurements. The results were in excellent agreement with the MISSE 2 PEACE Polymers Ey data obtained based on mass loss.

Fluoropolymers, such as PTFE and FEP, showed evidence of embrittlement through crack development near the chamfered protected edge. Hence, reflected solar radiation may increase the degree of radiation induced embrittlement through increased radiation dose and/or increased temperature.

Although eroded, surprisingly, clear FEP did not develop a cone texture. Yet, Al-FEP from MISSE 2 tray E6 (flown next to E5) was examined, and was found to contain very small cones, which may be attributed to greater heating (greater α/ε) and/or radiation exposure (reflected radiation) of the metallized FEP.

Clear FEP and Al-FEP were tested in an end Hall atomic oxygen beam and the metallized FEP was found to have a slightly higher erosion yield (15%) than the clear FEP. An analysis of the texture of these samples still needs to be conducted.

When comparing the results of FEP flown on MISSE with those from LDEF, it was found that LDEF Ag-FEP (E10) had significantly more erosion and substantially more developed texture (larger cones) than either MISSE Al-FEP or MISSE clear FEP with very similar atomic oxygen fluence exposures. The solar exposure may have contributed in two ways: first, LDEF had a greater total dose of radiation (LDEF FEP had 1.6-1.7X ESH as the MISSE FEP), and, second, the average structure temperature and the number of average suns was greater for LDEF than MISSE 2, possibly contributing to increased temperatures of the samples.

Studies should be continued to examine the remaining MISSE 2 PEACE Polymer samples, as valuable knowledge can be gained from examining each sample. Also, it would be of interest to conduct a study where the ash content of each polymer is compared with the cone density and erosion yield, to see if there is a correlation between ash content and erosion morphology. Lastly, separate temperature and radiation effects on atomic oxygen surface texture would also be of value to investigate, because of the surprising lack of texture for the MISSE 2 clear FEP Teflon, and the different in erosion yields between the LDEF and MISSE FEP for similar atomic oxygen fluences.

7. ACKNOWLEDGMENTS

The authors would like to thank Terry McCue, ASRC-Aerospace Corp at NASA Glenn Research Center, for very helpful advice, and for obtaining the BSE images and corresponding EDS analyzes of the Kapton H sample. We also gratefully acknowledge the opportunity to fly the MISSE 2 PEACE Polymers experiments, and therefore give our thanks to the MISSE program sponsors and managers. In particular, we would like to thank Gary Pippin (retired, Boeing Phantom Works) and Bill Kinard (retired, NASA Langley Research Center) for their support of this experiment. Lastly, we would also like to acknowledge that the work reported in this paper was sponsored by the ISS Research Program at NASA Headquarters (HQ) and our appreciation is given to Carl Waltz (retired, NASA HQ) and Fran Chiaramonte (NASA HQ).
8. REFERENCES


