



Overview of the MISSE 7 Polymers and Zenith Polymers Experiments After 1.5 Years of Space Exposure

Grace T. Yi
Hathaway Brown School, Shaker Heights, Ohio

Kim K. de Groh
Glenn Research Center, Cleveland, Ohio

Bruce A. Banks
Alphaport, Inc., Cleveland, Ohio

Athena Haloua, Emily C. Imka, and Gianna G. Mitchell
Hathaway Brown School, Shaker Heights, Ohio

Corrected Copy issued October 2016.

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI Program provides access to the NASA Technical Report Server—Registered (NTRS Reg) and NASA Technical Report Server—Public (NTRS) thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers, but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., “quick-release” reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.
- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- E-mail your question to help@sti.nasa.gov
- Fax your question to the NASA STI Information Desk at 757-864-6500
- Telephone the NASA STI Information Desk at 757-864-9658
- Write to:
NASA STI Program
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199



Overview of the MISSE 7 Polymers and Zenith Polymers Experiments After 1.5 Years of Space Exposure

Grace T. Yi
Hathaway Brown School, Shaker Heights, Ohio

Kim K. de Groh
Glenn Research Center, Cleveland, Ohio

Bruce A. Banks
Alphaport, Inc., Cleveland, Ohio

Athena Haloua, Emily C. Imka, and Gianna G. Mitchell
Hathaway Brown School, Shaker Heights, Ohio

Corrected Copy issued October 2016.

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

Acknowledgments

We would like to thank Patty Hunt for her continual support of the NASA Glenn Research Center (GRC) and Hathaway Brown School collaboration. We acknowledge and thank prior PEACE students for their help preparing and pre-flight characterizing the MISSE 7 samples. We extend our thanks to Ed Sechkar for his help with acquiring surface areas with the AutoCAD Trace Design software. We would like to thank Don Jaworske of NASA GRC for coordinating all the GRC MISSE experiments and for his help and dedication to the MISSE Program. We greatly appreciate the support provided of Carl Walz (retired) and Fran Chiamonte of NASA Headquarters, Fred Kohl and Tom St. Onge of NASA GRC, and Stu Cooke and Melissa Ashe of NASA Langley Research Center (LaRC) for their support of MISSE post-flight analyses. Finally, we would express our sincere appreciation to Phil Jenkins of the Naval Research Laboratory and Gary Pippin (retired) of Boeing for providing the unique opportunity to fly the Zenith Polymers and the Polymers Experiment, respectively, as part of MISSE 7. This research was supported by the International Space Station (ISS) Research Program and the MISSE-X Project.

Trade names and trademarks are used in this report for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA STI Program
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
703-605-6000

This report is available in electronic form at <http://www.sti.nasa.gov/> and <http://ntrs.nasa.gov/>

Corrected Copy

Issued October 2016 for

NASA/TM—2013-217848

Overview of the MISSE 7 Polymers and Zenith Polymers Experiments After 1.5 Years of Space Exposure

Grace T. Yi, Kim K. de Groh, Bruce A. Banks, Athena Haloua, Emily C. Imka, and Gianna G. Mitchell

March 2013

Several corrections have been made to the text, figures, references, and tables including updated erosion yield values based on updated density data.

The RDP has been deleted and the eDAA TN has changed.

Overview of the MISSE 7 Polymers and Zenith Polymers Experiments After 1.5 Years of Space Exposure

Grace T. Yi
Hathaway Brown School
Shaker Heights, Ohio 44122

Kim K. de Groh
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Bruce A. Banks
Alphaport, Inc.
Cleveland, Ohio 44135

Athena Haloua, Emily C. Imka, and Gianna G. Mitchell
Hathaway Brown School
Shaker Heights, Ohio 44122

Abstract

As part of the Materials International Space Station Experiment 7 (MISSE 7), two experiments called the Polymers Experiment and the Zenith Polymers Experiment were flown on the exterior of the International Space Station (ISS) and exposed to the low Earth orbit (LEO) space environment for 1.5 years. The Polymers Experiment contained 47 samples, which were flown in a ram or wake flight orientation. The objectives of the Polymers Experiment were to determine the LEO atomic oxygen erosion yield (E_y , volume loss per incident oxygen atoms, given in cm^3/atom) of the polymers, and to determine if atomic oxygen erosion of high and low ash containing polymers is dependent on fluence. The Zenith Polymers Experiment was flown in a zenith flight orientation. The primary objective of the Zenith Polymers Experiment was to determine the effect of solar exposure on the erosion of fluoropolymers. Kapton H[®] was flown in each experiment for atomic oxygen fluence determination. This paper provides an introduction to both the MISSE 7 Polymers Experiment and the MISSE 7 Zenith Polymers Experiment, and provides initial erosion yield results.

Introduction

Materials used in spacecraft design are often exposed to threats in LEO space environment, such as atomic oxygen (AO) interaction, ultraviolet radiation (UV), micrometeoroid and debris impacts, charged particle radiation, temperature effects and thermal cycling. These threats can result in embrittlement and degradation of exposed materials, threatening their performance and durability.

Of these threats, arguably the most prominent is AO erosion. Atomic oxygen is formed through photodissociation of molecular oxygen by short-wavelength UV radiation (>5.12 eV, <243 nm) from the sun (Ref. 1). At spacecraft velocities (~ 7.7 km/s), a number of chemical reactions with

surface molecules can occur, including elastic scattering, scattering with partial or full thermal accommodations, recombination, or excitation of ram species (Ref. 2). These reactions are vigorous enough to cause bond breakage, oxidation, and consequent material erosion. Exposure to LEO AO atmosphere causes structural degradation and problems with functionality. Therefore, it is essential to quantify the erosion yield (E_y) which is the volume lost per incident oxygen atom (cm^3/atom) of space-exposed polymers. Even materials protected from atomic oxygen can be susceptible to AO erosion. Imperfections in the substrate surfaces of atomic oxygen protected materials, such as microscopic scratches or dust particles, can cause defects in the respective protective coatings (Ref. 3). These defects provide a pathway for AO degradation and undercutting erosion of the substrate.

Another LEO threat to spacecraft materials is solar UV radiation, which has a typical wavelength of 0.1 to 0.4 micrometers (Ref. 4). UV radiation is energetic enough to cause the breaking of organic bonds such as $\text{C} = \text{C}$, $\text{C} = \text{O}$, and C-H as well as other functional groups (Ref. 5). A molecule is raised to an excited state when an organic molecule absorbs a photon of UV radiation; bond dissociation can occur if the molecule acquires enough energy at the excited state. Depending on the temperature and physical properties of the materials, the dissociated radical species are reactive intermediates, with the capability of diffusing several atomic distances from their point of origin and can participate in further reactions (Ref. 5). Solar radiation often results in bond breakage in materials as well as threats to functionality and stability of the materials. Of interest to this study is whether solar radiation can have an impact on the erosion of materials.

As part of the Materials International Space Station Experiment 7 (MISSE 7), two experiments called the Polymers Experiment and the Zenith Polymers Experiment were flown on the exterior of the International Space Station (ISS) and exposed to the low Earth orbit (LEO) space environment for 1.5 years. The primary objective of the Polymers Experiment was to determine the LEO atomic oxygen erosion yield (E_y , volume loss per incident oxygen atoms, given in cm^3/atom) of the polymers and the primary objective of the Zenith Polymers Experiment was to determine the effect of solar exposure on the erosion of fluoropolymers. This paper provides an introduction to both the MISSE 7 Polymers Experiment and the MISSE 7 Zenith Polymers Experiment, and provides initial erosion yield results.

Materials International Space Station Experiment (MISSE) Overview

MISSE is a series of experiments that have flown on the exterior of the International Space Station (ISS). The overall objective of the MISSE flight experiments is to analyze the durability and stability of materials in the space environment in order to both determine the best-suited materials for space applications and to gain knowledge about material characteristics in order to predict the longevity of new materials and components that could potentially be used in the future. Individual flight experiments are flown in containers called Passive Experiment Containers (PECs) that allow for exposure to the space environment. The PECs are closed during launch to protect the samples. Once on orbit, the PECs are opened back-to-back and exposed to the space environment for the duration of the mission (Ref. 3). The PECs are placed in a ram/wake or a zenith/nadir orientation. The orientation highly affects environmental exposure. The ram facing PEC will receive a high flux of directed AO and sweeping solar exposure. A zenith facing experiment will receive a low flux of grazing arrival AO and the highest solar exposure. Wake surfaces receive very low AO fluxes and solar radiation similar to ram experiments.

The MISSE 7 Polymers Experiment and Zenith Polymers Experiment were flown and placed on the exterior of the International Space Station (ISS) during the STS-129 Shuttle mission on November 23, 2009. The experiments were placed in two MISSE PECs, one of which was flown in a zenith/nadir orientation (designated as MISSE 7A Zenith Experiment) while the other was flown in a ram/wake orientation (designated as MISSE 7B Polymers Experiment). Once positioned, the experiments remained in low Earth orbit (LEO) for approximately 1.5 years, until they were retrieved during the STS-134 Shuttle mission on May 20, 2011. Figure 1 shows MISSE 7A and 7B as imaged during the STS-130 mission in February 2010.

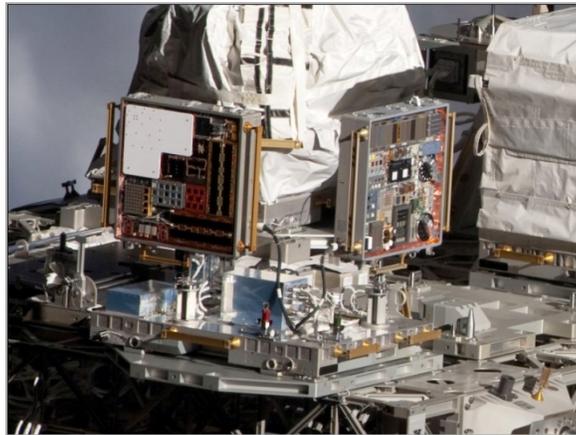


Figure 1. On-orbit photo of MISSE 7A (left, zenith surface shown) and 7B (right, ram surface shown) as imaged during the STS-130 shuttle mission in February 2010.

MISSE 7B Polymers Experiment

The MISSE 7B Polymers Experiment was a passive experiment that contained 44 samples, which were flown in both the ram and wake flight orientations in the MISSE 7B PEC. The two objectives of the Polymers Experiment were: 1) to determine the LEO atomic oxygen erosion yield (E_y , volume loss per incident oxygen atoms, given in cm^3/atom), of the polymers and 2) to determine if atomic oxygen erosion of high and low ash containing polymers is dependent on fluence. Thirty-seven of the samples were flown in the ram orientation, exposing them to high AO and solar radiation. Seven samples were flown in the wake orientation, exposing them to solar radiation with minimal AO. The high and low ash containing samples were exposed to varying levels of AO fluence by the inclusion of very thin sacrificial Kapton film covers.

Tables 1, 2, and 3 below provide a list of 20 MISSE 7B Polymers Experiment samples analyzed for mass loss based E_y , along with sample ID, sample size, film thickness, number of layers flown (to allow mass measurements to be made in the event that erosion of more than one layer would occur) and flight orientation (ram or wake exposure). The majority of samples were flown in two trays: Tray B7-R which held 15 – 1” (2.54 cm) square samples, shown in Figure 2, and Tray N5-R which held 16 – 0.75” (1.905 cm) square samples, shown in Figure 3. Samples B7-12 - B7-15 in Figure 2, and N5-9 – N5-11 in Figure 3 were part of other MISSE 7 experiments.

Kapton H[®] was flown as part of the Polymers Experiment for atomic oxygen fluence determination in the ram direction. In addition, numerous samples were flown in Al foil holders which were taped directly to the baseplate using thermal control tape to maximize sample

exposure on-orbit. Some of the taped sample holders contained tensile samples. PVC (B7-10) was flown on the top of a small Atomic Oxygen Scattering Chamber and hence was flown with a 0.127” (0.323 cm) diameter hole in the center. The results of the taped and tensile samples, and samples that are not characterized for mass-loss based on Ey are not discussed in this paper. Comparison of Ey values from other MISSE flight experiments will be discussed in future work.

Table 1. MISSE 7 Polymers Experiment Ram “B7-R” Tray Samples.

MISSE Sample ID	Material	Trade Name (Abbreviation)	Size	Thickness (mils)	Number of Layers
B7-1	Crystalline polyvinyl fluoride w/ white pigment	White Tedlar (PVF)	1" x 1"	2	1
B7-2	Crystalline polyvinyl fluoride w/ white pigment with a 0.5 mil Kapton H cover	White Tedlar (PVF)	1" x 1"	2	1
B7-3	Crystalline polyvinyl fluoride w/ white pigment with two 0.5 mil (1.0 mil) Kapton covers	White Tedlar (PVF)	1" x 1"	2	1
B7-8	Polyimide (PMDA)	Kapton H (PI)	1" x 1"	5	4
B7-9	Polyimide	Vespel	1" x 1"	19.7	1
B7-10	Polyvinyl chloride (small dia. hole) on top of AO Scattering chamber	ClearLay (PVC)	1" x 1"	5	1
B7-11	TiO ₂ /Al ₂ O ₃ /fluorinated ethylene propylene	(TiO ₂ /Al ₂ O ₃ /FEP)	1" x 1"	2	1

Table 2. MISSE 7 Polymers Experiment Ram “N5-R” Tray Samples.

MISSE Sample ID	Material	Trade Name (Abbreviation)	Size (inches)	Thickness (mils)	Number of Layers
N5-1	Polyethylene	(PE)	0.75 x 0.75	2	18
N5-2	Polymethylpentene	TPX (PMP)	0.75 x 0.75	2	9
N5-3	Polyethersulfone	(PES)	0.75 x 0.75	3	6
N5-4	Aluminized-fluorinated ethylene propylene*	Aluminized-Teflon (Al-FEP)	0.75 x 0.75	5	1
N5-5	Polyimide (PMDA)	Kapton H (PI)	0.75 x 0.75	5	4
N5-6	Polyimide (PMDA)	Kapton HN (PI)	0.75 x 0.75	5	4
N5-7	Polyimide (PMDA) with a 0.5 mil Kapton H cover	Kapton HN (PI)	0.75 x 0.75	5/0.5	4
N5-8	Polyimide (PMDA) with two 0.5 mil (1.0 mil) Kapton H covers	Kapton HN (PI)	0.75 x 0.75	5/1.0	4
N5-12	Polyamide-imide	Torlon 4203 (PAI)	0.75 x 0.75	70	1
N5-13	Polyvinyl alcohol (in Al holder)	MonoSol M1000 (PVOH)	0.75 x 0.75	1.5	24
N5-14	Cellulose nitrate	Celluloid (CN)	0.75 x 0.75	5	7
N5-15	Polyimide (AO resistant)	CORIN	0.75 x 0.75	6	7
N5-16	Urethane/liquid crystal polymer (LCP)	Urethane/Vectran mesh (Urethane/LCP mesh)	0.75 x 0.75	10	1

*Teflon layer was space facing

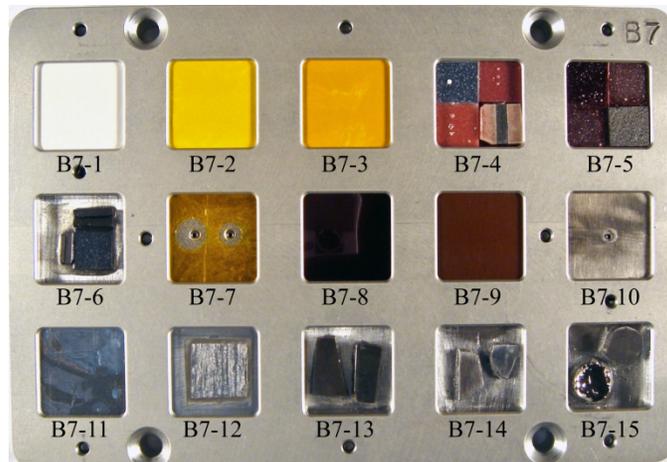


Figure 2. Pre-flight photo of the MISSE 7 B7-R Tray with sample IDs.



Figure 3. Pre-flight photo of the MISSE 7 N5-R Tray with sample IDs.

The MISSE 7B Polymers Experiment included samples from the Japan Aerospace Exploration Agency (JAXA), Towson University, Montana State University, NeXolve Corporation, ATK Space, NASA Langley Research Center (LaRC) and the National Institute of Aerospace.

MISSE 7A Zenith Polymers Experiment

The objective of the Zenith Polymers Experiment was to determine the effect of solar exposure on the E_y of fluoropolymers in the zenith orientation under high solar/low AO exposure. This was accomplished by comparing atomic oxygen fluence ratios to solar exposure, including samples flown as part of other MISSE polymer experiments, such as the MISSE 7B Polymers Experiment. Whether or not there is a synergistic effect of solar radiation on AO erosion is a concept that is a highly debated subject in the space environmental durability community (Ref. 6).

The experiment consisted of 15 square polymer samples, 1”x1” (2.54 cm²), flown in the MISSE 7A “Z” tray. The specific polymers flown are listed in Table 3 along with sample ID, sample size, film thickness and number of layers flown. Kapton H[®] was flown for atomic oxygen fluence determination in the zenith direction. Samples of Al-FEP and silvered-Teflon FEP (Ag-FEP) were included in order to determine the effects of metallization on AO E_y . Four program specific samples were also included: JWST sunshield material (Si/Kapton E/VDA), Orion LIDS Seal O-ring samples and two atomic oxygen and vacuum ultraviolet (VUV) radiation barrier coated FEP samples from Montana State University. A pre-flight photo of the Zenith Polymers Experiment sample tray is shown in Figure 4.

The Zenith Polymers Experiment also included 10 “taped” samples, flown in Al holders which were taped directly to the baseplate. Five of the taped samples were for mass loss based Ey and 2 holders contained five tensile samples. Analyses of the Orion LIDS Seal O-ring samples and the taped samples will be discussed in future work.

Table 3. MISSE 7 Zenith Experiment Samples.

MISSE Sample ID	Material	Trade Name (Abbreviation)	Size	Thickness (mils)	Number of Layers
Z-1	Polytetrafluoroethylene	Chemfilm DF-100 (PTFE)	1" x 1"	5	1
Z-2	Fluorinated ethylene propylene	Teflon (FEP)	1" x 1"	5	1
Z-3	Chlorotrifluoroethylene	Kel-F (CTFE)	1" x 1"	5	2
Z-4	Ethylene-tetrafluoroethylene copolymer	Tefzel ZM (ETFE)	1" x 1"	5	2
Z-5	Polyvinylidene fluoride	Kynar 740 (PVDF)	1" x 1"	3	2
Z-6	Ethylene-chlorotrifluoroethylene	Halar 300 (ECTFE)	1" x 1"	3	3
Z-7	Polyvinyl fluoride	Clear Tedlar (PVF)	1" x 1"	3	12
Z-8	Polyimide (PMDA)	Kapton H(PI)	1" x 1"	1	3
Z-9	Aluminized-fluorinated ethylene propylene*	Al-Teflon (Al-FEP)	1" x 1"	5	1
Z-10	Silvered-fluorinated ethylene propylene*	Ag-Teflon (Ag-FEP)	1" x 1"	5	1
Z-11	Polyethylene (low oxygen)	(PE)		5	8
Z-12	Si/Kapton E/vapor deposited aluminum	(Si/Kapton E/ VDA)	1" x 1"	2	1
Z-14	Al ₂ O ₃ /FEP	(Al ₂ O ₃ /FEP)	1" x 1"	2	1
Z-15	TiO ₂ /Al ₂ O ₃ /FEP	(TiO ₂ /Al ₂ O ₃ /FEP)	1" x 1"	2	1

*Teflon layer was space facing

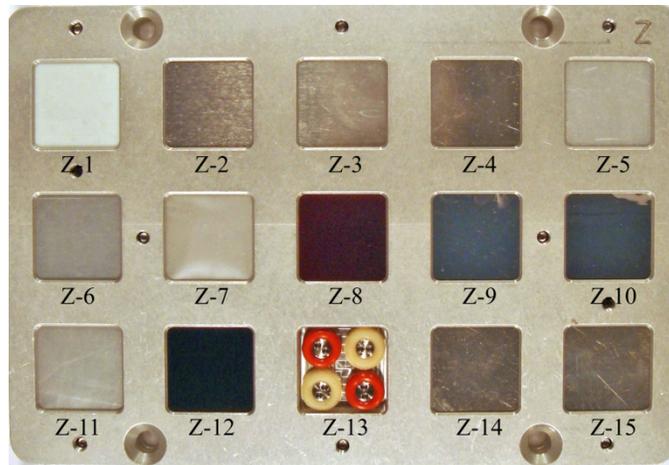


Figure 4. Pre-flight photo of the MISSE 7A Zenith Tray with sample IDs.

Erosion Yield and Atomic Oxygen Fluence Determination

The erosion yield (E_y) of the MISSE 7 flight samples was determined using mass loss measurements. The equation to find the E_y of a flat (non-stressed) sample calculates the volume lost per incident atomic oxygen atom:

$$E_y = \frac{\Delta M}{\rho A F} \quad (1)$$

where

- ΔM = dehydrated mass loss (g)
- ρ = polymer density (g/cm^3)
- A = exposed surface area (cm^2)
- F = atomic oxygen fluence (atoms/cm^2)

The AO fluence (F) is can be determined by measuring the mass loss of a Kapton H witness sample because Kapton H has a well characterized erosion yield ($3.0 \times 10^{-24} \text{ cm}^3/\text{atom}$) in the LEO environment (Refs. 7 to 10). The atomic oxygen fluence for the samples can be calculated by solving Equation 1 for F and using the Kapton H mass loss value and density.

Experimental Procedures

Mass Loss Determination

When using mass loss data to obtain accurate erosion yield measurements, it is critical to recognize the hygroscopic (absorbing up to 2% of their weight in moisture) properties of many polymer samples, including Kapton. This causes fluctuations in mass with corresponding humidity and temperature. It is therefore imperative that samples be fully dehydrated (i.e., in a vacuum desiccator) before measuring mass for both pre-flight and post-flight measurements.

All MISSE 7 flight samples were dehydrated in a vacuum desiccator with a mechanical roughing pump. The samples were placed under vacuum in the desiccators at a constant pressure of 0-100 mtorr (0-0.013kPa) for at least 72 hours prior to weighing. In order to keep all the samples under vacuum during the weighing process, the desiccator would be put back under vacuum immediately when an individual sample was removed for weighing.

Duration of time under vacuum, relative humidity and temperature in the room were recorded prior to each set of weighing. For each sample, time at which the sample was removed from the desiccator, times at which samples were weighed, and sample mass were also recorded. Previous tests determined that the mass of a dehydrated sample was not affected by quickly opening a desiccator to retrieve another sample and putting it under vacuum again, which allowed multiple samples to be dehydrated and weighed together in sets.

The average of three mass readings was used to calculate mass loss, which was determined by subtracting the average post-flight mass from the average pre-flight mass. Pre-flight mass measurements were obtained using a Mettler Balance 3M. Post-flight mass measurements were taken using a Sartorius ME 5 Microbalance.

Density Determination

The densities of the samples were based on density gradient column measurements of polymers for the MISSE 2 PEACE Polymers experiment (Refs. 6, 11, and 12). The density gradient columns for the PEACE experiment 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 known densities of the glass standards. A plot of 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 7 as was used for MISSE 2. Manufacturers' densities were used for Vespel, PVC, PMP, PES, Torlon, PVOH, CN, CORIN, Vectran Mesh, and Kapton E, as they were not flown as part of the PEACE experiment.

Surface Area Determination

The exposed surface area of the samples was generally determined by taking three different width measurements and three different length measurements of each sample tray opening with Max-Cal electronic digital calipers. The average width was multiplied by the average length to calculate the square opening. However, the trays have rounded corners with a 0.062 inch (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 exposed sample area.

For two irregularly shaped samples on the N5-R tray, PVOH (N5-13) and urethane coated Vectran Mesh (N5-16), AutoCAD computer design software was used to trace the surface area from a photograph of the sample taken with a Sony digital camera. An example of the photo trace on the Vectran mesh sample is shown in Figure 5 below.

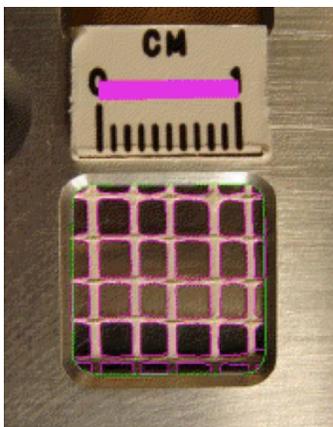


Figure 5. Example of AutoCAD phototrace (Vectran mesh (N5-16)).

Sample Stacking

For weighing, the samples were divided into 2 different parts. Part A consisted of the single top layer and Part B was made up of all additional layers. Part A and Part B were weighed separately post-flight. This way, only Part A needed to be weighed post-flight for samples with less than one layer of erosion.

Optical Microscopy

Optical microscopy was used to document select samples. The pictures were taken at magnifications of 7.5x to 20x with an Olympus SMZ stereo-zoom optical microscope equipped with a Canon digital camera.

Results and Discussion

Mass Loss Verification

The mass of the MISSE 7 control samples were obtained with the Sartorius ME 5 Microbalance used for post-flight massing and were found to be consistent with the pre-flight masses of the same samples taken with the Mettler Balance 3M.

Post-flight Inspection

B7-R Tray

Upon initial inspection post-flight, the B7-R tray showed discoloration and some sample degradation. This can be seen by comparing the post-flight photo of the B7-R tray, shown in Figure 6, to the pre-flight photo, shown in Figure 2. The Kapton films covering PVF (B7-2 and B7-3) were shown to have been completely eroded away. Samples exhibiting discoloration post-flight included FEP/PTFE/POM/PEO (B7-4), Kapton H/Mylar/PE/PG (B7-5), AO Pinhole Camera (B7-7), Kapton H (B7-8), Vespel (B7-9), and TiO₂/Al₂O₃/FEP (B7-11). Discoloration of samples can be attributed to erosion or radiation darkening. The FEP/PTFE/POM/PEO (B7-4) and Kapton H/Mylar/PE/PG (B7-5) samples, made for recession depth measurements, are not reported in this paper. Metal samples B7-12 - B7-15 are part of another experiment.

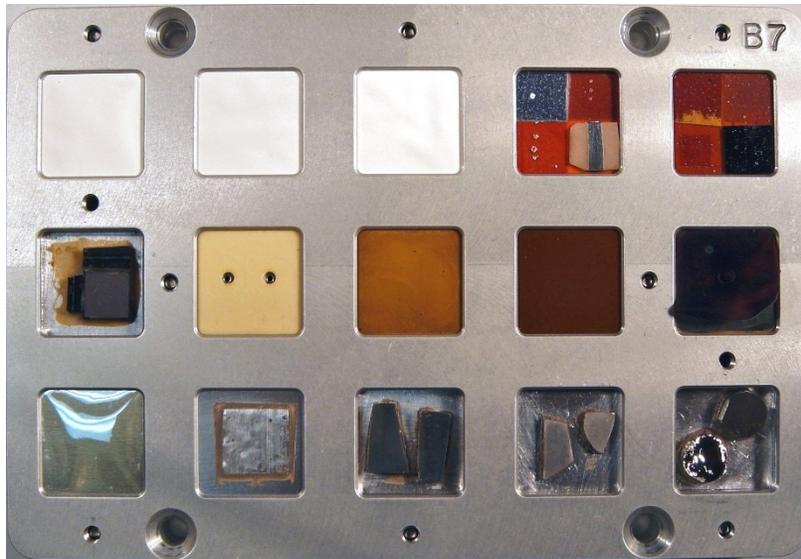


Figure 6. Post-flight photo of the MISSE 7 B7-R Tray.

The PVC sample (B7-10) also was found to have changed from a clear film to a very dark color, as shown in Figure 7. It was also eroded though at one edge and was curled up; hence, the E_y will be greater than the value determined. An impact site, formed by collision with micrometeorite or space debris, was discovered on the PVC sample and is shown in Figure 8.



Figure 7. The PVC flight sample (B7-10): a). Pre-flight photo, and b). Post-flight photo.



Figure 8. Micrometeoroid or debris impact site on the PVC (B7-10) flight sample.

N5-R Tray

During initial post-flight inspection, several samples in the N5-R tray showed significant discoloration and some sample degradation. This can be seen by comparing the post-flight photo of the N5-R tray, shown in Figure 9, to the pre-flight photo, shown in Figure 3. Samples showing discoloration included PE (N5-1), PES (N5-3), Kapton HN (N5-6), and Torlon (N5-12). An example of sample discoloration is shown in Figure 10 below for sample PES (N5-3).

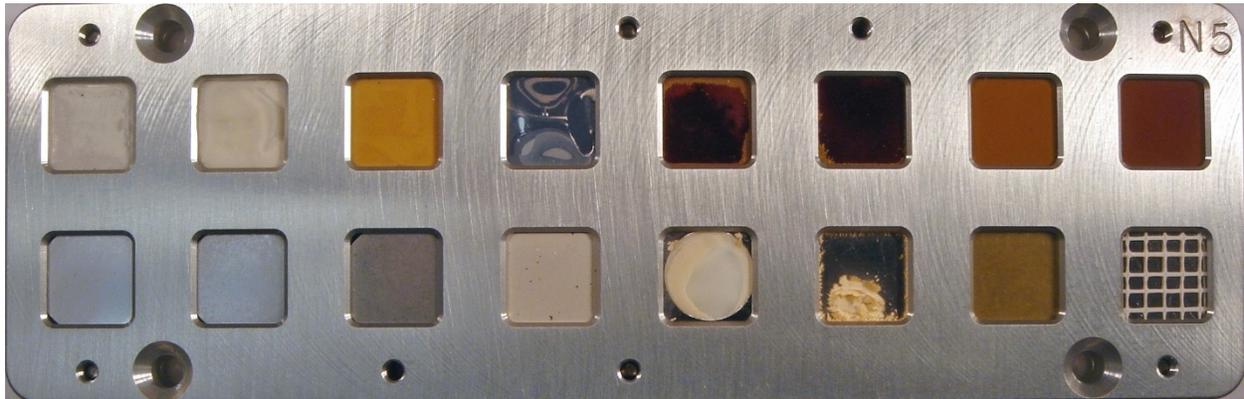


Figure 9. Post-flight photo of N5-R Tray.

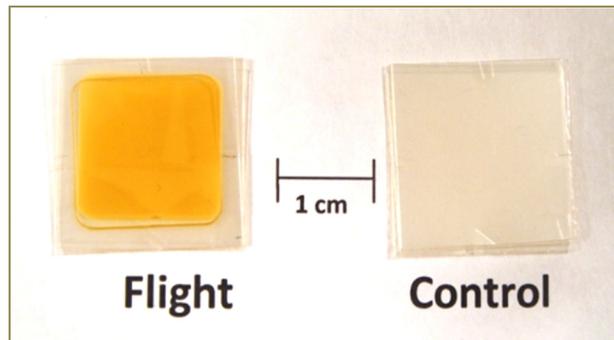


Figure 10. Post-flight photo of the PES (N5-3) flight sample (all layers stacked together) along with a control sample, showing sample discoloration.

Several samples showed substantial degradation, such as PE (N5-1), PMP (N5-2), Kapton H (N5-5), PVOH (N5-13), and CN (N5-14). The CN sample eroded completely through all seven layers flown, leaving a small amount of material in the exposed area, as can be seen in Figure 11. The erosion yield of this sample will be greater than the value determined. Figure 12 below shows a close up optical microscope picture taken of the fringe on the left side of the CN sample.

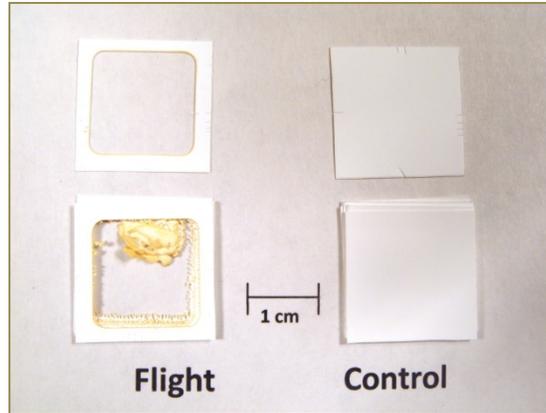


Figure 11. Post-flight photo of the CN (N5-14) flight sample (top layer (Part A) separated from bottom 6 layers (Part B)) along with a control sample, showing erosion through all layers.

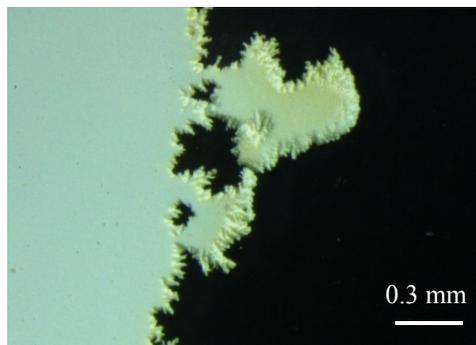


Figure 12. Close up photo of left border fringe on CN (N5-14) flight sample.

Zenith Tray

The Zenith tray exhibited significant sample discoloration and changes in texture. This can be seen by comparing the post-flight photo of the tray, shown in Figure 13, to the pre-flight photo, shown in Figure 4. Samples with discoloration included ETFE (Z-4), PVDF (Z-5), ECTFE (Z-6), PVF (Z-7), and Kapton H (Z-8). Samples with changes in texture included Kapton H (Z-8) and PE (Z-11), as shown in Figures 14 and 16 respectively. Figure 15 shows a close up image of the eroded border of the ETFE (Z-4) sample. For example, Kapton H (Z-8) developed a more matte appearance.



Figure 13. Post-flight photo of MISSE 7 Zenith Tray.

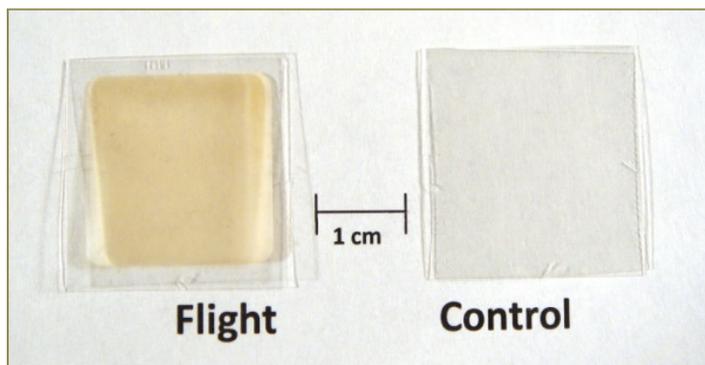


Figure 14. Post-flight photo of the ETFE (Z-4) flight sample (all layers stacked together) along with a control sample, showing sample degradation and discoloration.

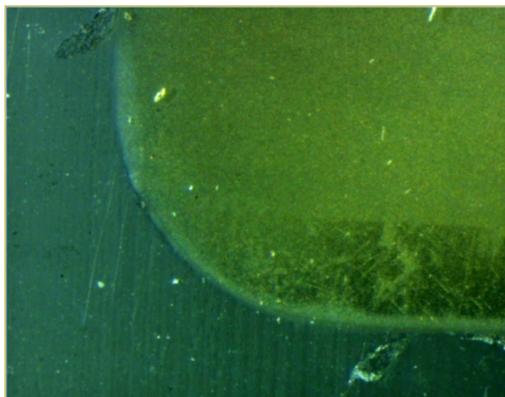


Figure 15. Close up of eroded border of ETFE (Z-4) flight sample.

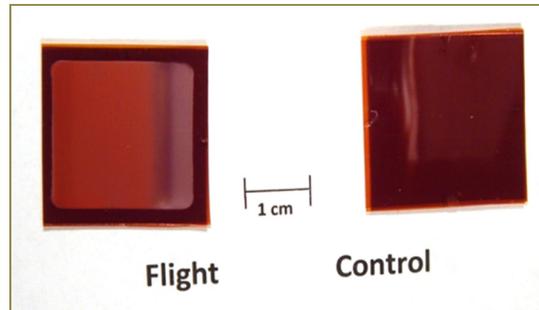


Figure 16. Post-flight photo of the Kapton H (Z-8) flight sample (all layers stacked together) along with a control sample, showing changes in sample texture.

Atomic Oxygen Fluence and Solar Exposure

The mass loss, surface area, density, erosion yield values, and computed fluence values are shown in Table 5 for the ram Kapton H fluence sample (B7-8) and the zenith Kapton H fluence sample (Z-8). The atomic oxygen fluence for the MISSE 7B ram tray was determined to be 4.22×10^{21} atoms/cm², and the atomic oxygen fluence for the MISSE 7A zenith tray was determined to be 1.58×10^{21} atoms/cm². Similar ram fluence values ($4.2 \pm 0.1 \times 10^{21}$ atoms/cm²) have been reported based on mass loss and thickness loss of Kapton HN (Ref. 13).

Table 5. Atomic Oxygen Fluence Determination.

MISSE 7 Tray	Sample ID	Material	Mass Loss (g)	Surface Area (cm ²)	Density (g/cm ³)	Kapton Ey (cm ³ /atom)	MISSE 7 Fluence (atom/cm ²)
Ram Tray B7-R	B7-8	Kapton H	0.077547	4.291	1.4273	3.00E-24	4.22E+21
Zenith Tray	Z-8	Kapton H	0.002897	4.278	1.4273	3.00E-24	1.58E+20

Estimates of solar exposure in equivalent sun hours (ESH) have been determined for the MISSE 7 ram, wake and zenith surfaces. The ram surface received an estimated 2,400 ESH and the wake surface received an estimated 2,000 ESH based on UV diode measurements on readings from ram and wake trays, respectively, monitored by the Lead-Free Technology Experiment in Space Environment (LTESE) (Ref. 13). Computations of the of zenith solar exposure have been conducted by Naval Research Laboratory (NRL) and were determine to be approximately 4,300 ESH (Ref. 14).

Erosion Yield Values

Ram Samples

Tables 6 and 7 provide sample ID, material, total mass loss, surface area, density, AO fluence, and erosion yield for the ram B7-R and ram N5-R trays, respectively. In the B7-R tray, samples with the highest Ey values and therefore the least durable included Kapton H (B7-8), Vespel (B7-9), and PVC (B7-10). Because the PVC sample was eroded through at one edge and curled up, as shown in Figure 7, the reported erosion yield is a lower bound. The polymer sample with the lowest erosion yield was the TiO₂/Al₂O₃ coated FEP sample (B7-11).

Table 6. Erosion Yield Values for B7-R Tray.

MISSE Sample ID	Material	Mass Loss (g)	Surface Area (cm ²)	Density (g/cm ³)	MISSE AO Fluence in atoms/cm ²	MISSE 7 Ey (cm ³ /atom)
B7-1	White Tedlar	0.004343	4.289	1.6241	4.22E+21	1.48E-25
B7-2	White Tedlar with a 0.5 mil Kapton H cover	0.004063	4.290	1.6241	3.79E+21	1.54E-25
B7-3	White Tedlar with two 0.5 mil Kapton covers (1.0 mil)	0.003907	4.281	1.6241	3.37E+21	1.67E-25
B7-8	Kapton H	0.077547	4.294	1.4273	4.22E+21	3.00E-24*
B7-9	Vespel	0.076224	4.292	1.43	4.22E+21	2.94E-24
B7-10	PVC (small dia. hole)	0.041485	4.209	1.34	4.22E+21	>1.74E-24
B7-11	TiO ₂ /Al ₂ O ₃ /FEP	0.000031	4.291	2.1443	4.22E+21	7.99E-28

*Kapton Ey from previous flight experiments (Refs. 7 to 10)

Table 7. Erosion Yield Values for N5-R Tray.

MISSE Sample ID	Material	Mass Loss (g)	Surface Area (cm ²)	Density (g/cm ³)	MISSE AO Fluence (atoms/cm ²)	MISSE 7 Ey (cm ³ /atom)
N5-1	Polyethylene (PE)	0.033375	2.097	0.918	4.22E+21	4.11E-24
N5-2	Polymethylpentene (PMP)	0.032763	2.096	0.833	4.22E+21	4.45E-24
N5-3	Polyethersulfone (PES)	0.033721	2.093	1.37	4.22E+21	2.79E-24
N5-4	Al-FEP*	0.003428	2.094	2.1443	4.22E+21	1.81E-25
N5-5	Kapton H	0.038461	2.095	1.4273	4.22E+21	3.05E-24
N5-6	Kapton HN	0.038111	2.095	1.4346	4.22E+21	3.01E-24
N5-7	Kapton HN with a 0.5 mil Kapton H cover	0.03257	2.097	1.4346	3.79E+21	2.85E-24
N5-8	Kapton HN with two 0.5 mil (1.0 mil) Kapton H covers	0.022312	2.094	1.4346	3.37E+21	2.20E-24
N5-12	Polyamide-imide (Torlon)	0.021855	2.099	1.42	4.22E+21	1.74E-24
N5-13	Polyvinyl alcohol (PVOH)	0.025248	1.490	1.28	4.22E+21	3.14E-24
N5-14	Cellulose nitrate (CN)	0.091079	2.099	1.5623	4.22E+21	>6.58E-24
N5-15	CORIN	0.000368	2.099	1.36	4.22E+21	3.05E-26
N5-16	Urethane/Vectran Mesh	0.001827	0.671	1.4	4.22E+21	4.61E-25

*Teflon layer was space facing

The Ey of the white Tedlar samples (B7-1, B7-2, B7-3) were analyzed. While B7-1 was flown as the sample uncovered, B7-2 and B7-3 were flown with Kapton H covers 0.5 mil and 1.0 mil thick respectively, which altered the fluence each white Tedlar sample received. Factoring in the fluence to erode each Kapton H film, fluence vs. Ey were plotted along with the Ey of a MISSE 2 sample (Ref. 6) and a line of best fit was graphed, as shown in Figure 17. As can be seen, the Ey decreases with increasing AO fluence. This is attributed to a buildup of AO durable TiO₂ particles on the surface of the samples with increasing AO exposure. The TiO₂ can protect the underlying material from erosion, thus decreasing the Ey with increasing AO fluence. White Tedlar results are further discussed in Banks 2012 (Ref. 15).

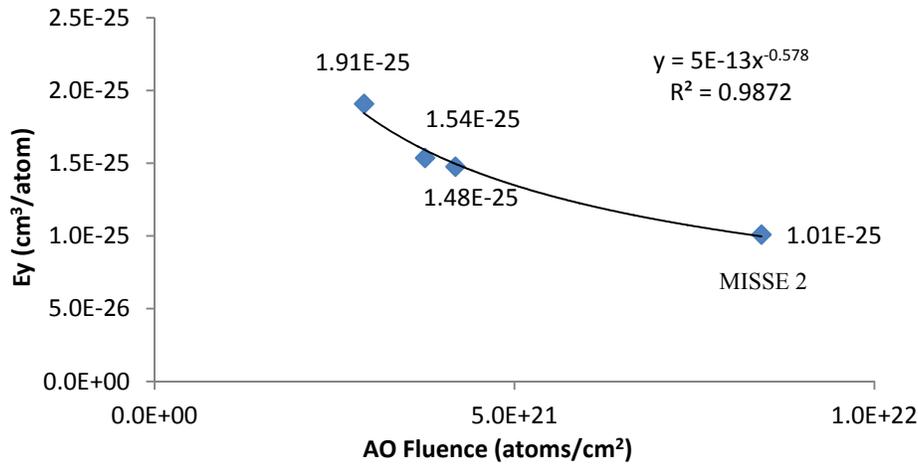


Figure 17. AO Fluence vs. E_y of White Tedlar from MISSE 2 and MISSE 7.

In the N5-R tray, the polymer sample with the highest erosion yield (most erosion) was CN (N5-14). Because the sample eroded all the way through during flight, the true E_y of the CN sample will be higher than the calculated E_y in this experiment. Other samples with notably high erosion yields included Kapton HN (N5-6), PE (N5-1), PMP (N5-2), and PVOH (N5-13).

The polymer sample with the lowest erosion yield was CORIN (N5-15), an AO resistant polymer. Other samples with low erosion yields included Al-FEP and the urethane coated Vectran mesh, samples that are commonly used in spacecraft applications.

Erosion yield values for Kapton HN covered with a 0.5 mil Kapton H cover (N5-7) and Kapton HN with a 1.0 mil Kapton H cover (N5-8) were found to have significantly lower erosion yields than expected. Even more surprising was that the three Kapton HN samples (N5-6 included) showed a trend of increasing E_y with increasing fluence. The reason for this is currently unknown.

Zenith Samples

Table 8 provides the sample ID, material, total mass loss, surface area, density, AO fluence, and erosion yield for the zenith “Z” samples. The polymer sample in the zenith tray with the greatest E_y was PE (Z-11). Other samples exhibiting high erosion yields included ECTFE (Z-6) and CTFE (Z-3). Samples with the lowest E_y include the three coated samples: Al₂O₃/FEP (Z-14) and TiO₂/Al₂O₃/FEP (Z-15) and Si/Kapton E/VDA (Z-12).

Table 8. Erosion Yield Values for Zenith Tray.

MISSE Sample ID	Material	Mass Loss (g)	Surface Area (cm ²)	Density (g/cm ³)	MISSE AO Fluence (atoms/cm ²)	MISSE 7 Ey (cm ³ /atom)
Z-1	Polytetrafluoroethylene (PTFE)	0.001330	4.256	2.1503	1.58E+20	9.19E-25
Z-2	Fluorinated ethylene propylene (FEP)	0.001407	4.263	2.1443	1.58E+20	9.74E-25
Z-3	Chlorotrifluoroethylene (CTFE)	0.002893	4.265	2.1327	1.58E+20	2.15E-24
Z-4	Ethylene-tetrafluoroethylene copolymer (ETFE)	0.001752	4.269	1.7397	1.58E+20	1.49E-24
Z-5	Polyvinylidene fluoride (PVDF)	0.002069	4.267	1.7623	1.58E+20	1.74E-24
Z-6	Ethylene-chlorotrifluoroethylene (ECTFE)	0.004038	4.281	1.6761	1.58E+20	3.56E-24
Z-7	Polyvinyl fluoride (PVF)	0.001347	4.280	1.3792	1.58E+20	1.44E-24
Z-8	Polyimide (Kapton H)	0.002897	4.279	1.4273	1.58E+20	3.00E-24*
Z-9	Aluminized-fluorinated ethylene propylene (Al-FEP)**	0.003219	4.285	2.1443	1.58E+20	2.22E-24
Z-10	Silvered-fluorinated ethylene propylene (Ag-FEP)**	0.001689	4.276	2.1443	1.58E+20	1.17E-24
Z-11	Polyethylene (low oxygen)	0.005077	4.303	0.918	1.58E+20	8.13E-24
Z-12	Si/Kapton E/Al	0.000116	4.279	1.4617	1.58E+20	1.17E-25
Z-14	Al ₂ O ₃ /FEP	0.000091	4.300	2.1443	1.58E+20	6.22E-26
Z-15	TiO ₂ /Al ₂ O ₃ /FEP	0.000020	4.289	2.1443	1.58E+20	1.40E-26

*Kapton Ey from previous flight experiments (Refs. 7 to 10)

**Teflon layer was space facing

Determination of the effect of UV radiation, and corresponding temperature effects, on the Ey of polymers flown in both ram and zenith directions can be made for PE, FEP and TiO₂/Al₂O₃/FEP. The Ey of the PE on the zenith tray, which received approximately 1.8X the ESH as the ram tray, was twice as high as the Ey of PE on the ram tray. The Ey of Teflon FEP on the zenith tray was an order of magnitude higher (12X) than the Ey on the ram tray. And, although the values were very small, the Ey of TiO₂/Al₂O₃/FEP on the zenith surface was approximately 18X greater in the zenith direction. These results indicate that solar radiation and corresponding temperature effects can play a significant role in polymer functionality and exacerbates degradation and therefore erosion of polymers in the space environment. It is desired to compare the Ey of these samples to similar polymers flown on previous MISSE missions, and other space exposure flight experiments.

Summary and Conclusions

MISSE 7, which contains the Polymers Experiment and the Zenith Polymers Experiment, flew on the ISS for 1.49 years. Mass loss, density, surface area, and fluence were determined to calculate the erosion yield of 34 samples flown as part of these two spaceflight experiments. Samples with the highest erosion yields included CN (N5-14), PMP (N5-2), PE (Z-11, N5-1), Kapton H (Z-8, B7-8, N5-5). Samples with the lowest erosion yields included TiO₂/Al₂O₃/FEP (B7-11, Z-15), Al₂O₃/FEP (Z-14), Si/Kapton E/VDA (Z-12) and urethane coated Vectran Mesh (N5-16).

Samples that flew on both N5-R (ram) and zenith trays exhibit much higher Ey values on the zenith tray (with more solar exposure and resulting higher average temperatures), indicating that solar exposure and therefore solar radiation play a vital role in polymer durability and intensify polymer degradation in space.

Desired future work includes: error analyses of fluence and Ey values, Ey determination of MISSE 7 wake and taped samples, erosion morphology studies, comparing MISSE 7 data to previous mission data for fluence effects, analysis of optical properties of samples, and more imagery and discussion on individual samples.

References

1. M. Nicolet and P. Mange, "The Dissociation of Oxygen in the High Atmosphere," *J. Geophys Res* (1954) Vol. 59, Issue 1, pp. 15-45.
2. Gregory: Gregory, J. C. "Proceedings of the NASA Workshop on Atomic Oxygen Effects," Nov. 10-11, 1986, JPL 87-14, 1987, pp. 29-30.
3. de Groh, K. K., Banks, B. A., Dever, J. A., Jaworske, K. J., Miller, S. K., Sechkar, E. A. and Panko, S. R., "NASA Glenn Research Center's Materials International Space Station Experiments (MISSE 1-7)," Proceedings of the International Symposium on "SM/MPAC&SEED Experiment," Tsukuba, Japan, March 10-11, 2008, JAXA-SP-08-015E, March 2009, pp. 91 – 119; also NASA TM-2008-215482, December 2008.
4. 2000 ASTM Standard Extraterrestrial Spectrum Reference E-490-00 2000, Available at <http://rrede.nrel.gov/solar/sectra/AMO>.
5. Dever, J. A., "Low Earth Orbital Atomic Oxygen and Ultraviolet Radiation Effects on Polymers," NASA TM 103711, February 1991.
6. de Groh, K. K. Banks, B. A. McCarthy, C. E. Rucker, R. N. Roberts L. M. and Berger, L. A., "MISSE 2 PEACE Polymers Atomic Oxygen Erosion Experiment on the International Space Station," *High Performance Polymers* 20 (2008) 388-409.
7. Banks, B. A., Mirtich, M. J., Rutledge, S. K. and Swec, D. M., "Sputtered Coatings for Protection of Spacecraft Polymers," *Thin Solid Films*, 127, pp. 107-114, 1985.
8. J. T. Visentine, L. J. Leger, J. F. Kuminecz and I. K. Spiker, "STS-8 Atomic Oxygen Effects Experiment," AIAA-85-0415, 1985.
9. Koontz, S. L., Leger, L. J., Visentine, J. T., Hunton, D. E., Cross, J. B. and Hakes, C. L., "EOIM-III Mass Spectrometry and Polymer Chemistry: STS 46, July-August 1992," *Journal of Spacecraft and Rockets*, Vol. 32, No. 3, May-June 1995, pp. 483-495.
10. Silverman, E., M., "Space Environmental Effects on Spacecraft: LEO Materials Selection Guide," NASA CR 4661, Part 1, August 1995.
11. de Groh, K. K., Banks, B. A., McCarthy, C. E., Berger, L. A., and Roberts, L. M., "Analysis of the MISSE PEACE Polymers International Space Station Environmental Exposure Experiment," ESA SP-616, September 2006.
12. de Groh, K. K., Banks, B. A., McCarthy, C. E., Rucker, R. N., Roberts, L. M., and Berger, L. A., "MISSE PEACE Polymers Atomic Oxygen Erosion Results," Proceedings of the 2006 National Space & Missile Materials Symposium (NSMMS); also NASA TM-2006-214482, November 2006.
13. Finckenor, M. M. (NASA Marshall Space Flight Center), personal communication, November 2012.
14. Jenkins, P. P. (Naval Research Laboratory), personal communication, November 2012
15. Banks, B. A., Simmons, J. C., de Groh, K. K., Miller, S. K., "The Effect of Ash and Inorganic Pigment Fill on the Atomic Oxygen Erosion of Polymers and Paints," Proceedings of the 12th International Symposium on Materials in the Space Environment (ISMSE 12)," Noordwijk, The Netherlands (ESA SP-705, March 2013).

