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Ground-Laboratory to In-Space Atomic Oxygen Correlation for the Polymer Erosion and Contamination Experiment (PEACE) Polymers

Arielle H. Stambler, Karen E. Inoshita, Lily M. Roberts, and Claire E. Barbagallo
Hathaway Brown School, Shaker Heights, Ohio

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

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

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Kim K. de Groh
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Alphaport, Inc., Cleveland, Ohio

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

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Arielle H. Stambler, Karen E. Inoshita, Lily M. Roberts, and Claire E. Barbagallo
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

Abstract

The Materials International Space Station Experiment 2 (MISSE 2) Polymer Erosion and Contamination Experiment (PEACE) polymers were exposed to the environment of low Earth orbit (LEO) for 3.95 years from 2001 to 2005. There were 41 different PEACE polymers, which were flown on the exterior of the International Space Station (ISS) in order to determine their atomic oxygen erosion yields. In LEO, atomic oxygen is an environmental durability threat, particularly for long duration mission exposures. Although spaceflight experiments, such as the MISSE 2 PEACE experiment, are ideal for determining LEO environmental durability of spacecraft materials, ground-laboratory testing is often relied upon for durability evaluation and prediction. Unfortunately, significant differences exist between LEO atomic oxygen exposure and atomic oxygen exposure in ground-laboratory facilities. These differences include variations in species, energies, thermal exposures and radiation exposures, all of which may result in different reactions and erosion rates. In an effort to improve the accuracy of ground-based durability testing, ground-laboratory to in-space atomic oxygen correlation experiments have been conducted. In these tests, the atomic oxygen erosion yields of the PEACE polymers were determined relative to Kapton H using a radio-frequency (RF) plasma asher (operated on air). The asher erosion yields were compared to the MISSE 2 PEACE erosion yields to determine the correlation between erosion rates in the two environments. This paper provides a summary of the MISSE 2 PEACE experiment; it reviews the specific polymers tested as well as the techniques used to determine erosion yield in the asher, and it provides a correlation between the space and ground-laboratory erosion yield values. Using the PEACE polymers' asher to in-space erosion yield ratios will allow more accurate in-space materials performance predictions to be made based on plasma asher durability evaluation.

Introduction

Vulnerable spacecraft materials are eroded by atomic oxygen (AO) interaction in low Earth orbit (LEO). Atomic oxygen is formed when short wavelength ultraviolet (UV) radiation photodissociates diatomic oxygen. In LEO, at spacecraft velocities of approximately 17,500 miles/hr (28,000 km/hr), spacecraft literally "ram" into the residual AO and oxidation of exterior spacecraft materials can occur. At International Space Station (ISS) altitudes ($\approx$400 km) the average impact energy is approximately 4.5 eV [1]. For materials with volatile oxidation products, such as most polymers, AO interaction results in erosion. Atomic oxygen erosion can result in serious structural and/or optical property degradation of exterior polymeric spacecraft components, such as thermal control insulation films.

Spaceflight opportunities are unique, expensive, and time-consuming, which is why AO ground-laboratory testing, such as in a radio frequency (RF) plasma asher, is often used for spacecraft material durability prediction. However, the correlation between in-space degradation and ground-testing degradation needs to be determined because multiple differences exist between ground facilities and space-exposure. These differences include variations in species, energies, thermal exposures and radiation exposures, all of which may result in different reactions and erosion rates. For example, differences can exist in the arrival direction in ground facilities compared to space. Materials exposed to the LEO environment often receive either directed or sweeping ram AO, whereas in a plasma asher the AO arrival is isotropic. The AO energy of a plasma asher is much lower ($\approx$0.05 eV) than the AO energy in LEO. Samples in a plasma asher receive an intense amount of UV radiation, whereas samples receive many types of radiation in LEO, including broad spectrum UV radiation, electron and proton radiation, and solar flare x-rays. Finally, AO as well as diatomic nitrogen, diatomic oxygen, and monatomic nitrogen in both excited and ground energy states are present in an asher when it is operated using air as the feed gas. However, ground state AO is the predominant species of the LEO environment [2]. All of these exposure differences may affect the rate of degradation of materials exposed to these various environments. As a consequence, the relative atomic oxygen erosion yields of polymers measured in RF plasma ashers can be significantly different than in LEO. Studies have been conducted to try to understand the effect of various factors within ground-test facilities on erosion yields of certain polymers. For example, Rutledge et. al conducted a series of experiments to isolate UV radiation and charged species during AO exposure of polyethylene (PE), Teflon fluorinated ethylene propylene (FEP), and Kapton HN relative to Kapton H in a plasma asher [3]. The same materials were also exposed to a hyperthermal AO beam [3]. The results were found to vary with the polymer and indicated that UV, charged particle exposure, and beam energy affect the erosion yield of FEP and PE but not Kapton HN.

In this experiment, the AO erosion yields of numerous polymers in an RF plasma asher were determined to provide a comparison between ground exposure and in-space exposure. The erosion yields of 39 different polymers were determined in a plasma asher relative to Kapton H polyimide. Kapton H is used as a reference because its in-space erosion yield is well-characterized in LEO (3.00 x 10^{-24} cm^3/atom) [4]. The asher erosion yield values were compared to in-space erosion yield values from the Polymer Erosion and Contamination Experiment (PEACE) Polymers experiment, flown as part of the Materials International Space Station Experiment 2 (MISSE 2) [5], to determine the correlation between asher AO exposure and in-space AO exposure.

Materials International Space Station Experiment 2 (MISSE 2)

MISSE is a series of materials flight experiments consisting of trays, called Passive Experiment Carriers (PECs), which are exposed to the space environment on the exterior of the ISS. The objective of MISSE is to test the long-term stability and durability of materials and devices in the space environment. The in-space erosion yield data used in this experiment came from the PEACE Polymers experiment flown as part of MISSE 2. MISSE 2 was exposed to the space environment on the exterior of the Quest Airlock for 3.95 years from August 16, 2001 until July 30, 2005 [5]. Figure 1 is a photograph taken during the attachment of MISSE PEC 2 to the ISS Quest Airlock during a spacewalk. The MISSE 2 PEACE Polymers tray is visible in this photograph. Figure 2 is a photograph of the Quest Airlock showing the location of MISSE PEC 2. The MISSE 2 PEACE Polymers experiment consisted of 39 different polymers and two Kapton H fluence witness samples.
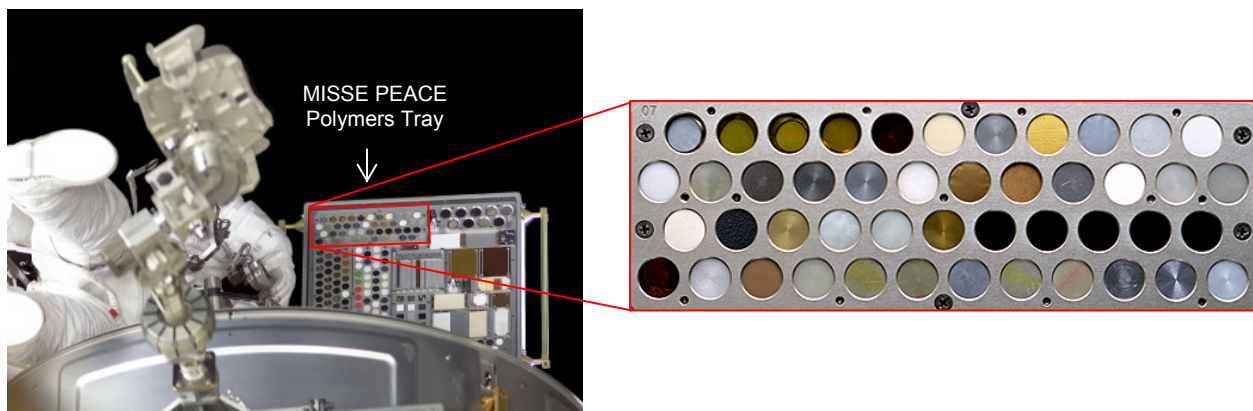

Figure 1. During a space walk on August 16, 2001, astronaut Patrick Forrester installs MISSE PEC 2 on the ISS Quest Airlock [NASA photo STS105E5302].
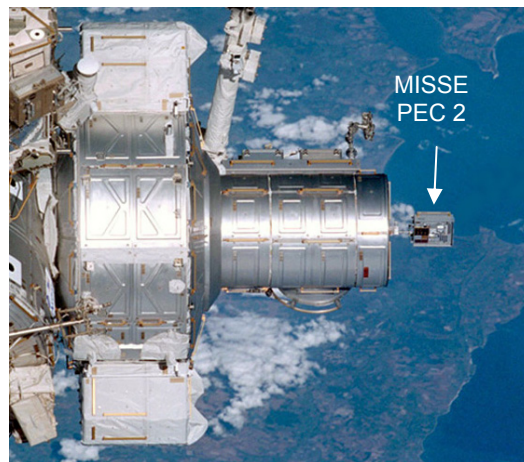

Figure 2. Photograph of the Quest Airlock and MISSE PEC 2 taken during the STS-105 mission [NASA photo STS105-329-028].

The purpose of the MISSE 2 PEACE Polymers experiment was to accurately determine the atomic oxygen erosion yield of a wide variety of polymeric materials exposed for an extended period of time to the LEO space environment. The polymers range from those commonly used for spacecraft applications, such as Teflon® fluorinated ethylene propylene (FEP), Mylar® and Kapton® to more recently developed polymers, such as high temperature polyimide PMR (polymerization of monomer reactants). Additional polymers, typically not desired for spacecraft applications, were included to explore erosion yield dependence upon chemical composition for predictive model development [5].

Materials

The polymers used in this experiment were MISSE 2 PEACE Polymer flight control samples. Therefore, the samples tested were from the same batch, and often the same sheet of film, as the ones used in the MISSE 2 PEACE Polymers experiment. Table 1 contains a list of the MISSE 2 PEACE polymers and provides the MISSE serial number, material name, trade name(s), abbreviation and sample thickness in mils (1 mil = 0.001" or 0.0025 cm). Although stacked layers of polymer films were flown in the MISSE 2 flight experiment (enough to last for a minimum of 3 years on-orbit), only single layer film samples were exposed in the plasma asher.

Experimental Procedures

1. Mass Measurements

In this experiment, erosion yield was determined based on mass loss. The samples were vacuum dehydrated for at least 48 hours prior to measuring their dehydrated masses both before and after atomic oxygen plasma exposure as recommended by ASTM E 2089-00, "Standard Practices for Ground Laboratory Atomic Oxygen Interaction Evaluation of Materials for Space Applications". Many polymeric materials are hygroscopic, and hence are apt to take on a certain amount of moisture depending on the percentage of humidity present in the air the day they are weighed. Unfortunately, this reduces the accuracy of weight measurements. The samples' dehydrated masses were obtained using a Mettler Balance with a sensitivity of ± 0.000001 g.

2. Ground-Laboratory RF Plasma Asher Exposure

Samples were exposed to an atomic oxygen environment in a Structure Probe, Inc. Plasma Prep II asher. This asher generates a plasma by exciting ambient air with 100 W of continuous RF power at 13.56 MHz [6]. The operating pressure was 0.5-1.0 x 10^2 mtorr. The plasma is composed of oxygen and nitrogen ions and atoms [7]. The nitrogen species have been found to have a negligible effect in the erosion processes [8]. The effective atomic oxygen fluence was calculated based on mass loss data of dehydrated 5 mil Kapton H polyimide samples, which were ashed with the test samples.

Six samples were ashed at a time using a specially designed holder with six sample openings (see Figure 3). The holder protected the edges and the backs of the samples from the plasma, which kept the samples from curling during exposure and provided a well defined exposure area. The holder was always placed in the same position in the asher in an effort to provide the same flux for each sample position. The sample positions are indicated in Figure 3.

Table 1. MISSE 2 PEACE Polymers Sample List

MISSE-2 Serial #	Material	Trade Name(s)	Abbrev.	Thickness (mils)
2-E5-6	Acrylonitrile butadiene styrene	Cycolac, Absylux	ABS	5
2-E5-7	Cellulose acetate	Clarifoil, Dexel, Tenite Acetate	CA	2
2-E5-8	Poly-(p-phenylene terephthalamide)	Kevlar 29 fabric	PPDT	2.2
2-E5-9	Polyethylene (low oxygen)		PE	2
2-E5-10	Polyvinyl fluoride	Tedlar TTR10SG3 (clear)	PVF	1
2-E5-11	Crystalline polyvinylfluoride w/white pigment	White Tedlar TWH10BS3	PVF	1
2-E5-12	Polyoxymethylene; acetal; polyformaldehyde	Delrin, Acetal (natural)	POM	10
2-E5-13	Polyacrylonitrile	Barex 210	PAN	2
2-E5-14	Allyl diglycol carbonate	CR-39, Homalite H-911	ADC	31
2-E5-15	Polystyrene	Trycite 1000	PS	2
2-E5-16	Polymethyl methacrylate (Impact. Mod.)	Plexiglas, Acrylite	PMMA	2
2-E5-17	Polyethylene oxide	Alkox E-30 (powder)	PEO	29
2-E5-18	Poly(p-phenylene-benzobisoxazole) , balanced biaxial film	Zylon	PBO	1
2-E5-19	Epoxide or epoxy	Hysol EA 956	EP	95
2-E5-20	Polypropylene	Contour 28	PP	20
2-E5-21	Polybutylene terephthalate	Valox 357 resin, Stabilux FR-1	PBT	3
2-E5-22	Polysulphone	Thermalux P1700-NT11, Udel P-1700 resin	PSU	2
2-E5-23	Polyeurethane	Dureflex PS8010	PU	2
2-E5-24	Polyphenylene isophthalate	Nomex Crepe Paper T-410	PPPA	2
2-E5-25	Pyrolytic Graphite		PG	75
2-E5-26	Polyetherimide	Ultem 1000	PEI	10
2-E5-27	Polyamide 6	Nylon 6	PA 6	2
2-E5-28	Polyamide 66	Nylon 66	PA 66	2
2-E5-29	Polyimide	CP1	PI (CP1)	3
2-E5-30 & 2-E5-33	Polyimide PMDA	Kapton H	PI (H)	5
2-E5-31	Polyimide PMDA	Kapton HN	PI (HN)	5
2-E5-32	Polyimide BPDA	Upilex-S	PI (S)	1
2-E5-34	High temperature polyimide resin	PMR-15	PMR-15	9
2-E5-35	Polybenzimidazole	Celazole	PBI	2
2-E5-36	Polycarbonate	PEEREX 61	PC	10
2-E5-37	Polyetheretherketone	Victrex PEEK 450	PEEK	3
2-E5-38	Polyethylene terephthalate	Mylar A-200	PET	2
2-E5-39	Chlorotrifluoroethylene	Kel-f, Neoflon M-300 (powder)	CTFE	5
2-E5-40	Ethylene-chlorotrifluoroethylene	Halar 300	ECTFE	3
2-E5-41	Tetrafluorethylene-ethylene copolymer	Tefzel ZM	ETFE	3
2-E5-42	Fluorinated ethylene propylene	Teflon FEP 200A	FEP	2
2-E5-43	Polytetrafluoroethylene	Chemfilm DF100	PTFE	2
2-E5-44	Perfluoroalkoxy	Teflon PFA 200 CLP	PFA	2
2-E5-45	Amorphous Fluoropolymer	Teflon AF 1601	AF	2
2-E5-46	Polyvinylidene fluoride	Kynar 740	PVDF	3

Figure 3. Sample holder with six polymer samples.

A Kapton H fluence witness sample was placed in position 1 of every test so that the atomic oxygen effective fluence could be determined. The effective fluence was calculated using the following formula:

$$F = \frac{\Delta M_K}{\left(A_K \rho_K E_K \right)}$$
(1)

where

$F =$ *plasma asher effective AO fluence (atoms/cm^2)*
$\Delta M_K =$ *mass loss of Kapton H witness sample (g)*
$A_K =$ *exposed surface area of Kapton H witness sample (cm^2)*
$\rho_K =$ *density of Kapton H (1.4273 g/cm^3)* [5]
$E_K =$ *erosion yield of Kapton H (3.00 x 10^{-24} cm^3/atom)*

3. Flux Tests

The atomic oxygen flux (atoms/cm^{2}sec) within a plasma asher can vary with position. Therefore, two flux tests were conducted to determine the effective flux in each of the six sample positions. The flux tests were run with Kapton H witness samples in each of the six sample positions. The effective flux was then determined for each position (based on dehydrated mass loss), and six "k" constants, one corresponding to each of the six positions in the holder, were calculated. The k constants were based on the relative flux compared to the flux of the witness in position 1, as shown below:

$$\begin{aligned}
f_1 &= f_1 \\
f_2 &= k_2 \, x \, f_1 \\
f_3 &= k_3 \, x \, f_1 \\
f_4 &= k_4 \, x \, f_1 \\
f_5 &= k_5 \, x \, f_1 \\
f_6 &= k_6 \, x \, f_1
\end{aligned}$$
(2)

where

$f_n =$ *flux of the sample in position n (atoms/cm²sec)*
$n =$ *sample holder position*
$k_n =$ *constant, a fraction of the fluence of a sample in position n relative to the fluence of the Kapton H sample in position one*

During the plasma asher exposures, in order to calculate the fluence that each sample was exposed to during a test, the effective fluence (effective flux x time) was determined for the Kapton H witness in position 1, and then that fluence was multiplied by the k factor for each position to get the fluence for each sample position.

4. Density Measurements

The density values for 36 of the polymers were obtained using calibrated density gradient columns [5]. The density solvents for the majority of polymers were made from cesium chloride (CsCl), which has a density of ≈ 2 g/cm³, and water (H_2O), which has a density of 1 g/cm³. The density solvents for the higher density polymers, such as the fluoropolymers, were carbon tetrachloride (CCl_4), which has a density of 1.594 g/cm³, and bromoform ($CHBr_3$), which has a density of 2.899 g/cm³. For the polymers whose densities did not fit within the range of the density columns or were of a form not easily sectioned for density column measurements (ABS, PE, PP, Nomex, and PG), the values were found in references or using the manufacturers' Materials Data and Safety Sheets [9-13].

5. Exposure Area Measurements

The exposure area of each sample opening in the metal holder was calculated using an average diameter, obtained by averaging measurements taken in ten different orientations. These measurements were taken using Fowler & NSK Max-Cal electronic digital calipers.

6. Erosion Yield Calculation

Once the mass loss, fluence, density, and exposure area values for each sample were determined, it was possible to compute the plasma asher erosion yield of every polymer. The erosion yield (E_y) was calculated using the following formula:

$$E_y = \frac{\Delta M_S}{\left(A_S \rho_S F\right)} \tag{3}$$

Where

$\Delta M_S =$ *mass loss of sample (g)*
$A_S =$ *surface area of sample exposed to atomic oxygen (cm²)*
$\rho_S =$ *density of sample (g/cm³)*
$F =$ *plasma asher Kapton H effective AO fluence (atoms/cm²)*

Once the asher erosion yield values were calculated, they were compared to the MISSE 2 in-space erosion yield data in order to determine the correlation between ground-testing and in-space testing for AO erosion.

7. Optical Microscopy

In order to determine the quality of the data collected, every sample was examined under an Olympus SMZ stereo-zoom optical microscope post-ashing. This allowed any existing contamination, or signs of excessive erosion to be identified thus indicating that the sample should be retested. Contamination could protect parts of the sample from AO erosion, which would change the exposure area.

Results and Discussion

1. Comparison of S2 k Values

Table 2 lists the k values calculated from the two flux tests that consisted of six Kapton H samples. In the first flux test, the fluxes, and hence the k values, for the samples in positions 3 and 4 were significantly lower than the flux in position 1. Also the fluxes, and hence the k values, in positions 5 and 6, were slightly higher than the flux in position 1. This pattern remained fairly consistent for Test 2, as well. The only inconsistency occurred in position 2. In Test 1, the position 2 flux was lower than that of position 1, but in test 2, the flux in position 2 was higher than the flux of position 1. The average k values, provided in Table 2, were used for determining the flux (and therefore the fluence) for each sample in positions 2-6 for the plasma asher exposure tests.

Table 2. Flux Test "k" Values

Position Number	Test 1 k	Test 2 k	Average k	Standard Deviation
1	1.000	1.000	1.000	0.000
2	0.904	1.010	0.957	0.075
3	0.773	0.882	0.827	0.077
4	0.720	0.882	0.801	0.114
5	1.164	1.149	1.157	0.010
6	1.065	1.160	1.113	0.067

2. Fluence and Erosion Yield Calculation

Table 3 shows the fluence and asher erosion yield values for all of the tested polymers, listed by test number. This table also lists the thickness, density, and exposure area of each sample. Samples were grouped into tests based on thickness and erosion yield in space, since polymers with a greater thickness and lower erosion yield could withstand a higher fluence, and thinner polymers with a higher erosion yield needed to be exposed to a lower fluence. The fluence values ranged from 7.7×10^{19} to 2.2×10^{21} atoms/cm^2. The asher erosion yield values ranged in order of magnitude from 10^{-25} to 10^{-23} cm^3/atom.

Table 3. Fluence and Erosion Yield Calculation Summary

Test #	Material	Sample Position Number	Difference in Mass (g)	Density of Sample (g/cm^3)	Exposure Area (cm^2)	Asher Exposure Time (sec)	Fluence (atoms/cm^2) based on Average K Values	Asher Ey (cm^3/atom) based on Average K Values
1	Kapton H	1	0.016956	1.4273	3.3546	337,680	1.2E+21	3.0E-24
	Kapton H	2	0.015283	1.4273	3.3433	337,680	1.1E+21	3.0E-24
	Kapton H	3	0.01311	1.4273	3.3559	337,680	9.1E+20	3.0E-24
	Kapton H	4	0.012217	1.4273	3.3566	337,680	8.5E+20	3.0E-24
	Kapton H	5	0.019786	1.4273	3.3631	337,680	1.4E+21	3.0E-24
	Kapton H	6	0.018054	1.4273	3.3543	337,680	1.3E+21	3.0E-24
2	Kapton H	1	0.006	1.4273	3.3546	123,900	4.2E+20	3.0E-24
	CA	2	0.0181	1.2911	3.3433	123,900	4.0E+20	1.1E-23
	Tedlar	3	0.0124	1.3792	3.3559	123,900	3.5E+20	7.7E-24
	PMMA	4	0.0141	1.1628	3.3566	123,900	3.4E+20	1.1E-23
	Mylar	5	0.0094	1.3925	3.3631	123,900	4.9E+20	4.1E-24
	Delrin	6	0.0557	1.3984	3.3543	123,900	4.7E+20	2.6E-23
3	Kapton H	1	0.006041	1.4273	3.3546	90,000	4.2E+20	3.0E-24
	PSU	2	0.006477	1.2199	3.3433	90,000	4.0E+20	4.0E-24
	PEEK	3	0.007366	1.2259	3.3559	90,000	3.5E+20	5.2E-24
	Halar	4	0.007119	1.6761	3.3566	90,000	3.4E+20	3.8E-24
	Teflon AF	5	0.004218	2.1463	3.3631	90,000	4.9E+20	1.2E-24
	PS	6	0.007236	1.0503	3.3543	90,000	4.7E+20	4.4E-24
4	Kapton H	1	0.00916	1.4273	3.3546	167,580	6.4E+20	3.0E-24
	ETFE	2	0.007325	1.7397	3.3433	167,580	6.1E+20	2.1E-24
	CP1	3	0.009291	1.4193	3.3559	167,580	5.3E+20	3.7E-24
	ABS	4	0.012175	1.05 [9]	3.3566	167,580	5.1E+20	6.8E-24
	PTFE	5	0.005996	2.1503	3.3631	167,580	7.4E+20	1.1E-24
	PBI	6	0.007914	1.2758	3.3543	167,580	7.1E+20	2.6E-24
5	Kapton H	1	0.015916	1.4273	3.3546	249,000	1.1E+21	3.0E-24
	PFA	2	0.010554	2.1383	3.3433	249,000	1.1E+21	1.4E-24
	CTFE	3	0.018114	2.1327	3.3559	249,000	9.2E+20	2.8E-24
	Kapton HN	4	0.012938	1.4345	3.3566	249,000	8.9E+20	3.0E-24
	PVDF	5	0.013181	1.7623	3.3631	249,000	1.3E+21	1.7E-24
	FEP	6	0.012716	2.1443	3.3543	249,000	1.2E+21	1.4E-24
6	Kapton H	1	0.026777	1.4273	3.3546	488,880	1.9E+21	3.0E-24
	PC	2	0.04768	1.1231	3.3433	488,880	1.8E+21	7.1E-24
	CR-39	3	0.1035	1.3173	3.3559	488,880	1.5E+21	1.5E-23
	PEI	4	0.02506	1.2873	3.3566	488,880	1.5E+21	3.9E-24
	PP	5	0.080402	0.9065 [10]	3.3631	488,880	2.2E+21	1.2E-23
	PEO	6	N/A	1.147	3.3543	488,880	2.1E+21	N/A

Table 3. Fluence and Erosion Yield Calculation Summary, cont.

Test #	Material	Sample Position Number	Difference in Mass (g)	Density of Sample (g/cm3)	Exposure Area (cm2)	Asher Exposure Time (sec)	Fluence (atoms/cm2) based on Average K Values	Asher Ey (cm3/atom) based on Average K Values
7	Kapton H	1	0.027276	1.4273	3.3546	408,600	1.9E+21	3.0E-24
	PMR-15	2	0.024802	1.3232	3.3433	408,600	1.8E+21	3.1E-24
	PG	3	0.005945	2.22 [11]	3.3559	408,600	1.6E+21	5.1E-25
	Epoxy	4	0.057241	1.115	3.3566	408,600	1.5E+21	1.0E-23
	Upilex S	5	N/A	1.3866	3.3631	408,600	2.2E+21	N/A
8	Kapton H	1	0.005286	1.4273	3.3546	106,800	3.7E+20	3.0E-24
	PBT	2	0.008893	1.3318	3.3433	106,800	3.5E+20	5.7E-24
	PA 66	3	0.010523	1.2252	3.3559	106,800	3.0E+20	8.4E-24
	PU	4	0.017694	1.2345	3.3566	106,800	3.0E+20	1.5E-23
	PAN	5	0.008248	1.1435	3.3631	106,800	4.3E+20	5.0E-24
	PA6	6	0.015072	1.1233	3.3543	106,800	4.1E+20	9.8E-24
9	Kapton H	1	0.004725	1.4273	3.3546	82,380	3.3E+20	3.0E-24
	Kevlar	**2**	**0.022898**	**1.4422**	**3.3433**	**82,380**	**3.2E+20**	**1.5E-23**
	PE	3	0.007795	0.918 [12]	3.3559	82,380	2.7E+20	9.3E-24
	PBO	4	0.006862	1.3976	3.3566	82,380	2.6E+20	5.6E-24
	White Tedlar	5	0.005838	1.6241	3.3631	82,380	3.8E+20	2.8E-24
	Nomex	6	0.009914	0.72 [13]	3.3543	82,380	3.7E+20	1.1E-23
10	Kapton H	1	0.004856	1.4273	3.3546	86,460	3.4E+20	3.0E-24
	PBO	**2**	**0.005646**	**1.3976**	**3.3433**	**86,460**	**3.2E+20**	**3.7E-24**
	Nomex	3	0.006833	0.72	3.3559	86,460	2.8E+20	1.0E-23
	White Tedlar	**4**	**0.005512**	**1.6241**	**3.3566**	**86,460**	**2.7E+20**	**3.7E-24**
	PE	**5**	**0.008259**	**0.918**	**3.3631**	**86,460**	**3.9E+20**	**6.8E-24**
	Tedlar	**6**	**0.008967**	**1.3792**	**3.3543**	**86,460**	**3.8E+20**	**5.2E-24**
11	Kapton H	1	0.013458	1.4273	3.3546	313,200	9.4E+20	3.0E-24
	Kapton H	2	0.013546	1.4273	3.3433	313,200	9.5E+20	3.0E-24
	Kapton H	3	0.011873	1.4273	3.3559	313,200	8.3E+20	3.0E-24
	Kapton H	4	0.011876	1.4273	3.3566	313,200	8.3E+20	3.0E-24
	Kapton H	5	0.015514	1.4273	3.3631	313,200	1.1E+21	3.0E-24
	Kapton H	6	0.015612	1.4273	3.3543	313,200	1.1E+21	3.0E-24
12	Kapton H	1	0.001375	1.4273	3.3546	28,800	9.6E+19	3.0E-24
	PEO	**2**	**0.006295**	**1.147**	**3.3433**	**28,800**	**9.2E+19**	**1.8E-23**
	Upilex S	**3**	**0.001238**	**1.3866**	**3.3559**	**28,800**	**7.9E+19**	**3.4E-24**
	Nomex	**4**	**0.001536**	**0.72**	**3.3566**	**28,800**	**7.7E+19**	**8.3E-24**

Seven samples had to be retested for various reasons, which is why some samples appear twice (and in the case of Nomex, three times) in Table 3. During its first ashing, Tedlar was eroded through its thickness in one area close to the edge, and so it needed to be re-tested. PEO and Upilex-S both had fingerprints discovered on them and this is why no erosion yield value is provided for them in the early tests. PE, PBO, and White Tedlar all eroded completely away during their first ashing, and therefore all had to be retested. Nomex was also re-tested, but, during the retest, it was eroded through in one area, and therefore had to be re-tested a second time. Tests 10 and 12 are the retests of these samples and the data provided in these tests is most accurate. For those samples that appear twice on the table, the bolded values are the erosion yields that are most precise and were used to calculate the asher-to-in-space erosion yield ratio. The majority of samples had a clear ring of non-eroded space on the outer rim where they had been covered by the holder. An example is shown in Figure 4 for a Kapton H witness sample.
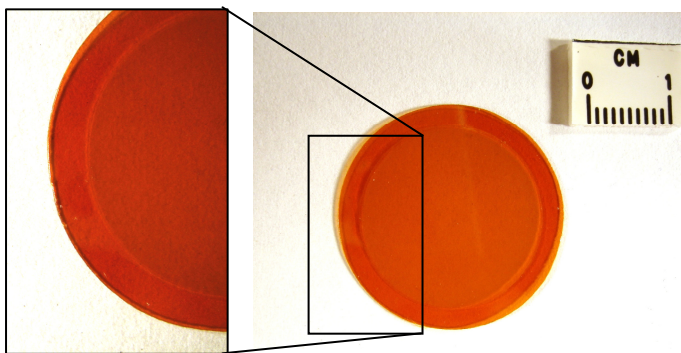
Figure 4. Picture of a Kapton H sample that was ashed during Test 11.

Test 9 underwent two ashings, the second of which was called Test 9B, because the first ashing did not allow for enough exposure time for the samples. Test 9B does not appear in Table 3 because none of the samples survived this second ashing. Four of the samples in Test 9 (PE, PBO, White Tedlar, and Nomex) were retested in other tests. The only sample for which the Test 9 data was used was Kevlar. Therefore, the exposure time for Test 9 (which does not include the exposure time for Test 9B) in Table 3 applies to Kevlar only. A similar incident occurred with Test 2. The Test 2 shown in Table 3 is actually comprised of the original Test 2 and a second ashing, called Test 2B. However, all of the samples survived this second ashing except for one, so the total exposure time for the Test 2 samples includes the exposure time of Test 2 and Test 2B. The only sample that did not survive the second ashing of Test 2 was Tedlar, and it was retested in Test 10.

3. MISSE 2 Erosion Yields vs. Asher Erosion Yields

Table 4 provides a list of the erosion yields of each of the PEACE polymers in space and in the asher, as well as the asher to in-space erosion yield ratios. All of the polymers had higher asher erosion yields than in-space erosion yields. This is due to the many differences that exist between in-space and asher exposure, as mentioned earlier.

Table 4. Ratio of Asher to MISSE 2 Erosion Yields

MISSE Serial #	Material	Abbrev.	MISSE 2 Erosion Yield Ey (cm³/atom)	Asher Ey (cm³/atom)	Asher to In-Space Ey Ratio
2-E5-6	Acrylonitrile butadiene styrene	ABS	1.09E-24	6.8E-24	6.2
2-E5-7	Cellulose acetate	CA	5.05E-24	1.1E-23	2.1
2-E5-8	Poly-(p-phenylene terephthalamide)	PPD-T (Kevlar)	6.28E-25	1.5E-23	24.0
2-E5-9	Polyethylene	PE	*>3.74E-24*	6.8E-24	1.8
2-E5-10	Polyvinyl fluoride	PVF (Tedlar)	3.19E-24	5.2E-24	1.6
2-E5-11	Crystalline polyvinylfluoride w/white pigment	PVF (White Tedlar)	1.01E-25	3.7E-24	37.1
2-E5-12	Polyoxymethylene; acetal; polyformaldehyde	POM (Delrin)	9.14E-24	2.6E-23	2.8
2-E5-13	Polyacrylonitrile	PAN	1.41E-24	5.0E-24	3.6
2-E5-14	Allyl diglycol carbonate	ADC (CR-39)	*>6.80E-24*	1.5E-23	2.2
2-E5-15	Polystyrene	PS	3.74E-24	4.4E-24	1.2
2-E5-16	Polymethyl methacrylate	PMMA	*>5.60E-24*	1.1E-23	1.9
2-E5-17	Polyethylene oxide	PEO	1.93E-24	1.8E-23	9.3
2-E5-18	Poly(p-phenylene-2 6-benzobisoxazole)	PBO (Zylon)	1.36E-24	3.7E-24	2.8
2-E5-19	Epoxide or epoxy	EP	4.21E-24	1.0E-23	2.4
2-E5-20	Polypropylene	PP	2.68E-24	1.2E-23	4.6
2-E5-21	Polybutylene terephthalate	PBT	9.11E-25	5.7E-24	6.2
2-E5-22	Polysulphone	PSU	2.94E-24	4.0E-24	1.3
2-E5-23	Polyeurethane	PU	1.56E-24	1.5E-23	9.3
2-E5-24	Polyphenylene isophthalate	PPPA (Nomex)	1.41E-24	8.3E-24	5.9
2-E5-25	Graphite	PG	4.15E-25	5.1E-25	1.2
2-E5-26	Polyetherimide	PEI	*>3.31E-24*	3.9E-24	1.2
2-E5-27	Polyamide 6 or Nylon 6	PA 6	3.51E-24	9.8E-24	2.8
2-E5-28	Polyamide 66 or Nylon 66	PA 66	1.80E-24	8.4E-24	4.7
2-E5-29	Polyimide	PI (CP1)	1.91E-24	3.7E-24	1.9
2-E5-30	Polyimide (PMDA)	PI (Kapton H)	3.00E-24	3.0E-24	1.0
2-E5-31	Polyimide (PMDA)	PI(Kapton HN)	2.81E-24	3.0E-24	1.1
2-E5-32	Polyimide (BPDA)	PI (Upilex-S)	9.22E-25	3.4E-24	3.6
2-E5-33	Polyimide (PMDA)	PI (Kapton H)	3.00E-24	3.0E-24	1.0
2-E5-34	High temperature polyimide resin	PI (PMR-15)	*>3.02E-24*	3.1E-24	1.0
2-E5-35	Polybenzimidazole	PBI	*>2.21E-24*	2.6E-24	1.2
2-E5-36	Polycarbonate	PC	4.29E-24	7.1E-24	1.7
2-E5-37	Polyetheretherkeytone	PEEK	2.99E-24	5.2E-24	1.7
2-E5-38	Polyethylene terephthalate	PET (Mylar)	3.01E-24	4.1E-24	1.4
2-E5-39	Chlorotrifluoroethylene	CTFE (Kel-f)	8.31E-25	2.8E-24	3.3
2-E5-40	Halar ethylene-chlorotrifluoroethylene	ECTFE (Halar)	1.79E-24	3.8E-24	2.1
2-E5-41	Tetrafluorethylene-ethylene copolymer	ETFE (Tefzel)	9.61E-25	2.1E-24	2.2
2-E5-42	Fluorinated ethylene propylene	FEP	2.00E-25	1.4E-24	7.2
2-E5-43	Polytetrafluoroethylene	PTFE	1.42E-25	1.1E-24	7.9
2-E5-44	Perfluoroalkoxy copolymer resin	PFA	1.73E-25	1.4E-24	8.0
2-E5-45	Amorphous Fluoropolymer	Teflon AF	1.98E-25	1.2E-24	6.1
2-E5-46	Polyvinylidene fluoride	PVDF (Kynar)	1.29E-24	1.7E-24	1.4

Most of the ratios of asher to in-space erosion yield were between one and three. In this table, it appears that PMR-15 had a ratio of 1.0, but the asher erosion yield was slightly higher (3.1×10^{-24} cm^{-3}/atom) than the in-space erosion yield ($>3.02 \times 10^{-24}$ cm^{-3}/atom). Some of the fluoropolymers such as Teflon AF, PTFE, PFA, and FEP had significantly higher ratios: 6.1, 7.9, 8.0, and 7.2, respectively. PP, PBT, PU, PEO, PA 66, ABS, and Nomex also had noticeably higher ratios: 4.6, 6.2, 9.3, 9.3, 4.7, 6.2, and 5.9, respectively. Kevlar and White Tedlar stand out as having ratios of 24.0 and 37.1 respectively, the highest of all the samples. For Kevlar, this is likely because the Kevlar sample is a woven fabric and in the asher AO can attack a greater surface area per atomic oxygen fluence than in LEO.

Another factor that appears to have greatly affected the erosion yield values of the samples is the content of AO durable particles within the polymer, such as in White Tedlar. The titanium dioxide pigment in White Tedlar is AO durable, and hence when the polymeric content of White Tedlar erodes during AO exposure it leaves a fine powder that is not volatile, and which resides on the sample surface. This can shield the underlying polymer from AO attack. For the MISSE flight experiment the AO arrival was primarily from the ram direction (normal to the polymer surface), and hence the residual powder appears to have formed a protective layer (if not disturbed). But, in the plasma asher, where the atomic oxygen arrival is isotropic and at thermal energy, the high AO flux can get underneath the protective particles and cause significantly greater erosion than in space. Hence, the erosion of White Tedlar is substantially greater in the plasma asher than it is in space.

4. Potential Differences between In-Space and Ground Laboratory Data

The atomic oxygen erosion yield for certain polymers, such as those that contain a certain amount of AO durable material (have a high ash content), may be AO fluence dependent. It is possible that the AO erosion yield of the polymer may decrease over time because AO durable particles are increasingly exposed on the sample surface with higher fluence, providing amplified protection of the underlying material that can be oxidized.

Figure 5 is a graph of the mass fraction of ash versus the asher to in-space erosion yield ratio for the MISSE 2 PEACE polymers. As seen in Figure 5, although there is a lot of scatter in the data, as the mass fraction of ash content of a polymer increases, the asher to in-space erosion yield ratio of the polymer increases. This trend is likely because of the differences in arrival direction of AO in the asher and space environments.

There are numerous tests that would be of interest to conduct to try to determine what specific component(s) in the asher provides a difference in the erosion yield as compared to space. For example, one proposed experiment would be to run a series of erosion yield determination tests in a plasma asher with each of the PEACE polymers placed inside Faraday cages, such as the tests conducted by Miller et al [3]. In a specially designed Faraday cage, AO can reach the sample, but the intense UV radiation and charged species cannot. Thus, these tests would determine if radiation and charged species contribute to the greater erosion rate of polymers in the asher as compared to space.
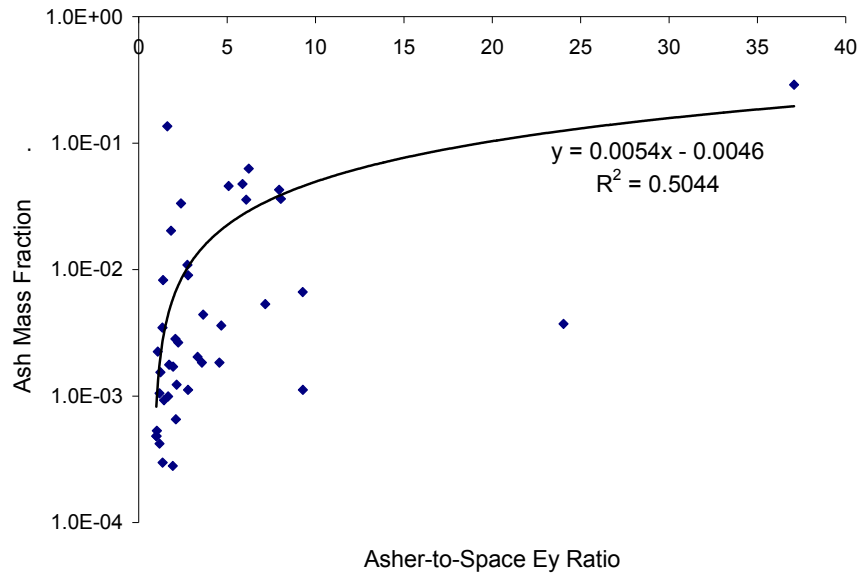
Figure 5. Asher to In-Space Erosion Yield Ratios vs. the Ash Mass Fraction.

In studies conducted by Rutledge and Banks, the erosion yield of Teflon FEP in a plasma asher was determined to be 1.12×10^{-24} cm^3/atom and the ratio of the erosion yield of Teflon FEP to the erosion yield of Kapton H was 0.3742 ± 0.03575 [14]. This test was conducted in a plasma asher using an aluminum holder. The asher erosion yield of Teflon FEP in the current experiment was 1.4×10^{-24} cm^3/atom and the ratio with respect to Kapton H was 0.5, which is similar to the Rutledge and Banks data. The Rutledge and Banks experiment also included tests that attempted to isolate the environmental factors that may cause a difference in asher and in-space erosion yields for Teflon FEP. Faraday cages were used to allow samples to be exposed to AO with no VUV radiation or charged particle species. Faraday cages with double and single mesh screens were used in attempt to block out charged species but allow vacuum ultraviolet (VUV) radiation and AO to enter as well. Most of the tests conducted within a Faraday cage were found to have a lower erosion yield than the tests conducted without a Faraday cage. For example, the Teflon FEP in a closed Faraday cage had an estimated erosion yield of 7.5×10^{-25} cm^3/atom, which is closer to space data [14].

As mentioned previously, in studies conducted by Miller et al, Teflon FEP, PE, and Kapton HN were tested in various AO exposure environments including Faraday cages [3]. One test was conducted with each polymer in an RF plasma asher on a metal plate, which is similar to the tests conducted in this experiment. In the experiment conducted by Miller et al using a metal holder, PE and Kapton HN had erosion yields that were very close to the erosion yields determined in this study. However, in the Miller et al experiment, Teflon FEP had an asher erosion yield that was approximately twice as large as the value determined in this experiment [3], and it was significantly greater than the value determined in the Rutledge and Banks study reported in reference 14. It should be noted that the AO fluence exposures differed between these three tests and the UV intensities may have varied also. Comparing various test results indicates how sensitive some materials, such as Teflon FEP, are to variations in AO exposure conditions.

Summary and Conclusions

To improve the accuracy of ground-based durability testing, ground-laboratory to in-space AO correlation experiments have been conducted. In these tests, the AO erosion yields of the 39 PEACE polymers were determined relative to Kapton H using a radio-frequency (RF) plasma asher operated on air, and with the samples in metal holders. The asher erosion yields were compared to the MISSE 2 erosion yields for the PEACE polymers to determine the correlation between erosion rates in the two environments. The asher erosion yield of every polymer was higher than that of its in-space counterpart, and the asher to in-space erosion yield ratios ranged from 1.0 to 37.1. However, the fluoropolymers in particular had slightly higher ratios, ranging from 6.1 to 8.0. Kevlar, a woven fabric, had a ratio of 24.0, and White Tedlar, a material containing AO durable filler particles, had a ratio of 37.1. The data from this experiment will be valuable for future ground-laboratory AO durability prediction tests using plasma asher facilities. It would be beneficial to do additional testing to try to identify which components in the asher and LEO environments cause the varying erosion yields of polymers in each environment.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The Materials International Space Station Experiment 2 (MISSE 2) Polymer Erosion and Contamination Experiment (PEACE) polymers were exposed to the environment of low Earth orbit (LEO) for 3.95 years from 2001 to 2005. There were 41 different PEACE polymers, which were flown on the exterior of the International Space Station (ISS) in order to determine their atomic oxygen erosion yields. In LEO, atomic oxygen is an environmental durability threat, particularly for long duration mission exposures. Although spaceflight experiments, such as the MISSE 2 PEACE experiment, are ideal for determining LEO environmental durability of spacecraft materials, ground-laboratory testing is often relied upon for durability evaluation and prediction. Unfortunately, significant differences exist between LEO atomic oxygen exposure and atomic oxygen exposure in ground-laboratory facilities. These differences include variations in species, energies, thermal exposures and radiation exposures, all of which may result in different reactions and erosion rates. In an effort to improve the accuracy of ground-based durability testing, ground-laboratory to in-space atomic oxygen correlation experiments have been conducted. In these tests, the atomic oxygen erosion yields of the PEACE polymers were determined relative to Kapton H using a radio-frequency (RF) plasma asher (operated on air). The asher erosion yields were compared to the MISSE 2 PEACE erosion yields to determine the correlation between erosion rates in the two environments. This paper provides a summary of the MISSE 2 PEACE experiment; it reviews the specific polymers tested as well as the techniques used to determine erosion yield in the asher, and it provides a correlation between the space and ground-laboratory erosion yield values. Using the PEACE polymers' asher to in-space erosion yield ratios will allow more accurate in-space materials performance predictions to be made based on plasma asher durability evaluation.

15. SUBJECT TERMS
Atomic oxygen; International Space Station; Space flight experiment; Environmental degradation; Erosion yield; Polymers

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