



Erosion Results of the MISSE 7 Polymers Experiment and Zenith Polymers Experiment After 1.5 Years of Space Exposure

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

Bruce A. Banks
Science Application International Corporation, Cleveland, Ohio

Grace T. Yi, Athena Haloua, Emily C. Imka, Gianna G. Mitchell, Olivia C. Asmar,
and Halle A. Leneghan
Hathaway Brown School, Shaker Heights, Ohio

Edward A. Sechkar
ZIN Technologies, Inc., Middleburg Heights, Ohio

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National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

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Page 11, Table 5: Corrections have been made.

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National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Bruce A. Banks
Science Application International Corporation
Cleveland, Ohio 44135

Grace T. Yi, Athena Haloua, Emily C. Imka, Gianna G. Mitchell
Olivia C. Asmar, and Halle A. Leneghan
Hathaway Brown School
Shaker Heights, Ohio 44122

Edward A. Sechkar
ZIN Technologies, Inc.
Middleburg Heights, Ohio 44130

Abstract

Polymers and other oxidizable materials on the exterior of spacecraft in the low Earth orbit (LEO) space environment can be eroded due to reaction with atomic oxygen (AO). Therefore, in order to design durable spacecraft it is important to know the LEO AO erosion yield (E_y , volume loss per incident oxygen atom) of materials susceptible to AO reaction. Two spaceflight experiments, the Polymers Experiment and the Zenith Polymers Experiment, were developed to determine the AO E_y of various polymers flown in ram, wake or zenith orientations in LEO. These experiments were flown as part of the Materials International Space Station Experiment 7 (MISSE 7) mission for 1.5 years on the exterior of the International Space Station (ISS). The experiments included Kapton H[®] witness samples for AO fluence determination in ram and zenith orientations. The Polymers Experiment also included samples to determine whether AO erosion of high and low ash containing polymers is dependent on fluence. This paper provides an overview of the MISSE 7 mission, a description of the flight experiments with details on the polymers flown, the characterization techniques used, the AO fluence for each exposure orientation, and the LEO E_y results. The E_y values ranged from 7.99×10^{-28} cm³/atom for TiO₂/Al₂O₃ coated Teflon[®] fluorinated ethylene propylene (FEP) flown in the ram orientation to 1.22×10^{-23} cm³/atom for polyvinyl alcohol (PVOH) flown in the zenith orientation. The E_y of similar samples flown in different orientations has been compared to help determine solar exposure and associated heating effects on AO erosion. The E_y data from these ISS spaceflight experiments provides valuable information for LEO spacecraft design purposes.

Acronyms

AFRL	Air Force Research Laboratory
Al-FEP	aluminized-fluorinated ethylene propylene
Ag-FEP	silvered-fluorinated ethylene propylene

AO	atomic oxygen
CN	cellulose nitrate
CTFE	chlorotrifluoroethylene
ECTFE	ethylene-chlorotrifluoroethylene
ELC	EXPRESS Logistic Carrier
ESH	equivalent sun hours
ETFE	ethylene-tetrafluoroethylene copolymer
EVA	extravehicular activity
E_y	erosion yield
FEP	fluorinated ethylene propylene
C-FEP	back-surface carbon painted fluorinated ethylene propylene
HB	Hathaway Brown School
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
LaRC	Langley Research Center
LCP	liquid crystal polymer
LDEF	Long Duration Exposure Facility
LEO	low Earth orbit
LIDS	Low Impact Docking System
MISSE	Materials International Space Station Experiment
MMOD	micrometeoroids and orbital debris
O ₂	diatomic oxygen
O ₃	ozone
PAI	polyamide-imide
PE	polyethylene
PEACE	Polymer Erosion and Contamination Experiment
PEC	Passive Experiment Containers
PEO	polyethylene oxide
PES	polyethersulfone
PI	polyimide
PMP	polymethylpentene
POSS	polyhedral oligomeric silsesquioxane
PP	polypropylene
PTFE	polytetrafluoroethylene
PVC	polyvinyl chloride
PVDF	polyvinylidene fluoride
PVF	polyvinyl fluoride
PVOH	polyvinyl alcohol
STS	Space Transportation System
UV	ultraviolet
VUV	vacuum ultraviolet
+XVV	X Axis Near Velocity Vector

Introduction

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

Atomic oxygen is formed in the LEO environment through photodissociation of diatomic oxygen (O_2). Short wavelength (<243 nm) solar radiation has sufficient energy to break the 5.12-eV O_2 diatomic bond in an environment where the mean free path is sufficiently long ($\sim 10^8$ m) that the probability of re-association, or the formation of ozone (O_3), is small (Refs. 1 and 2). In LEO, between the altitudes of 180 and 650 km, AO is the most abundant species (Ref. 3).

A number of processes can take place when an oxygen atom strikes a spacecraft surface as a result of its orbital velocity and the thermal velocity of the atoms. These include chemical reaction with surface molecules, elastic scattering, scattering with partial or full thermal accommodation, and recombination or excitation of ram species, which consists of predominantly of ground state $O(^3P)$ atomic oxygen atoms (Ref. 4). Atomic oxygen can react with polymers, carbon, and many metals to form oxygen bonds with atoms on the exposed surface. For most polymers, hydrogen abstraction, oxygen addition, or oxygen insertion can occur with the oxygen interaction pathways eventually lead to volatile oxidation products (Refs. 5 and 6). This results in gradual erosion of hydrocarbon or halocarbon material, with the exception of silicone materials. An example of the complete loss of a Kapton® H thermal blanket insulation layer, as well as degradation of other polymeric materials caused by AO erosion in LEO, is provided in Figure 1 (Ref. 7). Even materials with AO protective coatings can be susceptible to AO erosion as a result of microscopic scratches, dust particles, or other imperfections in the substrate surface which can result in defects or pin windows in the protective coating (Refs. 8 and 9). These coating defects can provide pathways for AO attack, and undercutting erosion of the substrate can occur, even under directed ram AO exposure in LEO. One of the first examples of directed ram AO undercutting erosion in LEO was reported by de Groh and Banks for aluminized-Kapton insulation blankets from the Long Duration Exposure Facility (LDEF) (Ref. 8).

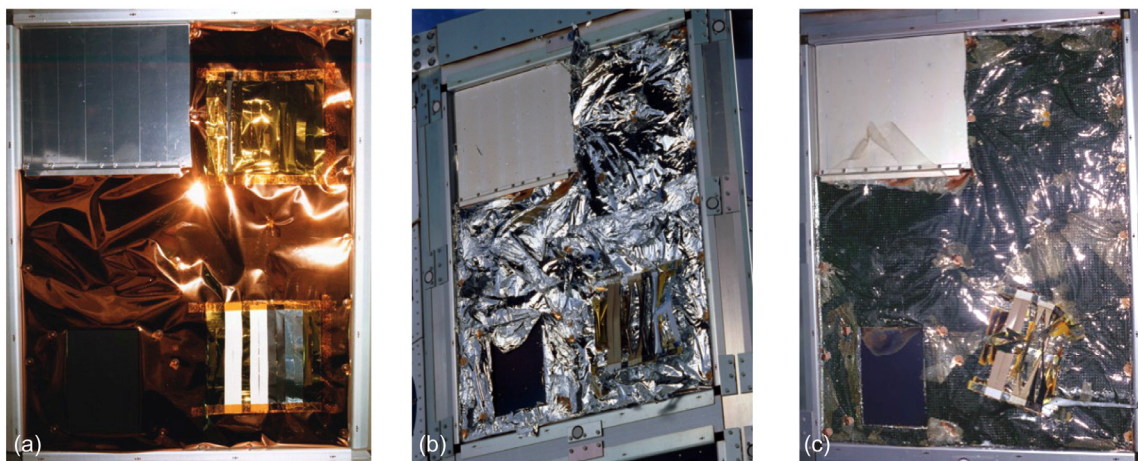


Figure 1.—Atomic oxygen erosion of a Kapton® insulation blanket from Long Duration Exposure Facility (LDEF) experiment Tray F09, located on the leading edge and exposed to direct-ram AO for 5.8 years: a). Pre-flight photo, b). On-orbit just prior to retrieval, and c). Post-flight photo (Ref. 7).

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

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

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

As part of the MISSE 7 mission, two NASA Glenn Research Center experiments called the Polymers Experiment and the Zenith Polymers Experiment were flown on the exterior of the ISS and exposed to the LEO space environment for 1.5 years. The primary objective of the Polymers Experiment was to determine the LEO AO E_y of the polymers. The primary objective of the Zenith Polymers Experiment was to determine the effect of solar exposure on the E_y of fluoropolymers. Both experiments included Kapton H witness samples for AO fluence determination. Both experiments also included tensile samples to assess mechanical property degradation after LEO space exposure, although these results are reported elsewhere. This paper provides an overview of the MISSE 7 mission, a description of the MISSE 7 Polymers Experiment and Zenith Polymers Experiment with details on the polymers flown, pre-flight and post-flight characterization techniques, the AO fluence for each exposure orientation, and a summary of the AO E_y results. The MISSE 7 E_y of similar samples flown in different orientations has been compared to help determine solar exposure and associated heating effects on LEO E_y values.

Materials International Space Station Experiment (MISSE) Overview

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

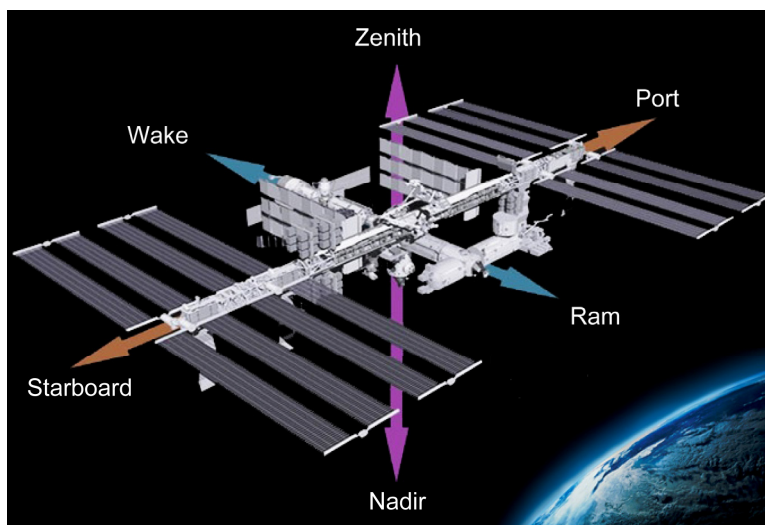


Figure 2.—Diagram showing ram (flight direction), wake, zenith, and nadir directions on the International Space Station.

and opened exposing the experiments to the space environment for the duration of the mission. A diagram showing ram, wake, zenith, and nadir directions on the ISS is shown in Figure 2. The flight orientation highly affects the environmental exposure. Ram facing experiments receive a high flux of directed AO and sweeping (moderate) solar exposure. Zenith facing experiments receive a low flux of grazing arrival AO and the highest solar exposure. Wake experiments receive very low AO flux and moderate solar radiation levels similar to ram experiments. Nadir experiments receive a low flux of grazing arrival AO and minimal solar radiation (albedo sunlight). All surfaces receive charged particle and cosmic radiation, which are omni-directional. It should be noted that the actual orientation of the ISS varies due to operational requirements with the majority of time spent within $\pm 15^\circ$ of the +XVV Z nadir flight attitude (X Axis Near Velocity Vector, Z Axis Nadir/Down). Deviations from this attitude to accommodate visiting spacecraft, and other ISS operational needs, can cause variations in the orientation directions, and hence variations in environmental exposures.

The MISSE 7 mission consisted of two PECs called MISSE 7A and 7B, which were flown in zenith/nadir and ram/wake orientations, respectively, on the ISS EXPRESS Logistic Carrier 2 (ELC-2) site. MISSE 7A and 7B were placed on the exterior of the ISS during the STS-129 Shuttle mission on November 23, 2009 and retrieved during the STS-134 Shuttle mission on May 20, 2011 after 1.49 years of space exposure. Figure 3 shows the location of MISSEs 7A and 7B on the ISS ELC-2. Figure 4 shows the zenith side of MISSE 7A and the ram side of 7B as imaged during the STS-130 mission in February 2010.

MISSE 7B Polymers Experiment

The MISSE 7B Polymers Experiment was a passive experiment with 45 samples, which were flown in ram or wake orientations on MISSE 7B. The objectives of the Polymers Experiment were: 1) to determine the LEO AO E_y of the polymers, 2) to determine if AO erosion of high and low ash (inorganic filler, which are usually metal oxides often used for coloring or processing) containing polymers is dependent on fluence, and 3) to assess changes in mechanical properties of polymers after ram or wake exposure. It is also desired to determine changes in the optical properties of the polymers after ram or wake exposure. Thirty-eight of the samples were flown in the ram direction, exposing them to high AO and solar radiation. Thirty ram samples were flown for E_y evaluation (27 for mass-based E_y determination and 3 for recession depth based E_y determination). Six ram tensile samples were flown for mechanical property assessment. A Kapton H[®] sample was flown in the ram direction for AO fluence determination,

and a fused alumina (Al_2O_3) slide was flown for contamination analyses. High and low ash content filled polymers were flown in the ram direction and exposed to varying levels of AO fluence by the inclusion of very thin sacrificial Kapton film covers. Seven samples were flown in the wake orientation, exposing them to solar radiation with minimal AO. Five samples were flown for mass based E_y determination and two tensile samples were flown for mechanical property assessment.

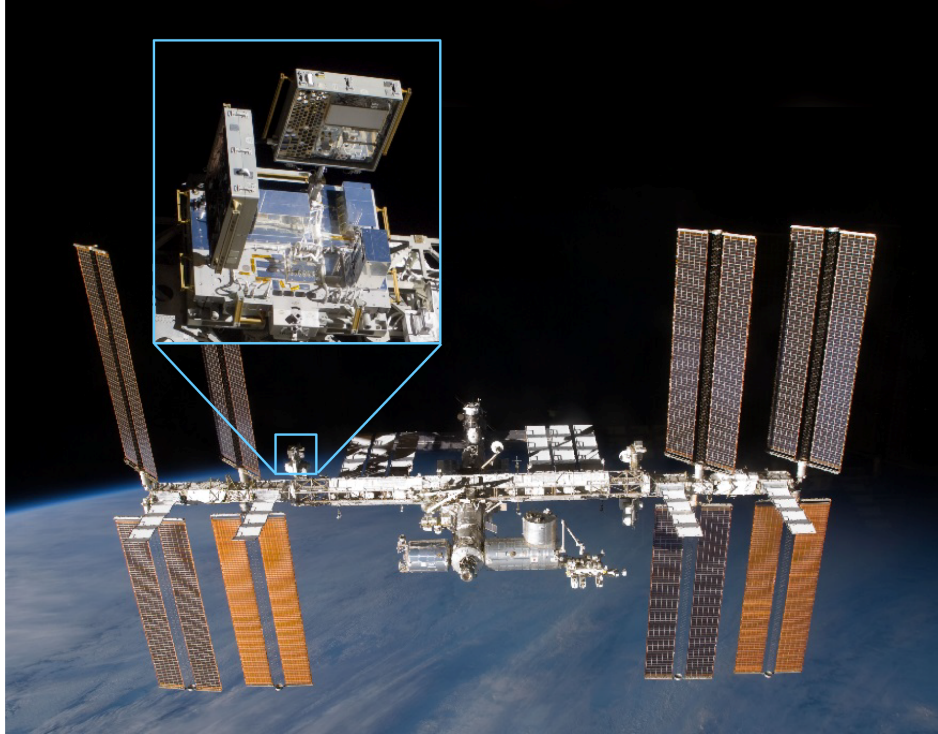


Figure 3.—Location of MISSEs 7A and 7B on the ISS ELC-2 as imaged during the STS-129 shuttle mission in November 2009 shortly after deployment.

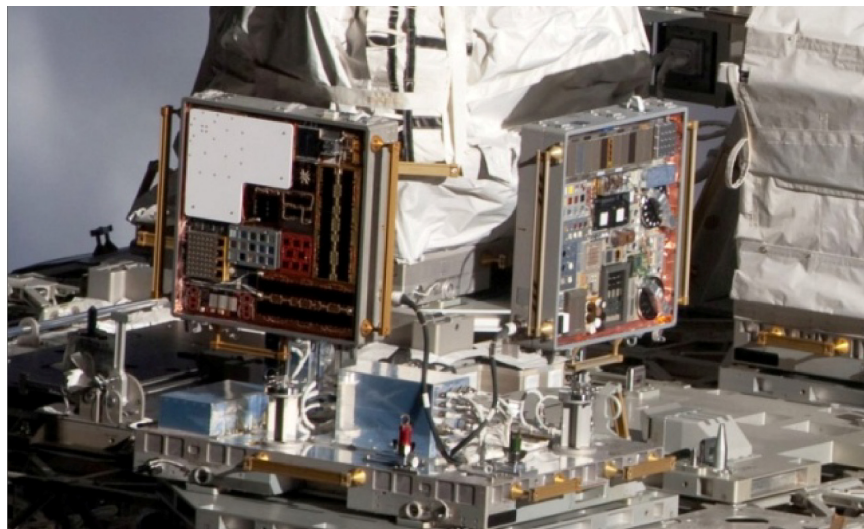


Figure 4.—On-orbit photo of MISSE 7A (left, zenith surface shown) and 7B (right, ram surface shown) as imaged during the STS-130 shuttle mission in February 2010.

The majority of samples were flown in two trays: Tray B7-R which held 15 to 1 in. (2.54 cm) square samples, shown in Figure 5, and Tray N5-R which held 16 to 0.75 in. (1.905 cm) square samples, shown in Figure 6. Samples B7-12 to B7-15 in Figure 5, and N5-9 to N5-11 in Figure 6 were part of other MISSE 7 experiments. In addition, numerous samples, including the tensile samples, were flown in hand-made Al foil holders which were taped directly to the baseplate using thermal control tape. The ram facing taped samples are shown in Figure 7. The wake facing taped samples are shown in Figure 8.

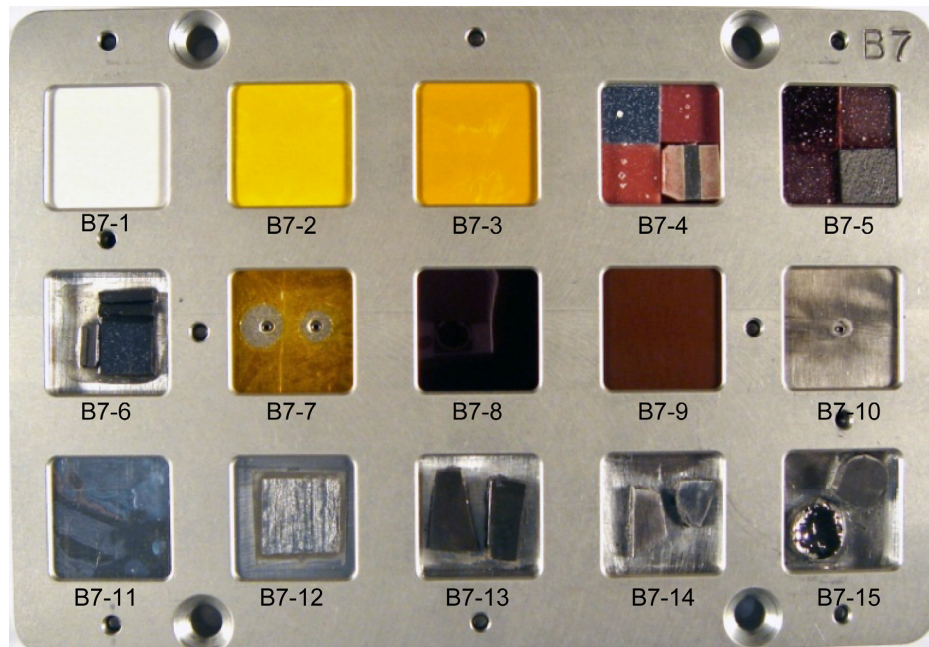


Figure 5.—Pre-flight photo of the MISSE 7 B7-R tray with sample Ids.

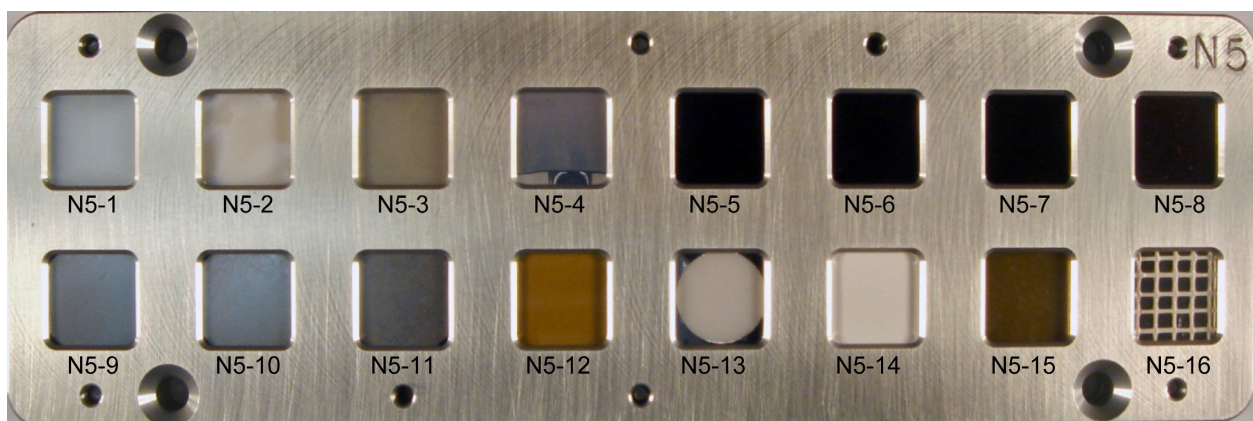


Figure 6.—Pre-flight photo of the MISSE 7 N5-R tray with sample Ids.

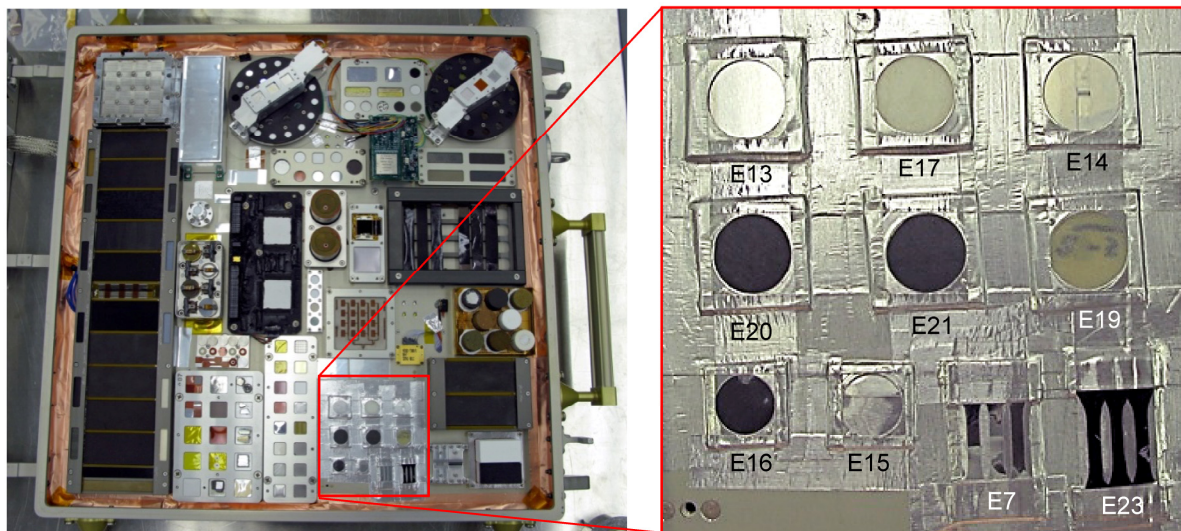


Figure 7.—Pre-flight photo of the MISSE 7B ram tray with a close-up photo of the taped samples along with their sample IDs. (Photo credit: Naval Research Laboratory)

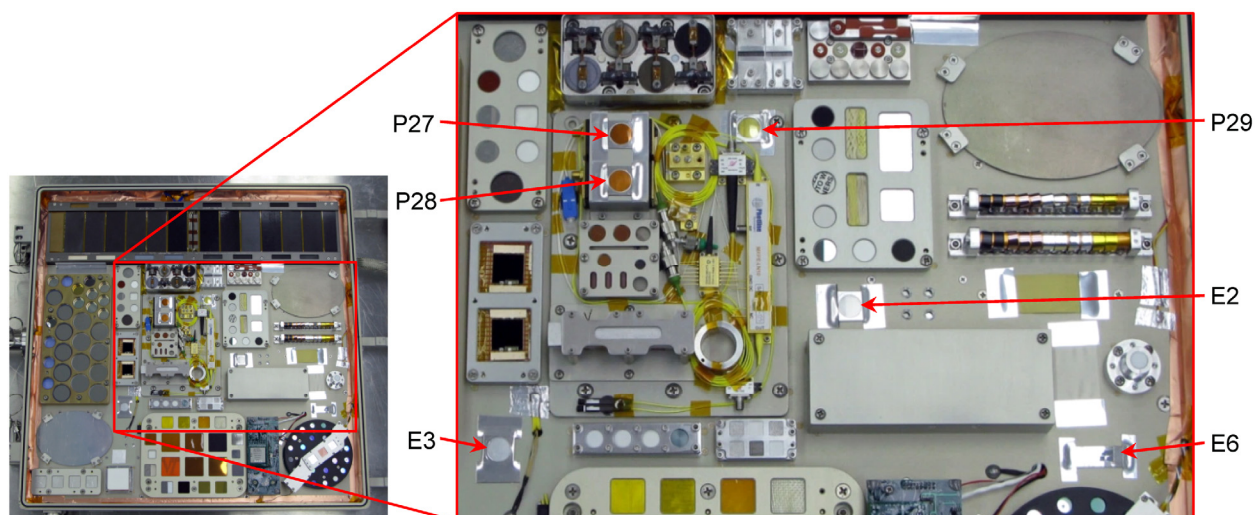


Figure 8.—Pre-flight photo of the MISSE 7B wake tray with a close-up photo of the taped samples along with their sample IDs. (Photo credit: Naval Research Laboratory)

Tables 1 to 4 provides lists of the MISSE 7B Polymers Experiment samples flown for mass-loss based E_y , along with the sample ID, sample size, film thickness and number of layers flown (to allow mass measurements to be made in the event that erosion of more than one layer would occur). The ram E_y samples are listed in Tables 1 to 3 and the wake E_y samples are listed in Table 4. A sample of polyvinyl chloride (PVC, B7-10) was flown on the top of a small aluminum covered Atomic Oxygen Scattering Chamber. The PVC was flown with a 0.127 in. (0.323 cm) diameter hole in the center. The back-surface carbon painted fluorinated ethylene propylene (C-FEP) taped samples (E16, and zenith sample E4 discussed below) were prepared by AO treating the non-exposed side of a clear FEP film to increase adherence prior to coating the surface with a layer of carbon paint. The Kapton H and Kapton HN polyimide samples are chemically identical except Kapton HN has a higher ash content (calcium phosphate dibasic (CaHPO_4)), which causes its E_y to be slightly lower. The MISSE 7B Polymers Experiment included samples from the Japan Aerospace Exploration Agency (JAXA), Towson University, Montana State University, NeXolve Corporation, ATK Space, Air Force Research Laboratory (AFRL), NASA Langley Research Center (LaRC) and the National Institute of Aerospace.

TABLE 1.—MISSE 7 POLYMERS EXPERIMENT RAM “B7-R” TRAY E_y SAMPLES

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

TABLE 2.—MISSE 7 POLYMERS EXPERIMENT RAM “N5-R” TRAY E_y SAMPLES

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

*Teflon layer is space facing

TABLE 3.—MISSE 7B POLYMERS EXPERIMENT RAM “TAPED” E_y SAMPLES

MISSE Sample ID	Material	Trade name (Abbreviation)	Size (in.)	Thickness (mil)	Layers
E14	Polypropylene	(PP)	1×1	20	1
E15	Copolymer of polytetrafluoroethylene, perfluoropropyl vinyl ether, perfluoromethyl vinyl ether	Hyflon 620, MFA	0.75×0.75	4	1
E16	Back-surface carbon painted fluorinated ethylene propylene	(C-FEP)	0.75×0.75	2	1
E17	Polyethylene oxide	(PEO)	1 in. dia. (1×1 foil)	36	1
E19	120FG/EX1515 Fiber Glass/Fiber/Cyanate Ester	120FG/EX1515	1 in. dia. (1×1 foil)	39	1
E20	M55J/954-3 Carbon Fiber/Cyanate Ester	M55J/954-3	1 in. dia. (1×1 foil)	35	1
E21	M55J/966 Carbon Fiber/Cyanate Ester with 10% Silicone	M55J/966	1 in. dia. (1×1 foil)	35	1

TABLE 4.—MISSE 7B POLYMERS EXPERIMENT WAKE “TAPED” E_y SAMPLES

MISSE Sample ID	Material	Trade name (Abbreviation)	Size (in.)	Thickness (mil)	Layers
P27	Polyhedral oligomeric silsesquioxane coated Kapton HN	POSS/Kapton HN	0.75×0.75	2	1
P28	Polyhedral oligomeric silsesquioxane coated abraded Kapton HN	POSS/abraded Kapton HN	0.75×0.75	2	1
P29	CORIN (AO resistant polyimide)	CORIN	0.75×0.75	2	7
E2	Polyvinyl fluoride	(PVF)	0.75×0.75	1	19
E3	Polypropylene	(PP)	0.75×0.75	20	1

It should be noted that the E_y data for the tray samples has been previously reported by Yi (Ref. 15). This report documents the E_y data for all the MISSE 7 mass-loss based E_y samples (tray and taped). The results of the ram samples for recession-depth based E_y and the ram alumina contamination sample will be discussed elsewhere. The ram and wake tensile samples (E6, E7, and E23) and their results are reported by de Groh (Ref. 16).

MISSE 7A Zenith Polymers Experiment

The Zenith Polymers Experiment consisted of 25 samples, which were flown in a zenith flight orientation. The objectives of the Zenith Polymers Experiment were: 1) to determine the effect of solar exposure on the E_y of fluoropolymers under high solar/low AO exposure, and 2) to assess changes in mechanical properties of polymers exposed to zenith exposure. In addition, similar to the Polymers Experiment, it is also desired to determine changes in the optical properties of the polymers after zenith space exposure. Determining the effect of solar exposure on the E_y under high solar/low AO exposure was accomplished by comparing the E_y of samples of varying solar/AO fluence ratios from other MISSE 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. 17). Twenty samples were flown for E_y determination and five tensile samples were flown for mechanical property assessment.

The experiment included 15 square samples, 1×1 in. (2.54 cm²), flown in the MISSE 7A “Z” tray. The specific polymers flown for mass based E_y are listed in Table 5 along with the sample ID, sample size, film thickness and number of layers flown. A pre-flight photo of the Zenith Polymers Experiment sample tray is shown in Figure 9. Kapton H[®] was flown for AO 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 AO and VUV radiation barrier coated FEP samples from Montana State University. Analyses of the Orion LIDS Seal O-ring samples (sample Z-13) are reported by Imka (Ref. 18).

TABLE 5.—MISSE 7 ZENITH “Z” TRAY E_y SAMPLES

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

*Teflon layer was space facing

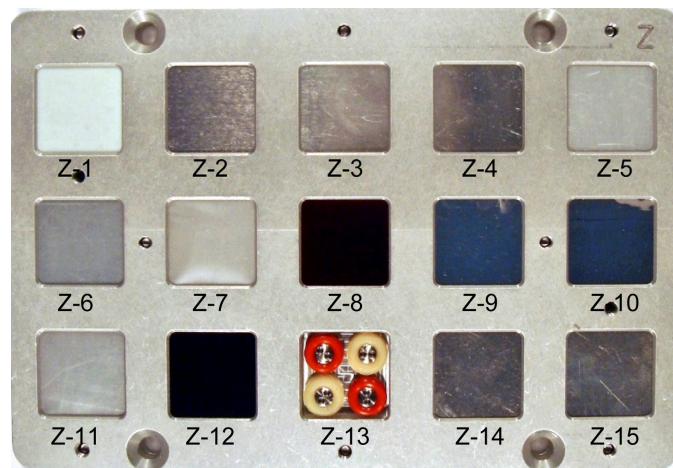


Figure 9.—Pre-flight photo of the MISSE 7A Zenith Tray with sample Ids.

The Zenith Polymers Experiment also included 10 “taped” samples, flown in Al holders which were taped directly to the baseplate (similar to the ram and wake taped samples). The zenith taped samples are shown in Figure 10. Five of the taped samples were for mass-loss based E_y and 2 holders contained five tensile samples for mechanical property assessment. The zenith Tray Z E_y samples are listed in Table 6 along with their sample ID, sample size, film thickness and number of layers flown.

Like the ram and wake tray samples, it should be noted that the E_y data for the zenith tray samples has been reported by Yi (Ref. 15). This report documents the E_y data for all the MISSE 7 zenith E_y samples (tray and taped). The zenith tensile samples (E6, E7, and E23) and their results are reported along with the ram and wake tensile data by de Groh (Ref. 16).

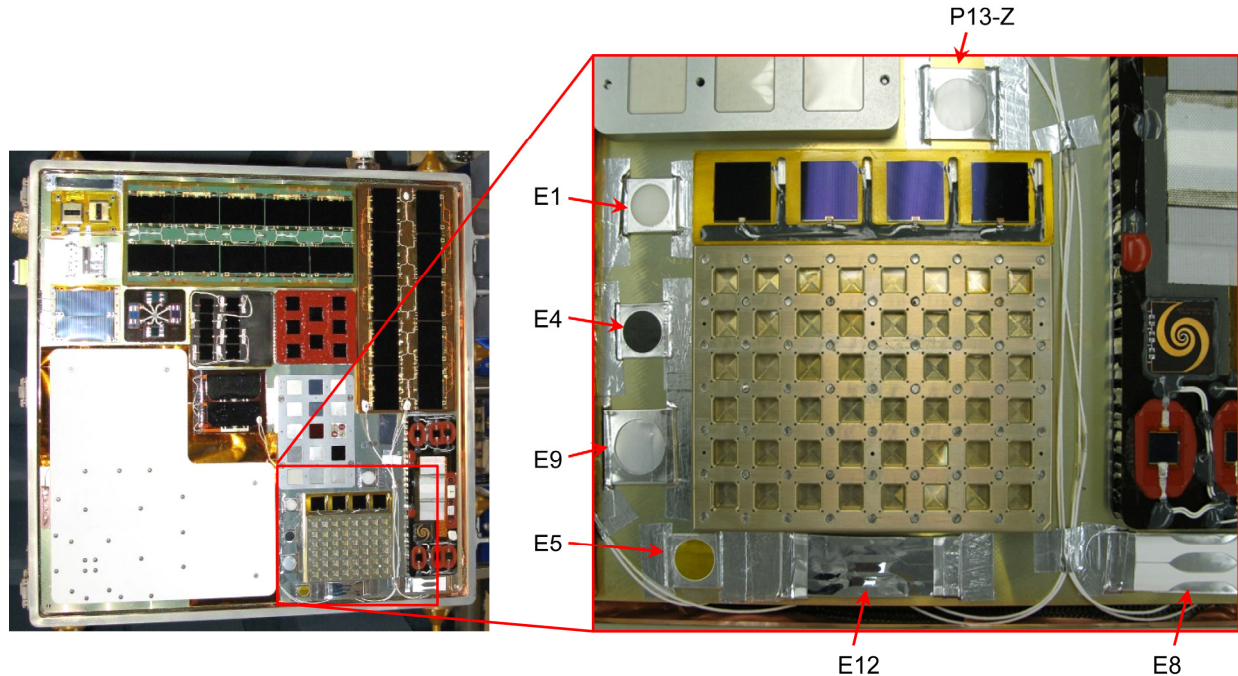


Figure 10.—Pre-flight photo of the MISSE 7A zenith tray with a close-up image of the taped samples along with their sample IDs. (Photos courtesy of the Naval Research Laboratory).

TABLE 6.—MISSE 7 ZENITH TAPED E_y SAMPLES

MISSE Sample ID	Material	Abbreviation	Size (in.)	Thickness (mils)	Number of layers
E1	Polyethylene oxide	PEO	0.75×0.75	36	1
E4	Back-surface carbon painted fluorinated ethylene propylene	C-FEP	0.75×0.75	2	1
E5	Side-chain polyhedral oligomeric silsesquixane	SC-POSS	0.75×0.75	2.8	1
E9	Polypropylene	PP	1×1	20	1
P13-Z	Polyvinyl alcohol	PVOH	1×1	1.5	12

MISSE 7 Erosion Yield and Atomic Oxygen Fluence Determination

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

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

Where

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

The AO fluence (F) can be determined through the mass loss of a Kapton H witness sample because Kapton H has a well characterized erosion yield, E_K (3.0×10^{-24} cm³/atom) in the LEO environment (Refs. 10 to 13). Therefore, the AO fluence can be calculated using the following equation:

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

Where

F	low Earth orbit AO fluence (atoms/cm ²)
ΔM_K	mass loss of Kapton H witness sample (g)
A_K	surface area of Kapton H witness sample exposed to AO (cm ²)
ρ_K	density of Kapton H witness sample (1.4273 g/cm ³)
E_K	erosion yield of Kapton H witness sample (3.0×10^{-24} cm ³ /atom)

Thus

$$E_y = E_K \frac{\Delta M_s A_K \rho_K}{\Delta M_K A_s \rho_s} \quad (3)$$

Experimental Procedures

Mass Loss Determination

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

Samples were dehydrated in a vacuum desiccator maintained at a pressure of 8.0 to 13.3 Pa (60 to 100 mtorr) with a mechanical roughing pump. Typically, five flight samples and their corresponding control samples were placed in a vacuum desiccator, in a particular order, and left under vacuum for a minimum of 72 hr. Once a sample was removed for weighing, the vacuum desiccator was immediately put back under vacuum to keep the other samples under vacuum. Previous tests showed that the mass of a dehydrated sample was not adversely affected if the desiccator was opened and quickly closed again and pumped back down to approximately 20 Pa (150 mtorr) prior to that sample being weighed. This process allows multiple samples to be dehydrated together.

The time at which the sample was first exposed to air was recorded along with the times at which it was weighed. A total of three mass readings were obtained and averaged. The total time it took to obtain the three readings, starting from the time air was let into the desiccator, was typically 5 min. The samples were weighed pre-flight using either a Mettler Balance 3M (0.000001 g sensitivity) or a Sartorius Balance R160P (0.00001 g sensitivity), depending on their total mass. Records of the following were kept: the sequence of sample weighing, the number of samples in each set, the time under vacuum prior to weighing, the temperature and humidity in the room, the time air was let into the desiccator and the time a sample was taken out of the desiccator, the time of each weighing and the mass. The same procedure and sequence was repeated with the same samples post-flight, but using a Sartorius ME 5 Microbalance (0.000001 g sensitivity) or the Sartorius Balance R160P. It should be noted that the mass of numerous 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.

Density Determination

The densities of the samples were based on density gradient column measurements of polymers for the MISSE 2 Polymer Erosion and Contamination Experiment (PEACE) Polymers experiment (Refs. 2 and 17) or density gradient column measurements conducted for this study. The density gradient columns were created in 50-mL burets with solvents of cesium chloride (CsCl , $\rho \approx 2 \text{ g/cm}^3$) and water (H_2O , $\rho = 1.0 \text{ g/cm}^3$), for less dense polymers, or carbon tetrachloride (CCl_4 , $\rho = 1.594 \text{ g/cm}^3$) and bromoform (CHBr_3 , $\rho = 2.899 \text{ g/cm}^3$), for more dense polymers. A quadratic calibration curve was developed for each column based on the equilibrium vertical position of three to four standards of known density ($\pm 0.0001 \text{ g/cm}^3$). Subsequently, density values of samples were calculated based on the vertical positions of small ($< 2 \text{ mm}$) pieces placed into the column and allowed to settle for 2 hr.

Where possible, the same batch of material was used for MISSE 7 as was used for MISSE 2. Manufacturers' or suppliers densities were used for Vespel, PE, PVC, PMP, PES, Torlon, PVOH, CN, CORIN, Vectran Mesh, and Kapton E, as they were not flown as part of the MISSE 2 PEACE experiment.

Surface Area Determination

The exposed surface area of the tray samples was 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 in. (0.1575 cm) radius. Therefore, 0.0213 cm^2 (the area of the four rounded corners) was subtracted from each square area to determine the actual exposed sample area.

The exposed surface area of the taped samples, two irregularly shaped samples on the N5-R tray (PVOH (N5-13), and urethane coated Vectran Mesh (N5-16)) was determined using AutoCAD computer design software to trace the border of the sample from a photograph of the sample. The photograph of the sample was taken along with a scale bar with a Sony digital camera. The surface area was computed using AutoCAD based on the traced area, and measurements of the scale bar. Examples of photo traces (pink line) on Vectran mesh (N5-16) and polypropylene (E14) are shown in Figures 11(a) and (b), respectively.

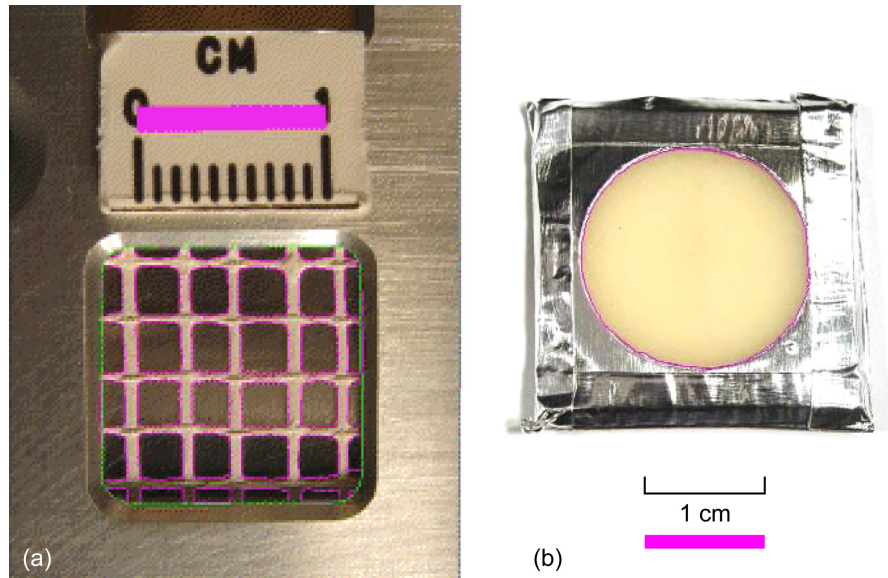


Figure 11.—Examples of AutoCAD photo-traces: a). Urethane coated Vectran mesh (N5-16) ram tray sample, and b). Polypropylene (E14) ram taped sample.

Sample Stacking

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

Optical Microscopy

Optical microscopy was used to document select samples. Images were taken at magnifications of 10x to 100x with an Olympus SMZ stereo-zoom optical microscope equipped with a Canon EOS D30 digital camera.

Results and Discussion

Atomic Oxygen Fluence and Solar Exposure

The mass loss, surface area, density, erosion yield values, and computed fluence values are shown in Table 7 for the ram Kapton H fluence sample (B7-8) and the zenith Kapton H fluence sample (Z-8). The AO fluence for the MISSE 7B ram tray was determined to be 4.22×10^{21} atoms/cm², and the AO 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, using erosion yield of 2.81×10^{-24} (Refs. 2, 17, and 19). These AO fluence results were previously reported by Yi (Ref. 15). The AO fluence for the MISSE 7B wake tray was determined to be $2.9 \pm 0.3 \times 10^{20}$ atoms/cm² as reported by Finckenor (Ref. 19).

TABLE 7.—ATOMIC OXYGEN FLUENCE DETERMINATION

MISSE 7 tray	Sample ID	Material	Mass loss (g)	Surface area (cm ²)	Density (g/cm ³)	Kapton E_y (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

The AO fluence necessary to erode away 0.5 mil and 1.0 mil Kapton H covers (based on an E_y of 3.0×10^{-24} cm³/atom) is 4.23×10^{20} and 8.47×10^{20} atoms/cm², respectively. Therefore, the fluence for the ram facing White Tedlar samples (B7-2 with a 0.5 mil Kapton H cover and B7-3 with a 1.0 mil Kapton H cover) was 3.79×10^{21} and 3.37×10^{21} atoms/cm², respectively. Likewise, the fluence for the ram facing Kapton HN samples (N5-7 with a 0.5 mil Kapton H cover and N5-8 with a 1.0 mil Kapton H cover) was 3.79×10^{21} and 3.37×10^{21} atoms/cm², respectively. It should be noted that the thickness of the 0.5 mil covers was verified with a Heidenhain MT12 digital thickness gauge (accuracy of ± 0.5 μ m). The thickness was measured in eight locations on both individual and stacked covers, and the average thickness of a 0.5 mil cover was verified to be 0.000495 in. or 0.5 mil.

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 (Ref. 20). Computations of the of zenith solar exposure have been conducted by the Naval Research Laboratory (NRL) and were determine to be approximately 4,300 ESH (Ref. 21).

Post-Flight Observations

Ram Samples (B7-R Tray)

Upon initial inspection post-flight, the B7-R ram samples showed discoloration and degradation of some of the E_y samples. This can be seen by comparing the post-flight photo of the B7-R tray shown in Figure 12(b) with the pre-flight photo provided in Figure 12(a) (also in Fig. 5). The mass based E_y samples exhibiting color changes post-flight included the three white Tedlar samples (B701, B702, and B7-3) which became brighter, the Kapton H (B7-8) sample which became brighter, and the PVC (B7-10) flight sample which became much darker. The Vespel (B7-9) flight sample appeared eroded and the exposed surface had a matt appearance, but the color did not change substantially because the erosion was not significant compared to the thickness of the sample. Also, as seen in Figure 12, the Kapton films covering the white Tedlar samples (B7-2 and B7-3) were completely eroded away. Appearance changes, or discoloration, of samples can be attributed to erosion texturing (i.e., microscopic cone development with directed ram AO exposure) and/or radiation darkening.

The Kapton H flight sample (B7-8) was flown with four 5 mil (127 μ m) layers. Discoloration of the Kapton H flight sample is observed when compared to the control sample, as shown in Figures 13(a) and (b). As can be seen in Figure 13(b) where the individual sample layers are shown, the top layer was completely eroded through, and the second layer was substantially eroded (with a fragile gossamer layer on the surface), and the third and fourth layers were not eroded. The erosion texture causes the top layer to be thinner and the surface to diffusely reflect light making the sample appear brighter.

The PVC sample (B7-10), which was set over an AO Pinhole Camera and had a small hole in the center, was found to have changed from a clear film to a very dark color, as shown in Figure 14. It was also eroded through at one edge and was curled up; hence, the E_y will be greater than the value determined. An impact site was present on the PVC sample near an edge and is shown in Figure 15.

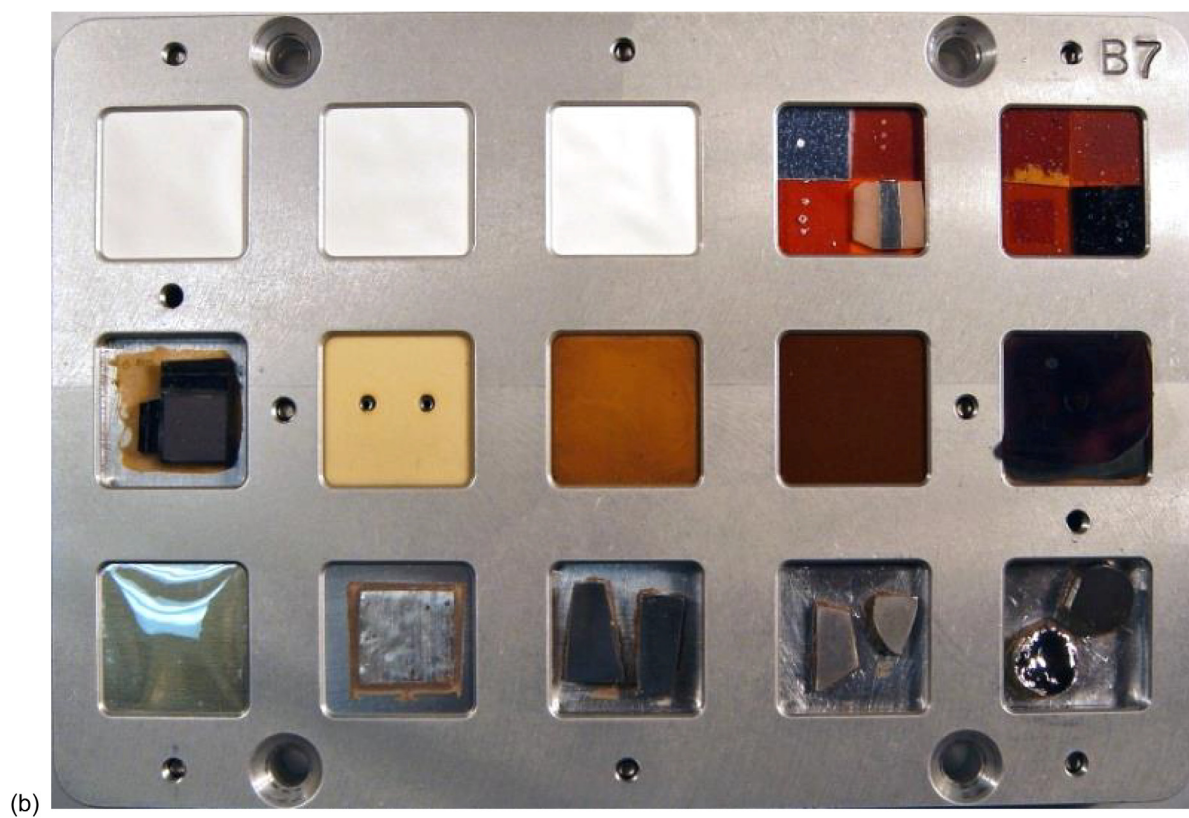
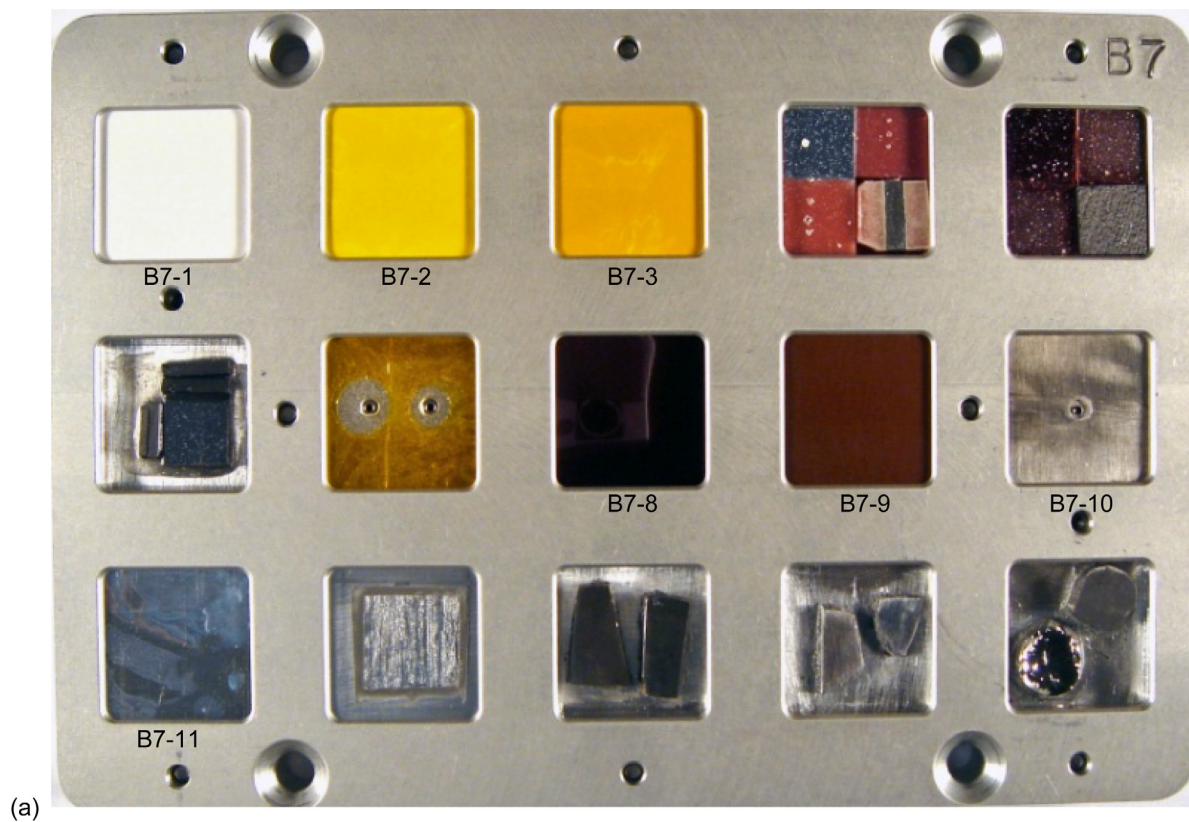


Figure 12.—MISSE 7 B7-R Tray: a). Pre-flight photo, and b). Post-flight photo.

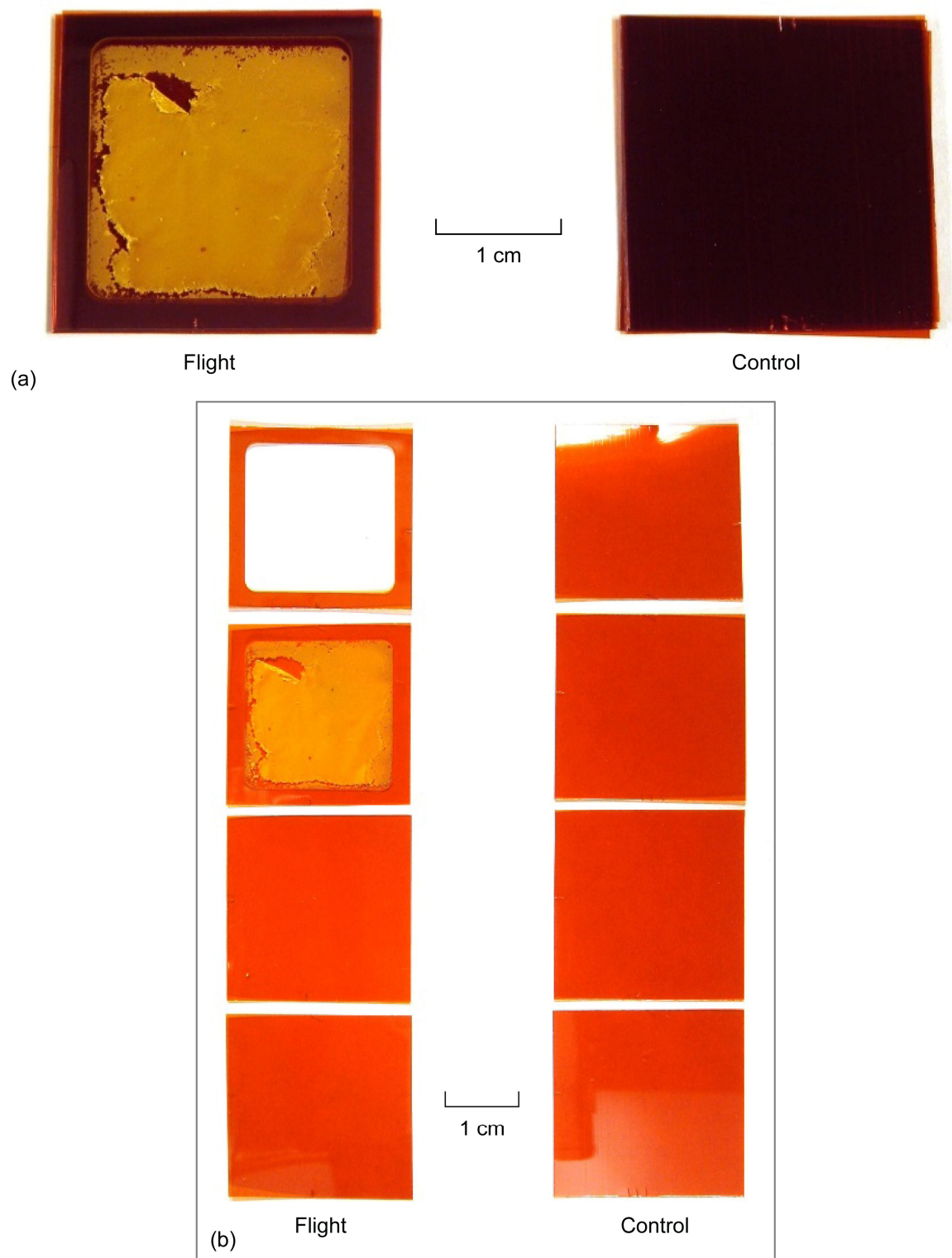


Figure 13.—The ram facing Kapton H flight sample (B7-8): a). Post-flight photo of the flight and control samples with all four layers stacked together, and b). Post-flight photo of the flight and control samples with all four layers separated (space exposed layer at the top).

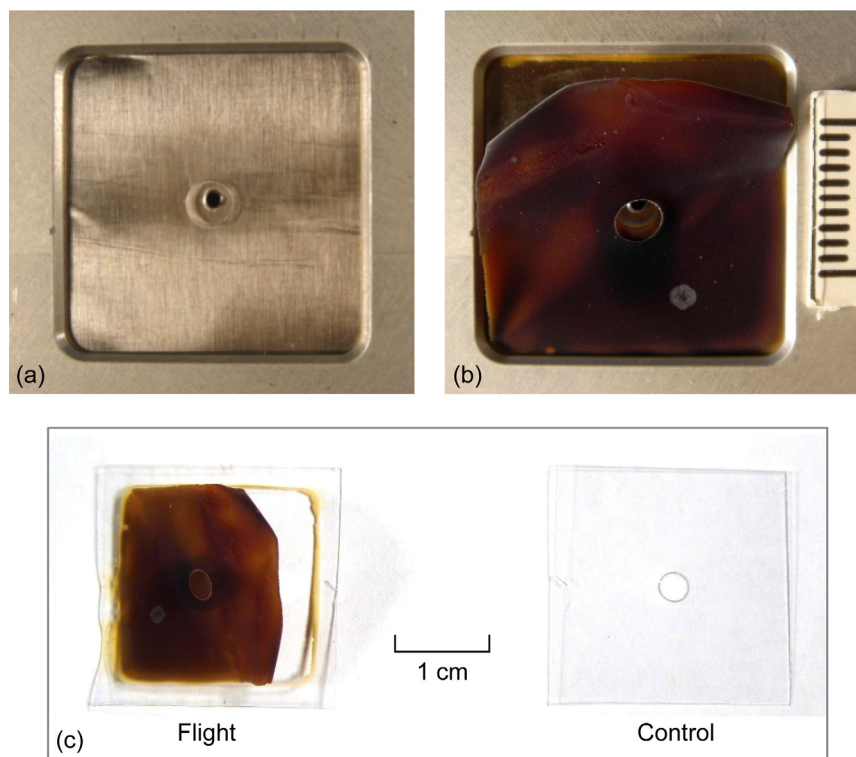


Figure 14.—The ram facing PVC flight sample (B7-10): a). Pre-flight photo in the B7-R tray, b). Post-flight photo showing the sample curling out of the B7-R tray, and c). Post-flight photo of the flight and control samples.

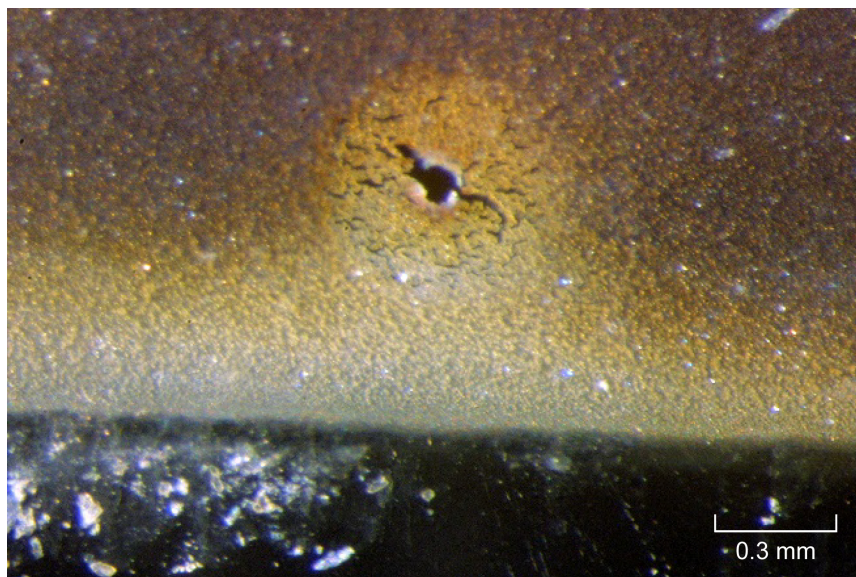


Figure 15.—Optical microscopy image of an impact site in the PVC (B7-10) flight sample near the exposed (light)/non-exposed (dark) border.

Figure 16(a) is post-flight photo of one the Kapton H covered White Tedlar samples (B7-2) in the B7-R tray. As can be seen, the 0.5 mil Kapton cover has been completely eroded away (as planned). Figure 16(b) is an optical microscope image of an impact site in the sample. The eroded through Kapton H layer and lightening of the exposed White Tedlar can be seen in the post-flight photo of the flight and control samples provided in Figure 17.

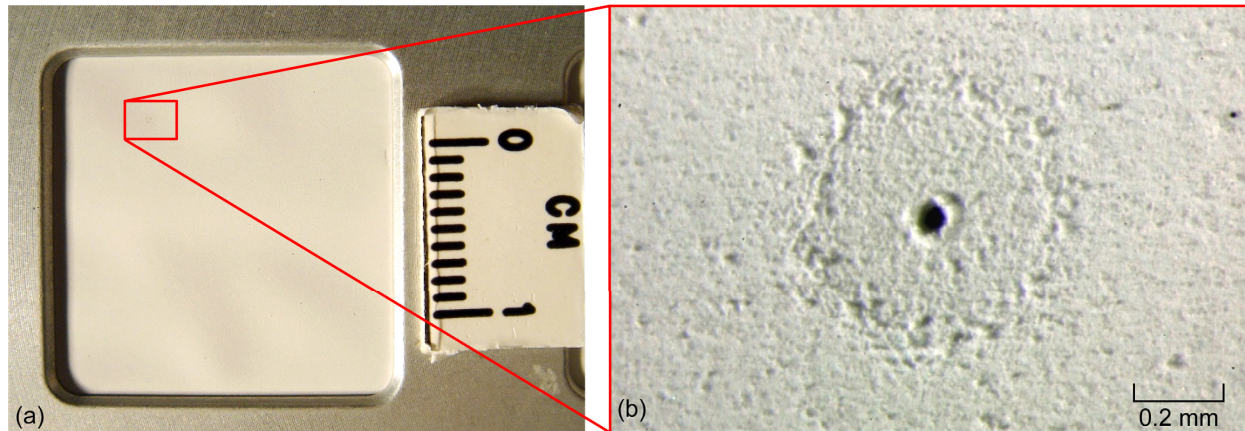


Figure 16.—The ram facing White Tedlar flight sample (B7-2): a). Post-flight photo in the B7-R tray, and b). Optical microscope image of an impact site.

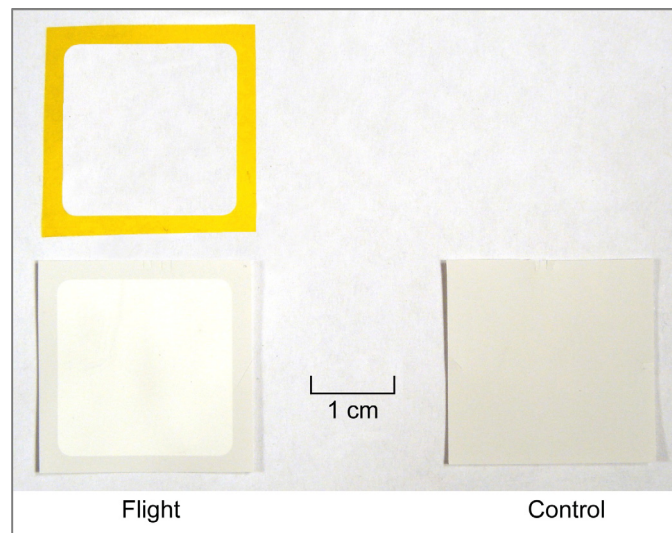
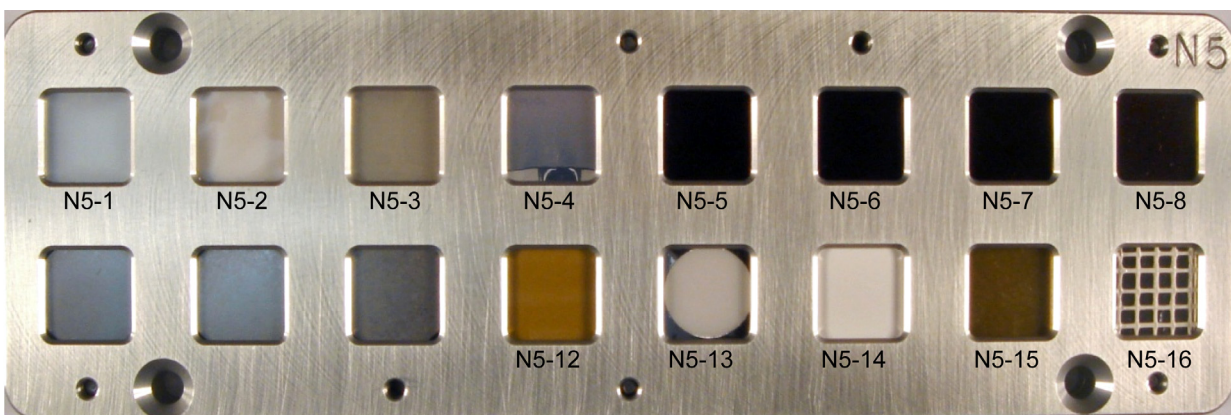


Figure 17.—Post-flight photo of the ram facing White Tedlar flight sample (B7-2) and control sample with the top 0.5 mil thick Kapton H layer completely eroded and separated from the flight sample.

Ram Samples (N5-R Tray)

Most of the polymer samples in the N5-R tray experienced some color change due to the ram space exposure as can be seen by comparing the post-flight photo of the N5-R tray shown in Figure 18(b) with the pre-flight photo provided in Figure 18(a) (also in Fig. 6). Polyethersulfone (PES, N5-3) underwent a very dramatic change in color, as can be seen in when comparing the flight and control samples in Figure 19. For the PES flight sample, six layers (3 mil thick) were flown. The top layer was completely eroded through, the 2nd layer was matte and significantly discolored (dark yellow-brown color), and the underlying layers were slightly discolored (light yellow) even though they were not eroded. The Torlon samples became significantly lighter with erosion, as shown in Figure 20. The urethane coated Vectran mesh flight sample (N5-16) became slightly brighter in the exposed area, as shown in the close-up image in Figure 21. Two samples which had little visible color change when compared to the control samples were Al-FEP (N5-4) and CORIN (N5-15), as shown in Figures 22(a) and (b), respectively.



(a)



(b)

Figure 18.—MISSE 7 N5-R Tray: a). Pre-flight photo, and b). Post-flight photo.

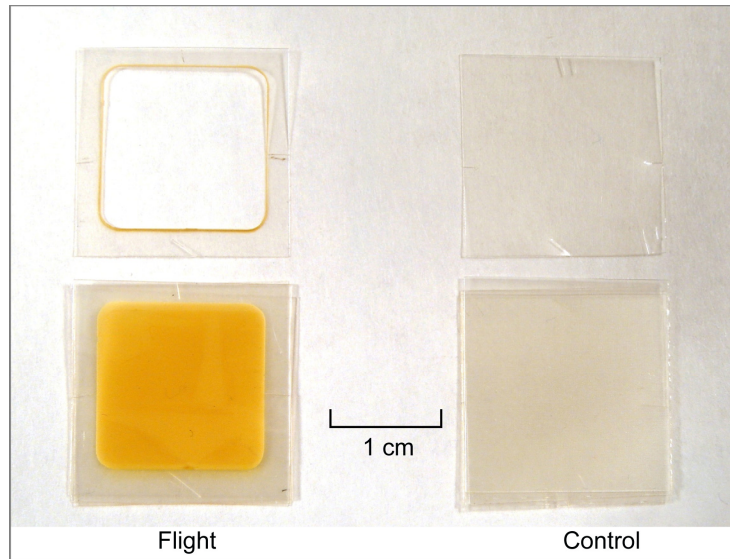


Figure 19.—Post-flight photo of the ram facing PES (N5-3) flight and control samples showing discoloration of the flight sample. The eroded top layer has been separated from the underlying 5 layers.



Figure 20.—Post-flight photo of the ram facing Torlon (N5-12) flight sample. Discoloration (lightening) of the space exposed eroded area can be seen as compared to the protected darker edge of the sample.

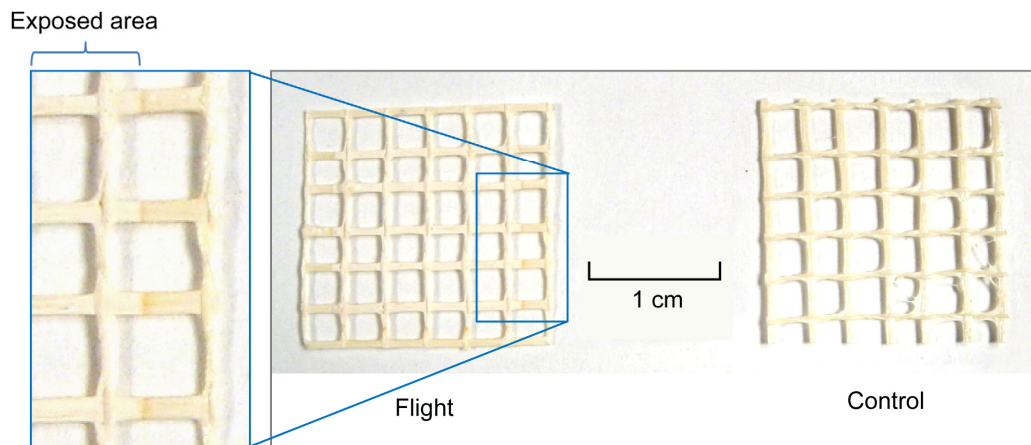
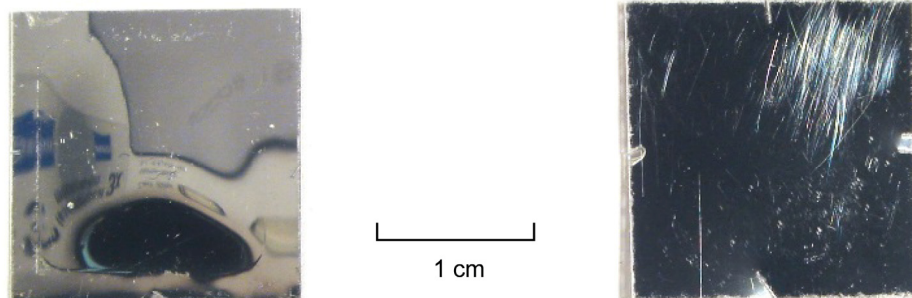


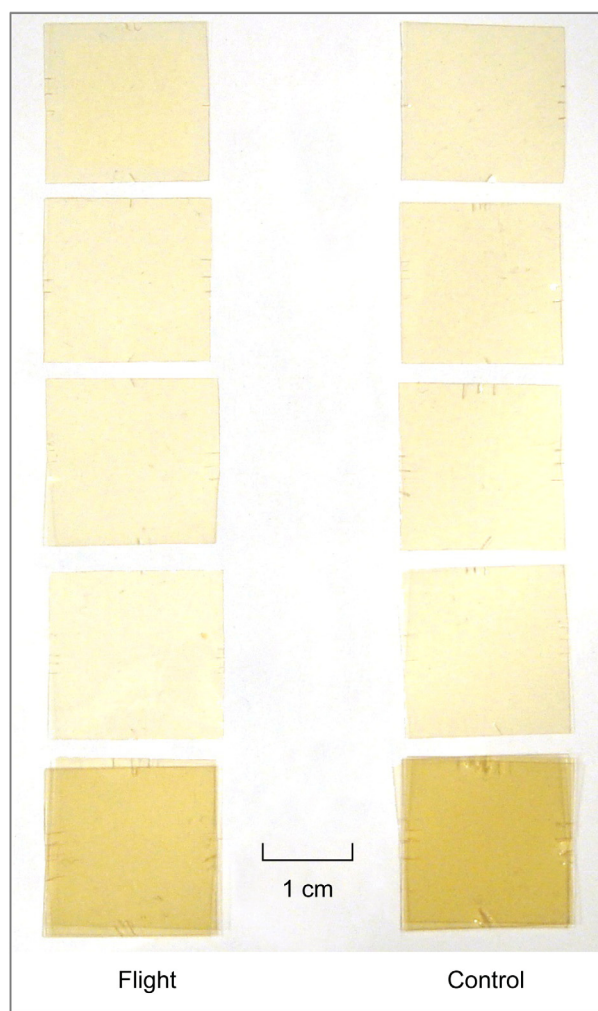
Figure 21.—Post-flight photo of the ram facing urethane coated Vectran mesh flight sample (N5-16) and control sample. The exposed area of the flight sample is brighter, as can be seen in the close-up image on the left.



(a)

Flight

Control



(b)

Flight

Control

Figure 22.—Ram facing N5-R samples with little visible color change: a). Al-FEP (N5-4) flight and control sample (1 layer), and b). CORIN (N5-15) flight and control samples (7 layers flown, top 4 layers shown separated from the stacked bottom 3 layers).

Several ram facing N5-R samples showed substantial erosion including PE (N5-1), PMP (N5-2), Kapton H (N5-5), the three Kapton HN samples (N5-6, N5-7, and N5-8) and PVOH (N5-13) as shown in Figure 23. The PE (N5-1) flight sample which was flown with 18 layers (2 mil thick) was eroded completely through the top three layers and into the fourth layer as shown in Figure 23(a). The PMP (N5-2) flight sample was flown with nine layers (2 mil thick). It was eroded completely through the top 2 layers, mostly through the third layer, and into the fourth layer, as can be seen in Figure 23(b). The Kapton H and HN samples are shown in Figures 23(c) to (f). The uncovered Kapton H (N5-5) and Kapton HN (N5-6) were both eroded through the top layer and partially through the second layer, as shown in Figures 23(c) and (d), respectively. The 0.5 and 1 mil covers on the Kapton HN samples (N5-7 and N5-8, respectively) were completely eroded through, as expected, and the top layer of 4 layers was partially eroded through, as seen in Figures 23(e) and (f), respectively. The PVOH sample, which included 25 layers, each 1.4 mil thick) was flown in an Al holder within the N5-R tray, as the layers curved during dehydration and were difficult to handle during weighing. Thus, a very thin Al holder with a circular opening was used to hold all 24 layers during pre-flight dehydration and weighing, during flight and post-flight for dehydration and weighing. The PVOH flight samples were eroded completely through the top two layers, mostly through the third layer and down into the fourth layer as shown in Figure 23(g). The CN (N5-14) sample eroded completely through all seven layers flown, leaving a small amount of material in the exposed area, as can be seen in Figure 24. The erosion yield of the CN sample will be greater than the value determined.

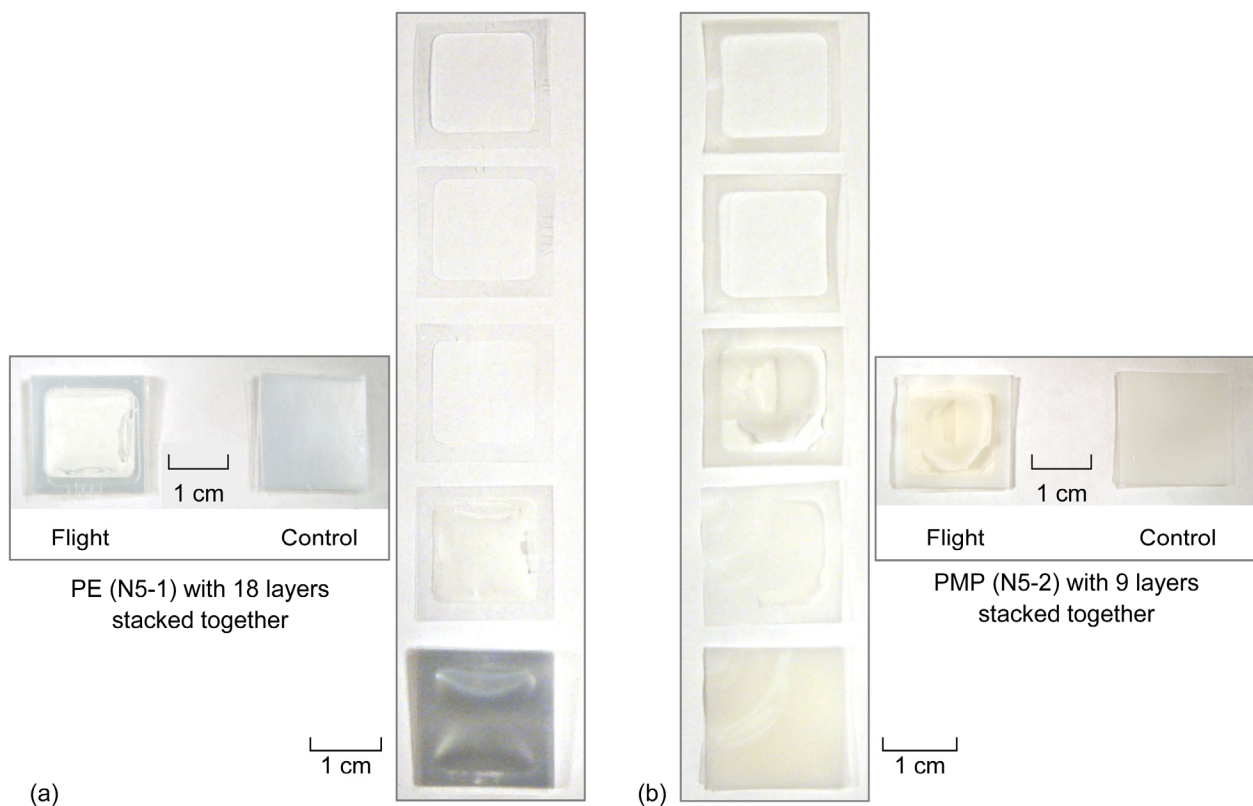


Figure 23.—Post-flight photos of ram facing N5-R samples: a). PE (N5-1) flight and control samples (18 layers with the top 4 layers separated), b). PMP (N5-2) flight and control samples (9 layers with the top 4 layers separated), c). Kapton H (N5-5) flight and control samples (4 layers), d). Kapton HN (N5-6) flight sample and control (4 layers), e). Kapton HN (N5-7) flight and control samples (eroded 0.5 mil Kapton H cover and top 2 layers separated), Kapton HN (N5-8) flight and control samples (eroded 2-0.5 mil Kapton H covers and top 2 layers separated), and g). PVOH (N5-13) flight and control samples (24 layers with the top 5 layers separated).

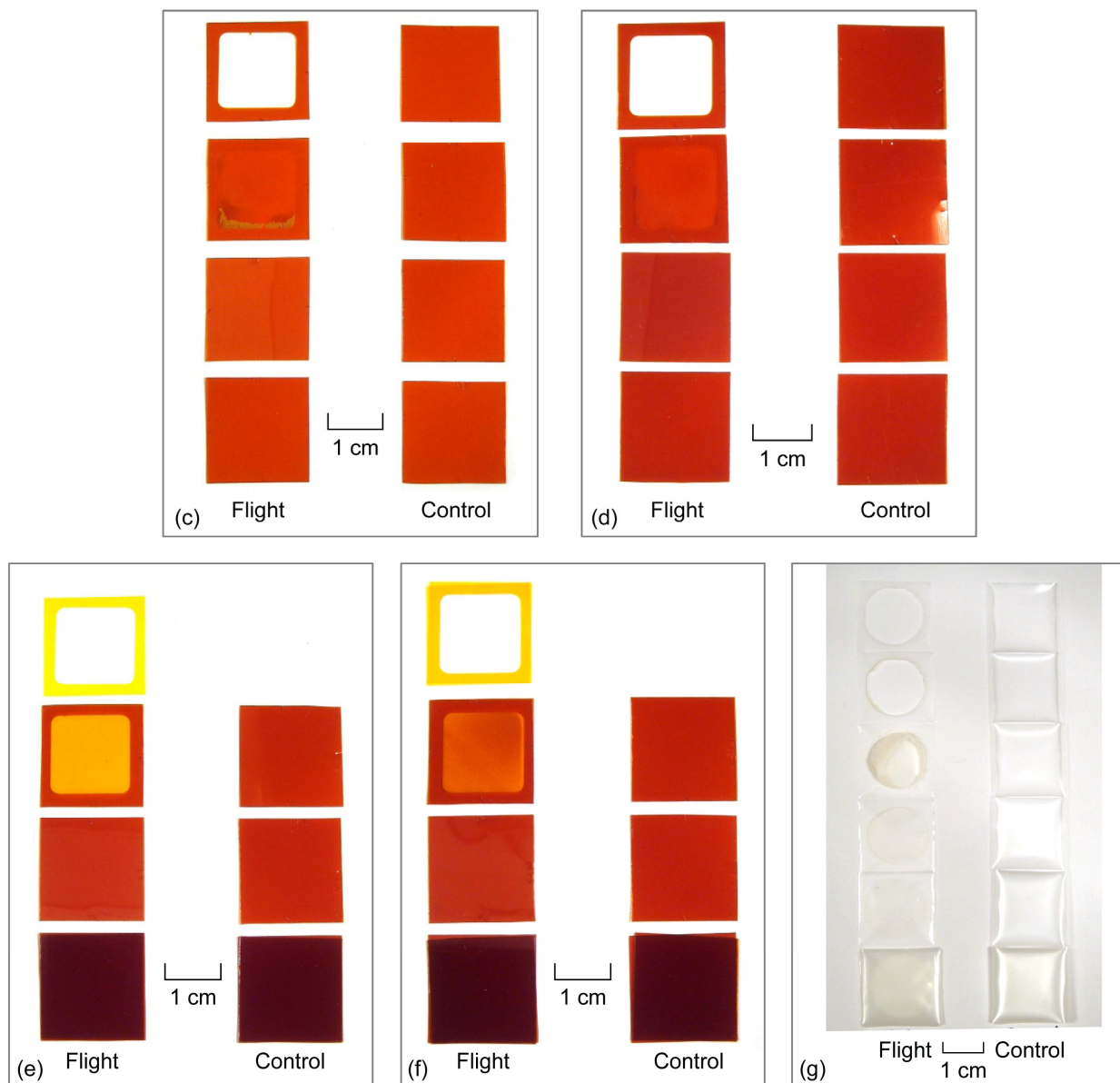


Figure 23.—Concluded.

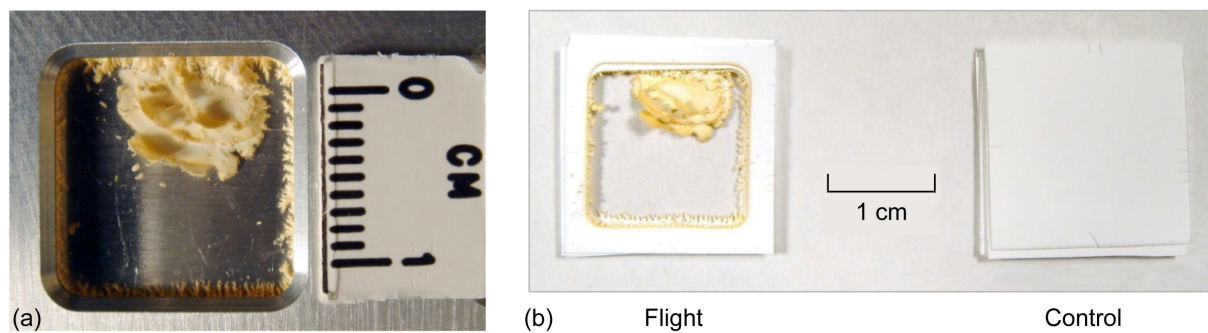


Figure 24.—Ram facing CN (N5-14) flight sample: a). Post-flight photo of the sample in the N5-R tray, and b). Post-flight photo of the flight and control samples, erosion through all flight sample layers.

Ram Taped Samples

Post-flight photos of the seven ram facing taped E_y samples are provided in Figures 25(a) to (g). Only a few of the samples had control samples, therefore only post-flight photos of the flight samples are shown. All samples, except the MFA (E15) underwent visible changes, as can be seen by comparing the exposed area to the protected edge of the sample, covered by the Al holder. The PP (E14), PEO (E17) and three composite samples (E19, E20, and E21) were textured and darkened in the exposed region. The MFA sample (Hyflon 620, E15) had no visible change. The C-FEP sample (E16) did not appear significantly eroded (the surface is still shiny), but it appears to have become very embrittled, as evident by the large full-thickness vertical crack in the center of the sample, as highlighted in Figure 25(c). This sample also had a relatively large impact site in it. It should be note that the AO ram energy (~ 4.5 eV) is below the sputter threshold for the polymers tested and the adhesive of the tape used to hold the taped samples down was acrylic-based, which does not cause contamination. Hence, discoloration of taped samples should not be due to contamination.

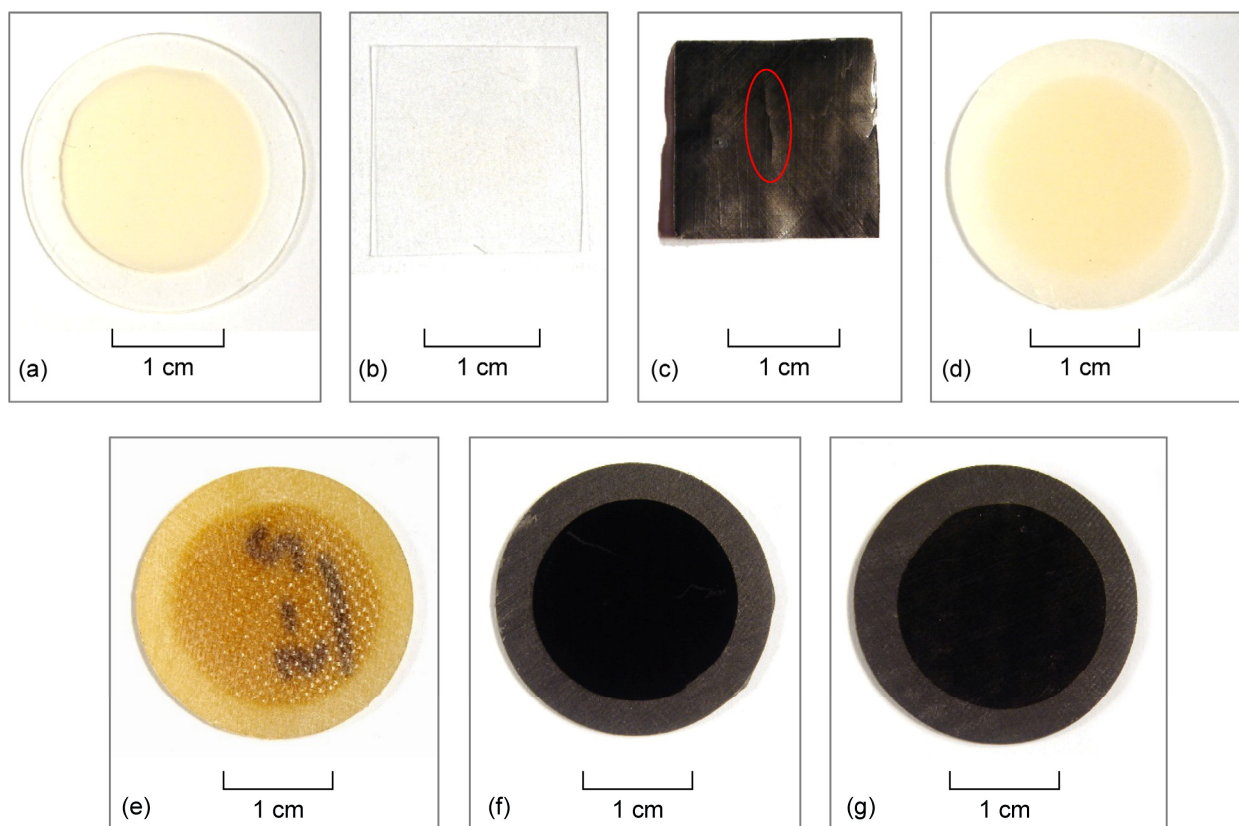


Figure 25.—Post-flight photos of ram facing taped E_y samples (1 layer each): a). PP (E14), b). MFA (E15), c). FEP/C (E16) with a large vertical crack circled, d). PEO (E17), e). 120FG/EX1515 composite (E19), f). M55J/954-3 composite (E20), and g). M55J/966 composite (E21).

Wake Taped Samples

Post-flight photos of the five wake facing taped E_y samples are provided in Figures 26(a) to (e). All samples, except the CORIN (E15) underwent significant visible changes. The POSS/Kapton HN (P27), POSS/abraded Kapton HN (P28), PVF (E2) and PP (E3) were textured and darkened in the exposed region. The PVF flight sample had significant darkening of the top layer, and the underlying layers were slightly discolored as well, shown in Figure 26(d), which was most notable when all layers were stacked together. The CORIN sample (P29) had very faint discoloration of the top layer, as shown in Figure 26(c).

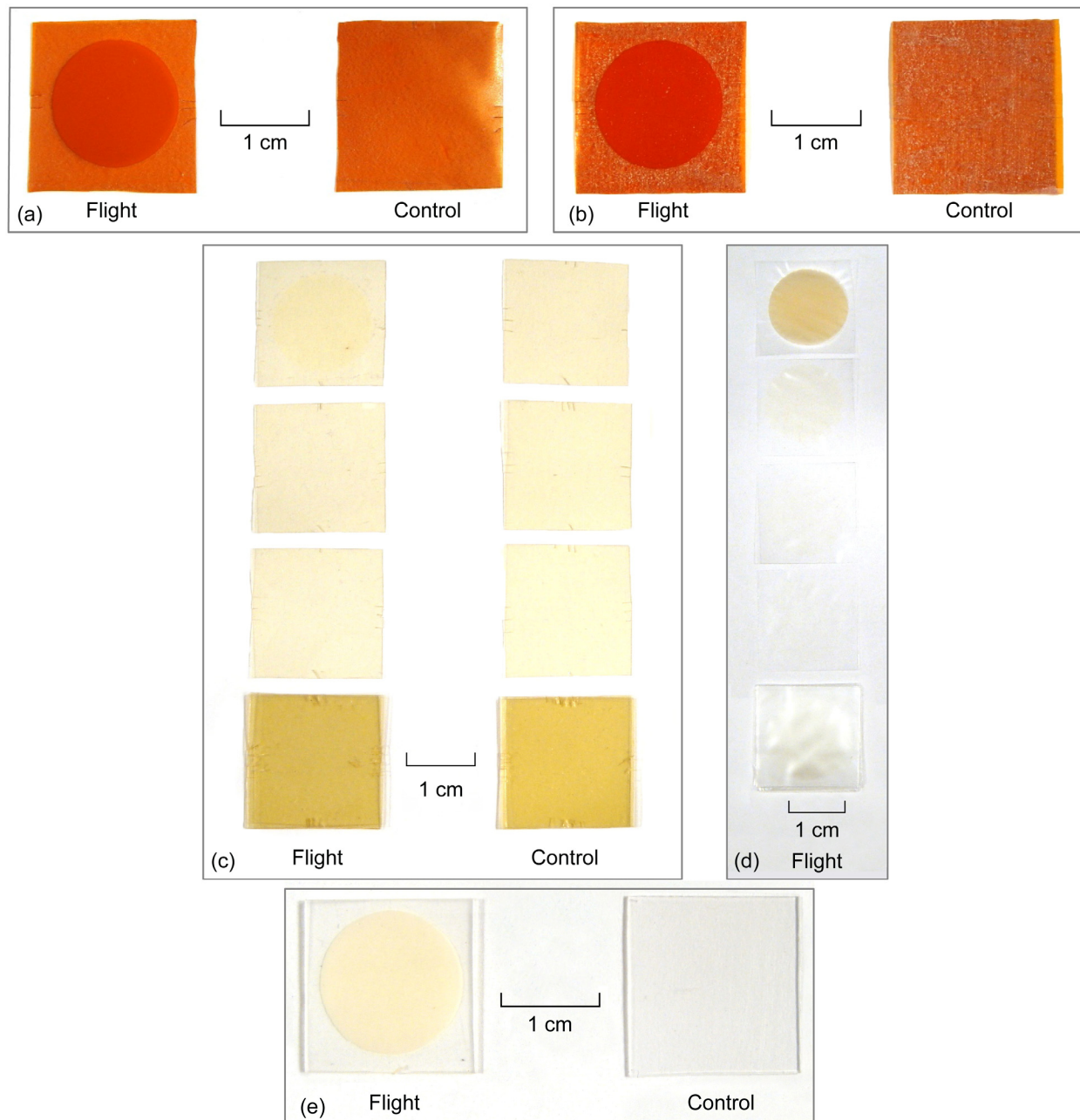


Figure 26.—Post-flight photos of wake facing taped samples: a). POSS/Kapton HN (P27) flight and control samples (1 layer), b). POSS/abraded Kapton HN (P28) flight and control samples (1 layer), c). CORIN sample (P29) flight and control samples (7 layers with the top 3 layers separated), d). PVF (E2) flight sample (19 layers with the top 4 layers separated), and e). PP (E3) flight and control samples (1 layer).

Zenith Tray

Numerous fluoropolymers flown in the zenith tray exhibited sample discoloration. This can be seen by comparing the post-flight photo of the tray, shown in Figure 27(b), to the pre-flight photo, shown in Figure 27(a) (and also in Fig. 9). Samples with significant discoloration included ETFE (Z-4), PVDF (Z-5), ECTFE (Z-6) and PVF (Z-7), as shown in Figure 28. As seen in Figures 27(b) the zenith facing ETCFE (Z-6) underwent the most dramatic change in color. For the ETCFE flight sample, three layers (3 mils thick) were flown. The top layer was significantly discolored (dark yellow-brown color, as shown in Fig. 28(c)) and matte. The second and third layers were not eroded, but had very slight color changes (very light yellow). The ETFE flight sample (Z-4) had 2 layers (5 mils thick). The top layer was discolored (shown in Fig. 28(a)) and the second layer had no noticeable change. The PVDF flight sample (Z-5) had 2 layers (3 mils thick). The top layer was discolored (shown in Fig. 28(b)) and the second layer had slight darkening. The PVF flight sample (Z-7) had 12 layers (3 mils thick). The top layer was significantly discolored (shown in Fig. 28(d)), and the second through twelfth layers had no noticeable change individually, but showed slight color change when stacked together. It should be noted that the PVF sample appears equally dark when comparing Figures 28(c) and (d) because lighting during photography made the PVF control appear extra bright, hence the image needed to be darkened as compared to the ETCFE sample. It is difficult to obtain good images of clear samples.

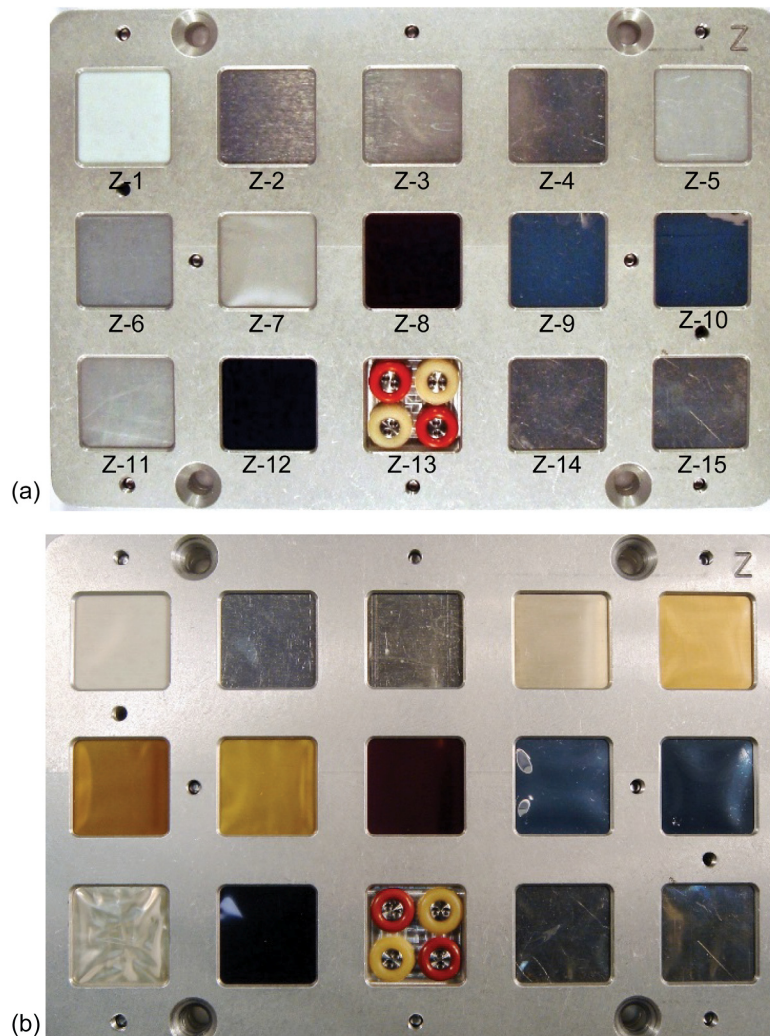


Figure 27.—MISSE 7A Z Tray: a). Pre-flight photo, and b). Post-flight photo.

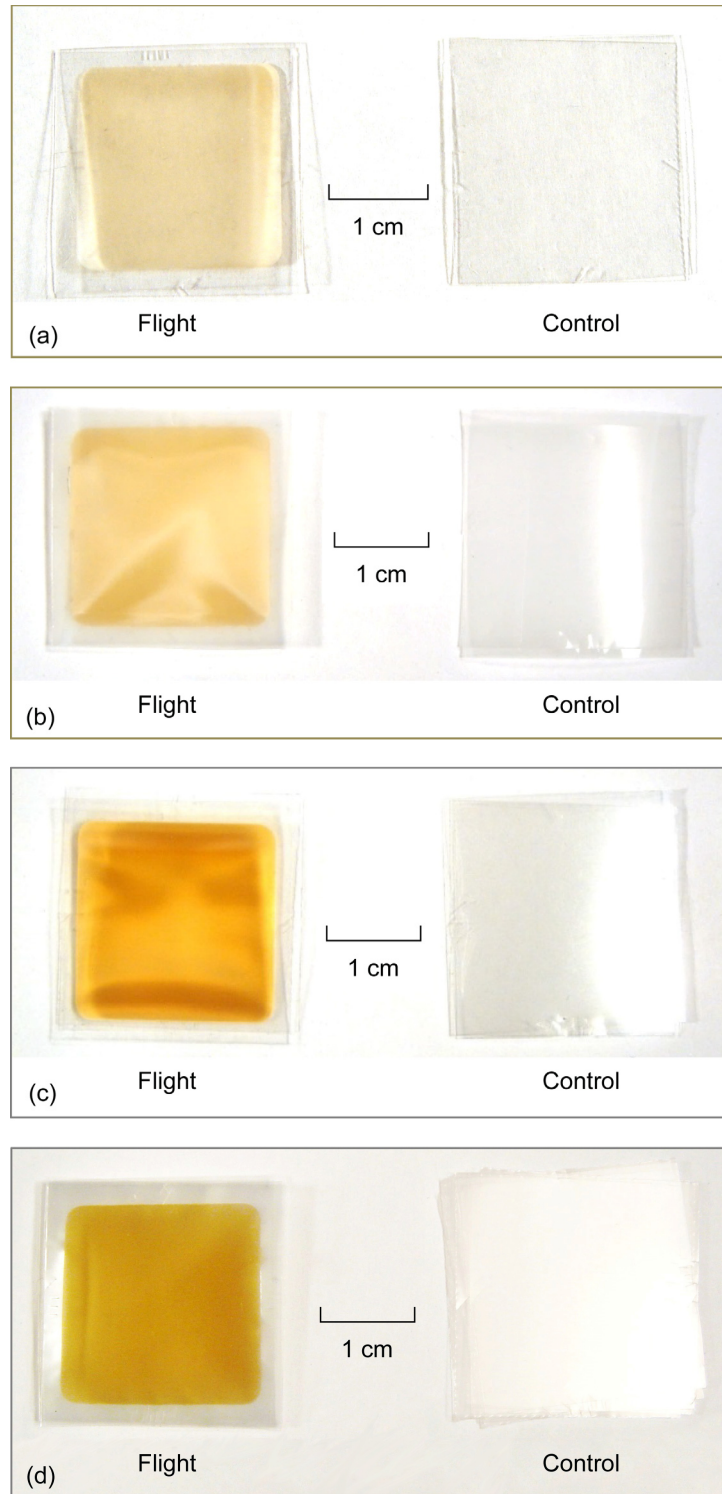


Figure 28.—Post-flight photos of zenith facing samples showing space induced discoloration in the flight samples (on left): a). ETFE (Z-4) flight and control samples (2 layers), b). PVDF (Z-5) flight and control samples (2 layers), c). ETCFE (Z-6) flight and control samples (3 layers) and d). PVF (Z-7) flight and control samples (12 layers).

Fluoropolymers with little to no observable color change included: PTFE (Z-1), FEP (Z-2), CTFE (Z-3), Al-FEP (Z-9) and Ag-FEP (Z-10), as shown in Figures 29(a) to (e), respectively. The PE flight sample (Z-11) had 8 layers (2 mil thick) and became wrinkled and possibly shrunk, as shown in Figure 30. It had a very slight color change with all layers were stacked together. The Kapton H flight sample (Z-8) had 3 layers (5 mil thick). The top layer appeared slightly brighter due to erosion texturing. The texture was not uniform, as shown in Figure 31, due to shadowing of the incoming grazing AO (on the leading edge) as the sample is slightly recessed within the tray. The second and third layers appeared unchanged. The Si/Kapton E/VDA flight sample (Z-12) was flown as a single layer (2 mil thick) and had no observable color or texture change in the exposed region. The two coated FEP flight samples ($\text{Al}_2\text{O}_3/\text{FEP}$ (Z-14) and $\text{TiO}_2/\text{Al}_2\text{O}_3/\text{FEP}$ (Z-15)) were both flown as single layers (2 mil thick) had both displayed very minor discoloration in the exposed region. The Si/ Kapton E/VDA (Z-12), $\text{Al}_2\text{O}_3/\text{FEP}$ (Z-14) and $\text{TiO}_2/\text{Al}_2\text{O}_3/\text{FEP}$ (Z-15) flight samples and their control samples are shown in Figures 32(a) to (c), respectively. Optical properties of the MISSE 7 ram, wake and zenith samples are being obtained, and will be reported elsewhere.

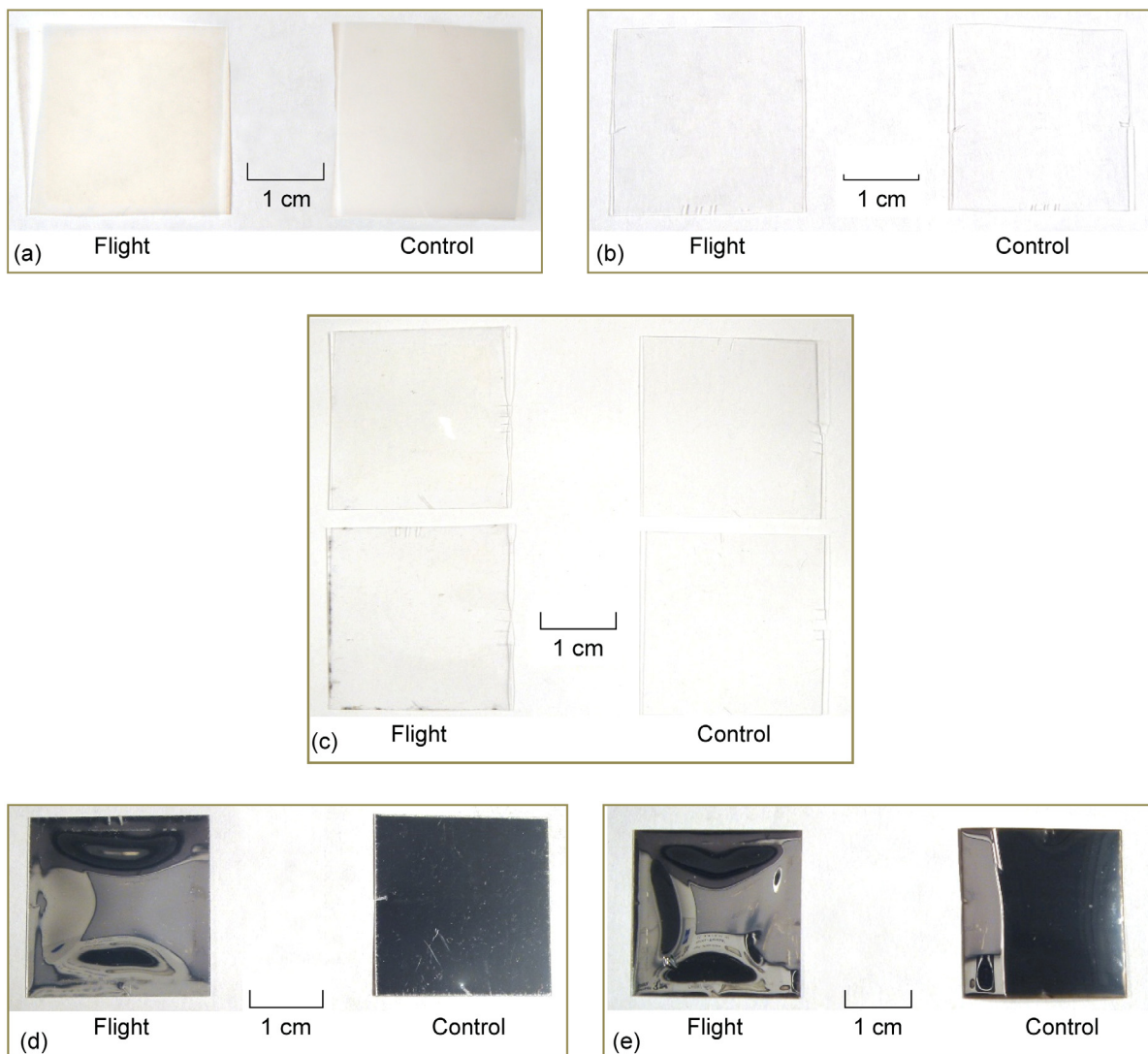


Figure 29.—Post-flight photos of zenith facing samples with no notable space induced discoloration of the flight samples (on left): a). PTFE (Z-1) flight and control samples (1 layer), b). FEP (Z-2) flight and control samples (1 layer), c). CTFE (Z-3) flight and control samples (2 layers), d). Al-FEP (Z-9) flight and control samples (1 layer), and e). Ag-FEP (Z-10) flight and control samples (1 layer).

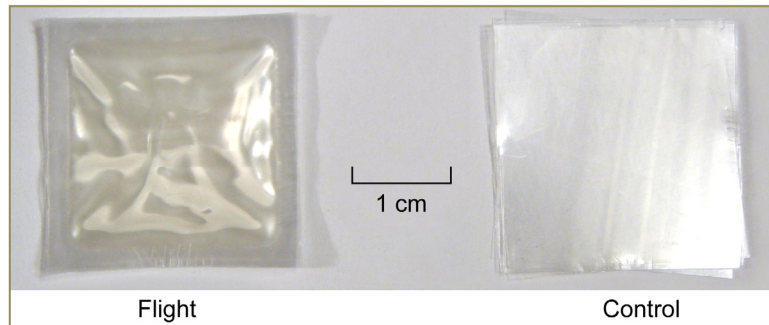


Figure 30.—Post-flight photo of the PE (Z-11) flight sample and control sample (all 8 layers stacked together). The flight sample is wavy and slightly discolored.

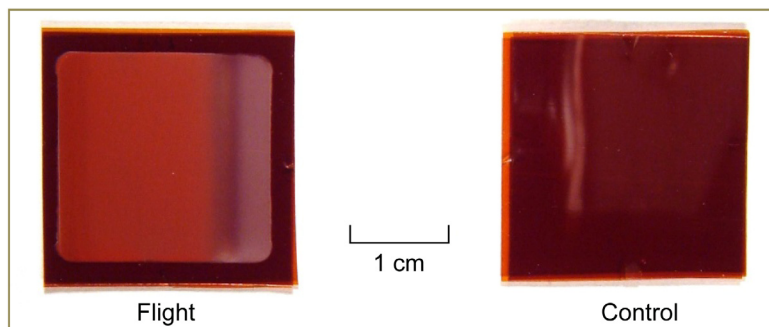


Figure 31.—Post-flight photo of the Kapton H (Z-8) flight sample and control sample (all 3 layers stacked together). The flight sample is textured and lighter in color in the exposed area. There is a gradient of texture on the right side of the sample due to shadowing of the AO arrival at the leading edge.

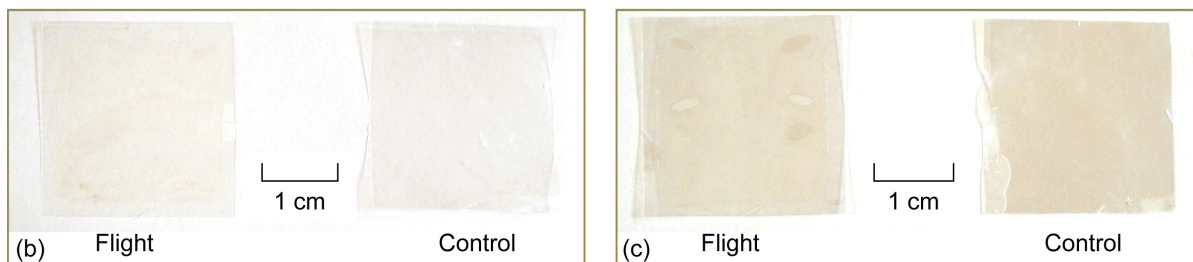
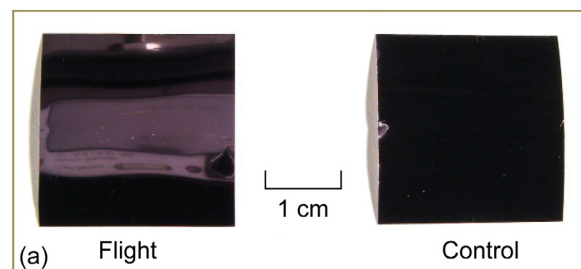


Figure 32.—Post-flight photos of zenith facing flight samples with protective coatings: a). Si/ Kapton E/VDA (Z-12) flight and control samples (1 layer), b). $\text{Al}_2\text{O}_3/\text{FEP}$ (Z-14) flight and control samples (1 layer), and c). $\text{TiO}_2/\text{Al}_2\text{O}_3/\text{FEP}$ (Z-15) flight and control samples (1 layer).

Erosion Yield Results

Ram Samples

Tables 8 to 10 provide the MISSE sample ID, material, total mass loss, exposed surface area, density, MISSE 7 AO fluence, and the E_y for the 1 in. (2.54 cm) square B7-R ram samples, the 0.75 in. (1.91 cm) square N5-R ram samples, and the taped ram samples, respectively. As stated previously, the MISSE 7B ram AO fluence was 4.22×10^{21} atoms/cm² as determined using the mass loss of the Kapton H (B7-8) flight sample.

When comparing all the ram orientated samples, the sample with the highest E_y was CN (N5-14) with an E_y of $>6.58 \times 10^{-24}$ cm³/atom. Because the sample was eroded through all seven layers, leaving only residual material as shown in Figure 24, the actual E_y is higher than the value reported. Other samples with notably high E_y values included PMP (N5-2) with an E_y of 4.45×10^{-24} cm³/atom and PE (N5-1) with an E_y of 4.11×10^{-24} cm³/atom. Eight polymers had E_y values between 2.2 to 3.14×10^{-24} cm³/atom. These include: PVOH (N5-13), Vespel (B7-9), PP (E14), PES (N5-3), PEO (E17), and the Kapton samples (N5-5, N5-6, N5-7, and N5-8). Torlon (N5-12) and PVC (B7-10) had slightly lower E_y values of 1.74×10^{-24} cm³/atom. But, because the PVC sample was eroded completely through at one edge and curled up, as shown in Figure 14, the actual E_y of PVC will be higher than the value reported.

The ram facing uncoated polymer with the lowest E_y was CORIN (N5-15), an AO resistant polymer. The E_y was found to be 3.05×10^{-26} cm³/atom. This modified polyimide had an E_y *two orders of magnitude* lower than Kapton H or HN. Other samples flown in the ram orientation with low E_y values ($\times 10^{-25}$ cm³/atom) included the three composites (E19, E20, and E21), urethane coated Vectran mesh, the fluorinated polymers Al-FEP (N5-4), C-FEP (E16), MFA (E15), and the three white Tedlar samples (B7-1, B7-2, B7-3). The polymer sample with the lowest E_y was the TiO₂/Al₂O₃/FEP sample (B7-11). The TiO₂/Al₂O₃ coating appears to have provided good protection to the FEP as the E_y was 7.99×10^{-28} cm³/atom, which is over two orders of magnitude less than unprotected FEP.

TABLE 8.—EROSION YIELD VALUES FOR MISSE 7B B7-R RAM TRAY

MISSE Sample ID	Material	Mass loss (g)	Surface area (cm ²)	Density (g/cm ³)	MISSE AO fluence (atoms/cm ²)	MISSE 7 E_y (cm ³ /atom)
B7-8	Kapton H	0.077547	4.294	1.4273	4.22E+21	3.00E-24*
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
B7-9	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 E_y from previous flight experiments (Refs. 10 and 13).

TABLE 9.—EROSION YIELD VALUES FOR MISSE 7B N5-R RAM TRAY

MISSE Sample ID	Material	Mass loss (g)	Surface area (cm ²)	Density (g/cm ³)	MISSE AO fluence (atoms/cm ²)	MISSE 7 E_y (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	0.032565	2.097	1.4346	3.79E+21	2.85E-24
N5-8	Kapton HN with two 0.5 mil Kapton H covers (1.0 mil)	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) in Al holder	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.

TABLE 10.—EROSION YIELD VALUES FOR MISSE 7B RAM TAPED SAMPLES

MISSE Sample ID	Material	Mass Loss (g)	Surface Area (cm ²)	Density (g/cm ³)	MISSE AO Fluence (atoms/cm ²)	MISSE 7 E_y (cm ³ /atom)
E14	Polypropylene (PP)	0.031718	2.660	0.907	4.22E+21	3.12E-24
E15	Hyflon MFA 620	0.001516	1.580	2.129	4.22E+21	1.07E-25
E16	C-FEP	0.002209	1.557	2.1443	4.22E+21	1.57E-25
E17	Polyethylene oxide (PEO)	0.036320	2.731	1.1470	4.22E+21	2.75E-24
E19	120FG/EX1515	0.004746	2.703	1.728	4.22E+21	2.41E-25
E20	M55J/954-3	0.009843	2.730	1.588	4.22E+21	5.38E-25
E21	M55J/966	0.006156	2.692	1.575	4.22E+21	3.44E-25

One surprising result was that the E_y of the 2 mil thick ram facing C-FEP (E16, $E_y = 1.57 \times 10^{-25}$ cm³/atom) was lower than the E_y of the 5 mil thick Al-FEP (N5-4, $E_y = 1.81 \times 10^{-25}$ cm³/atom). It has been expected that the higher on-orbit passive heating of the C-FEP would have resulted in increased erosion of the FEP. It should be noted that the Al-FEP (N5-4) sample flight tray had a beveled edge, while the C-FEP taped sample did not. Therefore, the actual AO fluence of the Al-FEP sample would have been somewhat higher relative to the taped sample. Thus, it would be beneficial to fly similar samples in the same type of flight holder in a future flight for a better comparison.

Effects of Inorganic Fillers and Sample Size

The E_y of the white Tedlar samples (B7-1, B7-2, B7-3) exposed to varying AO fluences have been compared to help determine if AO erosion of high ash (inorganic filler) containing polymers is dependent on fluence, as the inorganic TiO_2 white particles in white Tedlar are AO durable. The B7-1 white Tedlar sample was flown uncovered and received the full 4.22×10^{21} atoms/cm² AO exposure. The white Tedlar samples B7-2 and B7-3 were flown with Kapton H covers 0.5 and 1.0 mil thick, respectively, and therefore were exposed to atom oxygen fluences of 3.79×10^{21} and 3.37×10^{21} atoms/cm², respectively. The MISSE 7B E_y values for these three samples, along with a white Tedlar sample exposed to an AO fluence of 8.43×10^{21} atoms/cm² on MISSE (Refs. 2 and 17), were plotted versus AO fluence in Figure 33. As can be seen, the E_y decreases with increasing AO fluence following a power law dependence. This is attributed to a buildup of AO durable TiO_2 particles on the surface of the samples with increasing AO exposure. The TiO_2 can protect the underlying material from erosion, if undisturbed, thus decreasing the E_y with increasing AO fluence. Further investigations on the effect of inorganic filler on the AO erosion of polymers and paints are reported by Banks (Ref. 22).

The Kapton H N5-5 sample, which had a significantly smaller exposed surface area (2.095 cm²) than the Kapton H B7-8 witness sample (4.294 cm²), had a slightly higher E_y of 3.05×10^{-24} cm³/atom (as compared to 3.0×10^{-24} cm³/atom for the witness E_y). This was expected due to the greater perimeter-to-sample area ratio for the smaller sample. The reason for this is that the MISSE tray holder edges are chamfered at a 45° angle (as shown in Figs. 11(a), 14(a) and 16(a) and 24(a)) and AO scattering occurs along the chamfered perimeters which provides higher fluxes along the exposed sample edges as illustrated in Figure 34. Therefore, there is a greater total fluence and thus greater relative erosion for greater perimeter-to-sample area ratio samples. This experiment, in which the same material was flown in varying sizes in the same orientation, provided support of this theory. The effects of AO flux concentration due to scattering off the chamfered edges can be seen in numerous samples, where the exposed edge of the sample is preferentially eroded. A good example is the PVC sample (B7-10), where the sample is eroded through three of four edges, as shown in Figures 14(b) and (c).

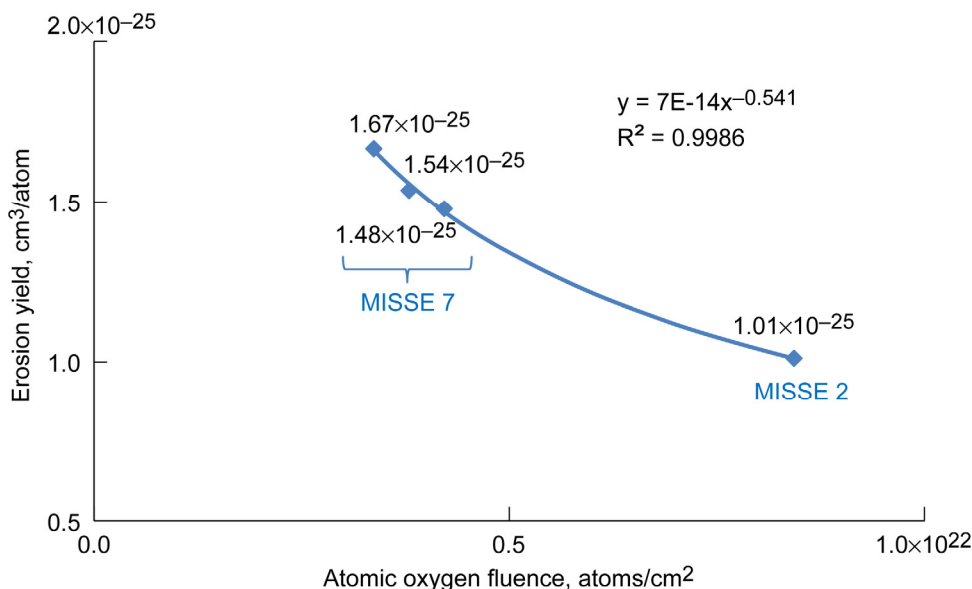


Figure 33.—Erosion yield versus AO fluence for white Tedlar samples flown on MISSE 2 and MISSE 7 showing decreasing E_y with increasing AO fluence.

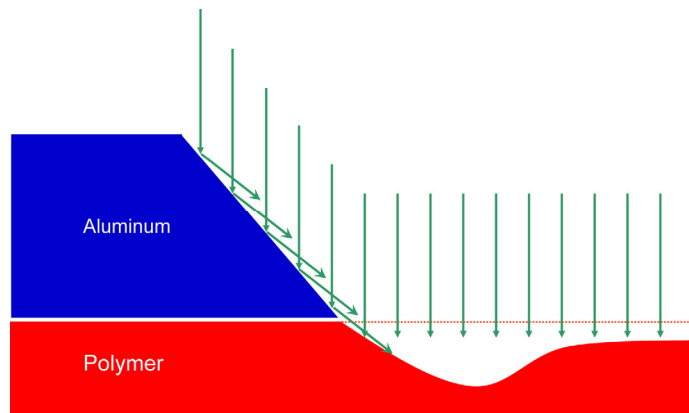


Figure 34.—Flux concentration along exposed edge of sample from chamfered MISSE holders (Ref. 23).

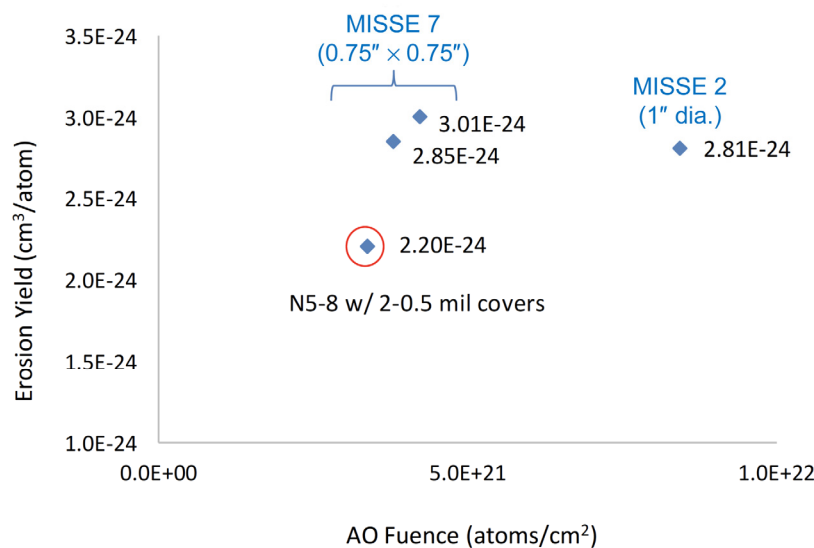


Figure 35.—Erosion yield versus AO fluence for Kapton HN samples flown on MISSE 2 and MISSE 7.

Similar to the Kapton H sample, the uncovered Kapton HN sample (N5-6) with an exposed surface area of 2.095 cm² had a higher E_y value of 3.01×10^{-24} cm³/atom than for a 1 in. (2.54 cm) diameter Kapton HN sample flown on MISSE 2. The MISSE 2 Kapton HN sample had an exposed surface area of 3.5676 cm² and an E_y of 2.81×10^{-24} cm³/atom (Refs. 2 and 17). These data provide additional support that perimeter-to-sample area ratios for chambered sample holders impact the total fluence and hence the E_y of samples.

The E_y of the three N5-R Kapton HN samples has been plotted versus AO fluence in Figure 35, along with the E_y for the MISSE 2 Kapton HN sample. The E_y appears to be relatively stable versus fluence, with the exception of the sample N5-8 which was covered with two 0.5 mil (1.0 mil) Kapton H covers. This sample was found to have a substantially lower E_y than expected (2.20×10^{-24} cm³/atom). The reason for this anomaly is currently unknown.

TABLE 11.—EROSION YIELD VALUES FOR MISSE 7B WAKE TAPED SAMPLES

MISSE Sample ID	Material	Mass loss (g)	Surface area (cm ²)	Density (g/cm ³)	MISSE AO Fluence (atoms/cm ²)	MISSE 7 E_y (cm ³ /atom)
P27	POSS coated Kapton HN	0.001764	1.572	1.4345	2.90E+20	2.70E-24
P28	POSS coated abraded Kapton HN	0.001588	1.631	1.4345	2.90E+20	2.34E-24
P29	CORIN (AO resistant polyimide)	0.000033	1.656	1.36	2.90E+20	5.10E-26
E2	Polyvinyl fluoride (PVF)	0.002261	1.600	1.3792	2.90E+20	3.53E-24
E3	Polypropylene (PP)	0.001665	1.651	0.907	2.90E+20	3.83E-24

Wake Samples

Table 11 provides the sample ID, material, total mass loss, surface area, density, MISSE 7 AO fluence, and the E_y for the wake taped samples. The POSS coating appears to have only a small impact on decreasing the E_y of the Kapton HN samples (P27 and P28). The E_y of the POSS coated samples was 2.34 to 2.70×10⁻²⁴ cm³/atom, whereas the E_y of Kapton HN was found to be 3.01×10⁻²⁴ cm³/atom (for a larger sample in the ram orientation). The PVF (E2) and PP (E3) samples had E_y values of 3.53×10⁻²⁴ cm³/atom and 3.83×10⁻²⁴ cm³/atom, respectively. These values will be further discussed in the section below comparing the E_y of polymers flown in different orientations on MISSE 7. The E_y of the CORIN wake sample was 5.10×10⁻²⁶ cm³/atom. This value will also be compared to the E_y for the same material flown in the ram direction in the comparison section below.

Zenith Samples

Tables 12 and 13 provide the sample ID, material, total mass loss, surface area, density, AO fluence, and erosion yield for the zenith “Z tray” samples. The polymer sample in the zenith orientation with the greatest E_y was PVOH (P13) with an E_y of 1.22×10⁻²³ cm³/atom. Other polymers with high E_y values included PE (Z-11) with an E_y of 8.13×10⁻²⁴ cm³/atom and PEO sample (E1) with an E_y of 6.76×10⁻²⁴ cm³/atom. Most of the fluorinated polymers had E_y values from 1.17 to 3.57×10⁻²⁴ cm³/atom. Once again, the coated samples (Al₂O₃/FEP (Z-14), TiO₂/Al₂O₃/FEP (Z-15) and Si/Kapton E/VDA (Z-12)) had low E_y values. The SC-POSS material actually gained mass, hence no E_y is reported. This is due to the formation of a passivating silica layer upon reaction with the AO in LEO (Ref. 24). It should be noted that the POSS coated samples flown in the wake orientation were provided by a different organization (LaRC) than the SC-POSS material flown in the zenith orientation (provided by AFRL).

The zenith 5 mil thick Al-FEP (Z-9) had a higher E_y (2.22×10⁻²⁴ cm³/atom) than the zenith 5 mil thick clear FEP (Z-2) which had an E_y = 9.74×10⁻²⁵ cm³/atom. It should be noted that both of these samples are similar in size, and were flown in similar holders, hence they received the same fluence exposure. These results were consistent with those for similar size samples of clear and aluminized-FEP flown in the same type of flight holder on MISSE 2, where the E_y of the Al-FEP (2.11×10⁻²⁵ cm³/atom) was higher than the E_y of the clear FEP (2.00×10⁻²⁵ cm³/atom) (Ref. 25). The higher E_y for the Al-FEP may be attributed to the fact that it is a second-surface mirror, and hence visible light radiation passed through the FEP twice thus heating it twice as much as uncoated FEP. Like the ram samples, the E_y of the 2 mil thick zenith facing C-FEP (E4, E_y = 1.90×10⁻²⁴ cm³/atom) was unexpectedly lower than the E_y of the 5 mil thick Al-FEP (Z-9, E_y = 2.22×10⁻²⁴ cm³/atom). Again, the C-FEP was a taped sample, therefore in a holder without a beveled edge, while the Al-FEP was in a holder with a beveled edge. Hence, the Al-FEP had a slightly higher fluence relative to the taped sample. The exact fluence difference is not known.

TABLE 12.—EROSION YIELD VALUES FOR MISSE 7A ZENITH TRAY SAMPLES

MISSE Sample ID	Material	Mass loss (g)	Surface area (cm ²)	Density (g/cm ³)	MISSE AO Fluence (atoms/cm ²)	MISSE 7 E_y (cm ³ /atom)
Z-8	Polyimide (Kapton H)	0.002897	4.279	1.4273	1.58E+20	3.00E-24*
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-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 (PE)	0.005077	4.303	0.918	1.58E+20	8.13E-24
Z-12	Si/Kapton E/VDA	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 E_y from previous flight experiments (Refs. 10 to 13).

**Teflon layer was space facing

TABLE 13.—EROSION YIELD VALUES FOR MISSE 7A ZENITH TAPED SAMPLES

MISSE Sample ID	Material	Mass loss (g)	Surface area (cm ²)	Density (g/cm ³)	MISSE AO fluence (atoms/cm ²)	MISSE 7 E_y (cm ³ /atom)
E1	Polyethylene oxide (PEO)	0.002050	1.673	1.147	1.58E+20	6.76E-24
E4	Back-surface carbon painted FEP (C-FEP)	0.001066	1.653	2.1443	1.58E+20	1.90E-24
E5	Side-chain polyhedral oligomeric silsesquixane (SC-POSS)	-0.000137	1.648	TBD	1.58E+20	Mass gained
E9	Polypropylene (PP)	0.001090	2.746	0.907	1.58E+20	2.77E-24
P13	Polyvinyl alcohol (PVOH)	0.006569	2.661	1.28	1.58E+20	1.22E-23

Erosion Yield Comparison of Polymers Flown in Different Orientations on MISSE 7

Prior flight data have indicated that the solar exposure (sun hours with corresponding temperature effects, and possibly x-rays) plays a significant role in the erosion of some polymers, such as FEP (Refs. 25 and 26). For example, the E_y of Hubble Space Telescope (HST) Bay 8 FEP after 19 years in space, which was exposed to 89,300 ESH and an AO fluence of 4.65×10^{20} atom/cm², was 1.37×10^{-23} cm³/atom. This is an order of magnitude greater than the E_y of HST Bay 5 FEP ($E_y = 1.43 \times 10^{-24}$ cm³/atom) also retrieved after 19 years in space, but exposed to 24,300 ESH and a similar AO fluence (4.28×10^{20} atom/cm²) (Ref. 26). Thus, by flying similar polymers in different orientations on MISSE missions, the effect of solar exposure (both radiation dose and heating effects) on the E_y of various polymers can be assessed. Table 14 provides ratios of solar exposure (in equivalent sun hours (ESH)) to AO exposure (in fluence (atoms/cm²)) for the MISSE 7 ram, wake and zenith orientations. As can be seen, the wake orientation provided an order of magnitude greater solar-to-AO exposure compared to the high AO flux ram orientation (~70X), and the zenith exposure provided almost two orders of magnitude greater solar-to-AO exposure than the ram orientation (~270X). These numbers have been rounded, since the ESH value are not exact.

TABLE 14.—SOLAR EXPOSURE TO ATOMIC OXYGEN FLUENCE RATIOS

MISSE 7 orientation	MISSE 7 fluence (atom/cm ²)	Solar exposure (ESH)	Approximate Solar/AO ratio (E-19 ESH*cm ² /atom)
Ram	4.22E+21	2,400	6
Wake	2.9E+20	2,000	70
Zenith	1.58E+20	~4,300	270

TABLE 15.—EROSION YIELD COMPARISON FOR POLYMERS FLOWN IN DIFFERENT ORIENTATIONS

	Ram		Wake		Zenith		Wake- to- Ram E_y Ratio	Zenith- to- Wake E_y Ratio	Zenith- to- Ram E_y Ratio
AO (atom/cm ²)	4.22E+21		2.90E+20		1.58E+20				
Solar Exposure (ESH)	2,400		2,000		4,300				
Solar/AO (E-19 ESH*cm ² /atom)	6		70		270				
Material	E_y		E_y		E_y				
	ID	(cm ³ /atom)	ID	(cm ³ /atom)	ID	(cm ³ /atom)			
PVF	-	-	E2	3.53E-24	Z-7	1.44E-24	-	0.4	-
PP	E14	3.12E-24	E3	3.83E-24	E9	2.77E-24	1.2	0.7	0.9
CORIN	N5-15	3.05E-26	P29	5.10E-26	-	-	1.7	-	-
PE	N5-1	4.11E-24	-	-	Z-11	8.13E-24	-	-	2.0
PVOH	N5-13	3.14E-24	-	-	P13 Z	1.22E-23	-	-	3.9
C-FEP	E16	1.57E-25	-	-	E4	1.90E-24	-	-	12.1
Al-FEP	N5-4	1.81E-25	-	-	Z-9	2.22E-24	-	-	12.3
TiO ₂ /Al ₂ O ₃ /FEP	B7-11	7.99E-28	-	-	Z-15	1.40E-26	-	-	17.5

Table 15 provides E_y ratios for polymers with samples flown in more than one orientation during the MISSE 7 mission. Solar exposure did not increase the E_y for two polymers (PVF and PP). In fact, the E_y of these polymers in the zenith orientation was lower than in the wake and/or ram directions. But, the E_y of six other materials (CORIN, PE, PVOH, and three types of FEP (C-FEP, Al-FEP and TiO₂/Al₂O₃/FEP)) was found to be greater with increased solar to AO ratio. The E_y of the CORIN, PE and PVOH was approximately 2 to 4 times greater with greater ESH/AO exposure. The three FEP materials all displayed an order of magnitude greater E_y in the zenith orientation than in the ram orientation. These results are consistent with prior flight data, indicating that solar radiation, and corresponding temperature effects, can play a significant role in the erosion of certain polymers, such as FEP, in the space environment.

Summary and Conclusions

The MISSE 7 Polymers Experiment and Zenith Polymers Experiments were successfully flown on the exterior of the ISS, and retrieved for post-flight analyses after 1.49 years of space exposure. A total of 70 samples were flown in ram, wake, or zenith orientations in order to determine AO fluence, AO E_y , in addition to contamination, optical, and/or mechanical property effects of LEO space exposure. The AO fluences for the ram, wake, and zenith orientations were determined to be 4.22×10^{21} atoms/cm², 2.9×10^{20} atoms/cm², and 1.58×10^{21} atoms/cm², respectively, based on mass loss of Kapton H witness samples. The solar exposures for the ram, wake and zenith orientations were determined to be 2,400 ESH, 2,000 ESH and 4,300 ESH, respectively. The LEO AO E_y values were determined for 49 samples based on mass loss (26 ram oriented samples, 5 wake oriented samples and 18 zenith oriented samples).

Samples of high and low amounts of inorganic filler (white Tedlar and Kapton HN, respectively) were exposed to three different AO fluence levels to determine how the erosion of ash (inorganic filler) containing polymers is dependent on fluence. The low ash containing Kapton HN samples did not show an effect of fluence on E_y (if the outlier sample is not considered). But, the E_y of the high ash containing white Tedlar was found to decrease with increasing AO fluence, following a power law dependence. This is attributed to a buildup of AO durable TiO_2 particles on the surface of the samples with increasing AO fluence, which protects the underlying material from erosion.

Various samples provided evidence that perimeter-to-sample area ratios for chambered sample holders impact the total fluence and hence the E_y of samples. Further verification studies are desired to study the effect of perimeter-to-sample area ratios in future MISSE flight experiments. These results also highlighted the importance of flying samples for direct comparison in the same type of flight tray or holders, to ensure similar fluence exposures during the mission.

Several polymer samples were flown in more than one orientation during the MISSE 7 mission. By comparing the E_y for these polymers, the effect of solar exposure and heating effects on erosion could be assessed. The solar exposure did not increase the E_y for two polymers (PVF and PP). But, the E_y of six other materials (CORIN, PE, PVOH, and three types of FEP (C-FEP, Al-FEP and $\text{TiO}_2/\text{Al}_2\text{O}_3/\text{FEP}$)) was found to be greater with increased solar-to-AO ratio. The three FEP materials all displayed an order of magnitude greater E_y in the zenith orientation than in the ram orientation. These results are consistent with prior flight data, indicating that solar radiation, and corresponding temperature effects, can play a significant role in the erosion of certain polymers, such as FEP, in the space environment. Surprisingly, the back-surface carbon painted FEP (C-FEP) did not have a higher E_y than the Al-FEP, in either the ram direction or the zenith direction, which had been expected due to the higher passive heating on-orbit. Further studies on the effect of passive heating on the E_y of polymers are desired for future MISSE flight experiments.

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