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# MISSE 2 PEACE Polymers Experiment Atomic Oxygen Erosion Yield Error Analysis

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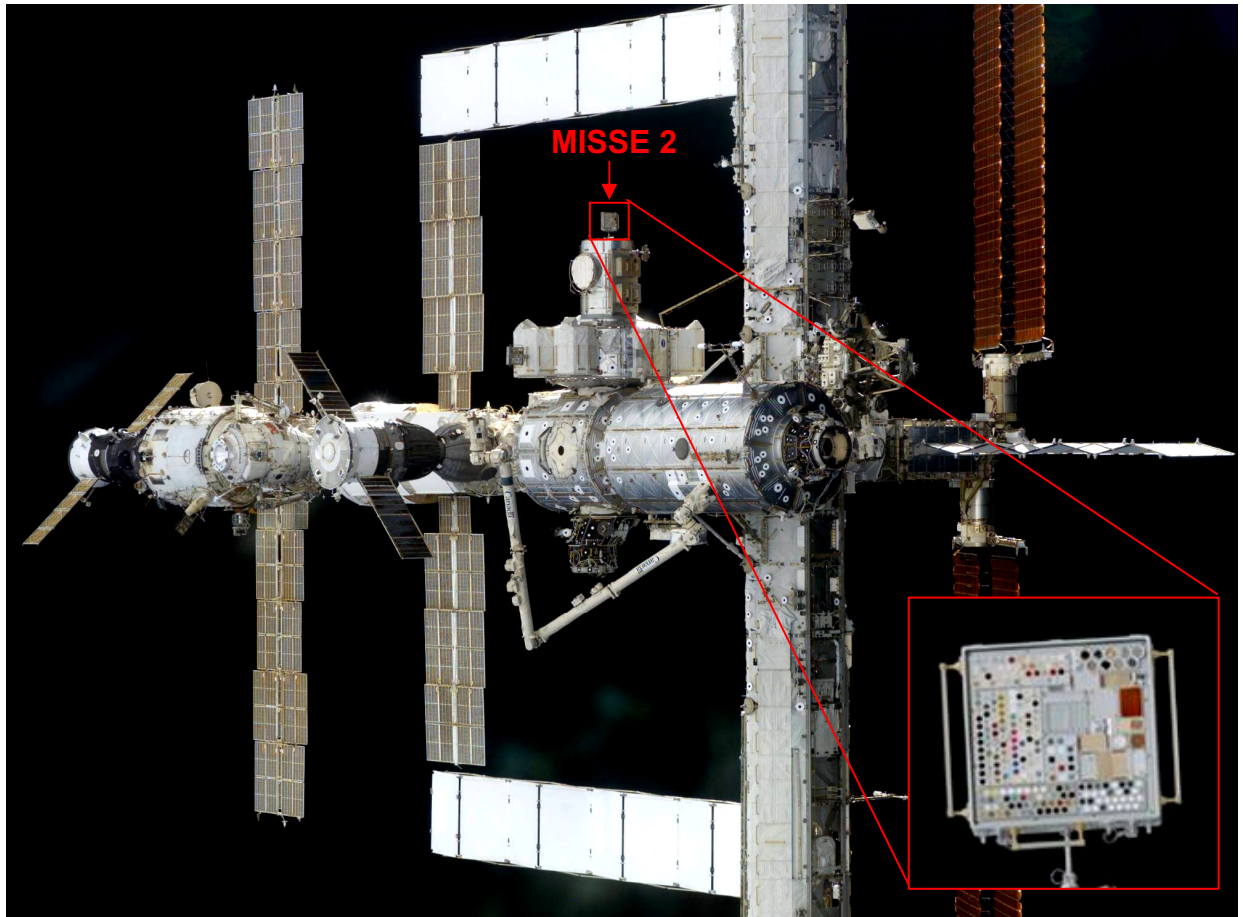
## ABSTRACT

Atomic oxygen erosion of polymers in low Earth orbit (LEO) poses a serious threat to spacecraft performance and durability. To address this, 40 different polymer samples and a sample of pyrolytic graphite, collectively called the PEACE (Polymer Erosion and Contamination Experiment) Polymers, were exposed to the LEO space environment on the exterior of the International Space Station (ISS) for nearly four years as part of the Materials International Space Station Experiment 1 & 2 (MISSE 1 & 2). The purpose of the PEACE Polymers experiment was to obtain accurate mass loss measurements in space to combine with ground measurements in order to accurately calculate the atomic oxygen erosion yields of a wide variety of polymeric materials exposed to the LEO space environment for a long period of time. Error calculations were performed in order to determine the accuracy of the mass measurements and therefore of the erosion yield values. The standard deviation, or error, of each factor was incorporated into the fractional uncertainty of the erosion yield for each of three different situations, depending on the post-flight weighing procedure. The resulting error calculations showed the erosion yield values to be very accurate, with an average error of  $\pm 3.30$  percent.

## 1. INTRODUCTION

### *1.1 MISSE 2 Polymer Erosion and Contamination Experiment (PEACE) Polymers*

Spacecraft in the low Earth orbit (LEO) environment (between 200 and 2000 km above the surface of the Earth) endure extremely harsh conditions, including exposure to ultraviolet, x-ray, and charged particle radiation; micrometeoroids and debris; and atomic oxygen, diatomic oxygen photodissociated by short wavelength ultraviolet radiation from the sun. Atomic oxygen erosion of polymers in LEO poses a serious threat to spacecraft performance and durability. Therefore in order to design durable high-performance spacecraft systems, it is essential to understand the atomic oxygen erosion yield ( $E$ , the volume loss per incident oxygen atom, in  $\text{cm}^3/\text{atom}$ ) of polymers being considered for spacecraft applications.



*Figure 1. MISSE 2 PEC 2 Tray 1, containing the PEACE Polymers experiment attached to the ISS, exposed to space from August 16, 2001 to July 30, 2005.*

Forty polymer samples (including two Kapton H polyimide atomic oxygen fluence witness samples) and pyrolytic graphite, collectively called the PEACE (Polymer Erosion and Contamination Experiment) Polymers, were exposed to the LEO space environment on the exterior of the ISS as part of the Materials International Space Station Experiment 1 & 2 (MISSE 1 & 2).<sup>1-3</sup> The PEACE Polymers experiment was flown in MISSE Passive Experiment Container 2 (PEC 2) on the ram-facing tray (Tray 1) in sample tray E5. MISSE PEC 2 (MISSE 2) was attached to the exterior of the ISS Quest Airlock, as shown in Figure 1. The one-inch-diameter samples encountered atomic oxygen and solar and charged particle radiation during a 3.95-year exposure to the LEO environment from August 16, 2001 to July 30, 2005, when the experiment was successfully retrieved via spacewalk during Discovery's STS-114 Return to Flight mission.

The purpose of the MISSE 2 PEACE Polymers experiment was to obtain accurate mass loss measurements of passive samples exposed to atomic oxygen in space to combine with ground measurements in order to accurately calculate the atomic oxygen erosion yield of a wide variety of polymeric materials exposed to the LEO space environment for a long period of time.<sup>1-3</sup> The data obtained could then help explain the dependence of erosion yield upon polymer chemistry for predictive tool development. Figures 2 and 3 show pre-flight and post-flight photos, respectively, of the MISSE 2 PEACE Polymers experiment tray containing the 41 samples.

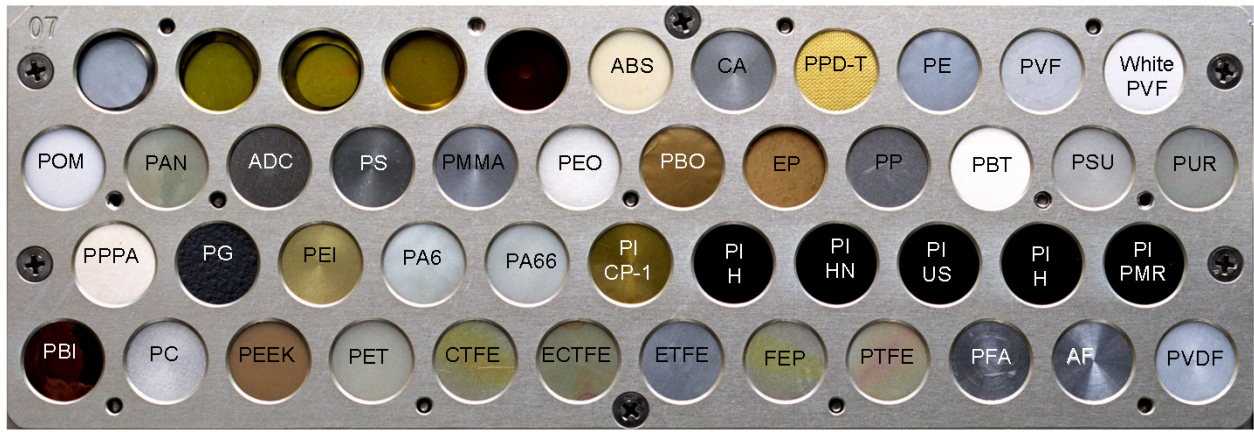


Figure 2. Pre-flight photograph of the MISSE 2 PEACE Polymers experiment. Abbreviations are defined in Table 1.



Figure 3. Post-flight photograph of the MISSE 2 PEACE Polymers experiment.

The 40 different materials (41 samples) tested included those commonly used for spacecraft applications, such as Teflon FEP, as well as more recently developed polymers, such as high temperature polyimide PMR-15 (polymerization of monomer reactants), and pyrolytic graphite, which was included for more diverse chemistry.

The atomic oxygen fluence for the experiment tray was found to be  $8.43 \times 10^{21}$  atoms/cm<sup>2</sup> based on the average of the two fluence witness samples.<sup>1-3</sup> The total equivalent sun hours (ESH) for the E5 tray was estimated to be 6,300 ESH.<sup>1-4</sup> The base-plate thermal cycling temperature range for MISSE 2 was nominally between +40°C and -30°C, with occasional short-term excursions to more extreme temperatures.\*<sup>4</sup> Results of x-ray photoelectron spectroscopy (XPS) contamination analysis of two MISSE 2 sapphire witness samples in sample tray E6 (located next to tray E5) indicated the experiment had received very little contamination; the sapphire witness samples sustained only extremely thin silica contaminant layers, one 1.3 nm thick and one 1.4 nm thick.<sup>5</sup>

\* Details of atomic oxygen fluence calculations, the specific polymers flown, flight sample fabrication, solar and ionizing radiation environmental exposure, and pre-flight and post-flight characterization techniques are presented in Refs. 1-3. Additional details on environmental exposure are provided by Pippin in Ref. 4.

In any experiment, it is critical to determine the accuracy of the data obtained. To address this, the error in each polymer's experimental erosion yield value was calculated using equations for fractional uncertainty derived from the equation used to find erosion yield.

### 1.2 Erosion Yield

The equation to find the erosion yield ( $E$ ) of a polymer calculates the volume lost per incident atomic oxygen atom:

$$E = \frac{4 \cdot \Delta M}{\pi \cdot \rho \cdot D^2 \cdot F} \quad (1)$$

where  $\Delta M$  is mass loss (g),  $\rho$  is the polymer density ( $\text{g}/\text{cm}^3$ ), and  $D$  is the exposed diameter of the polymer (cm).  $F$  is the atomic oxygen fluence ( $\text{atoms}/\text{cm}^2$ ), which is how many atoms of atomic oxygen came into contact with the polymer during the period of exposure. Two Kapton H witness samples were used to calculate the fluence because Kapton H has a well-established erosion yield in LEO,  $3.0 \times 10^{-24} \text{ cm}^3/\text{atom}$ .<sup>6</sup> The atomic oxygen fluence for the samples can be calculated by solving Equation 1 for  $F$  and using the Kapton H mass loss value and density. The fluence was based on the frontal exposed area of each sample.<sup>†</sup>

### 1.3 Fractional Uncertainty

Fractional uncertainty, also called relative uncertainty or percent error, is a way of quantifying the error of a data value. In this investigation the fractional uncertainty represents the fractional standard deviation of the values and is calculated by dividing the standard deviation of the value by the value itself. The general equation for fractional uncertainty in atomic oxygen erosion yield is

$$\frac{\delta E}{E} = \sqrt{\sum_i \left[ \left( \frac{1}{E} \cdot \frac{\partial E}{\partial x_i} \cdot \delta x \right)^2 \right]} \quad (2)$$

where  $E$  is atomic oxygen erosion yield and  $x_i$  is the  $i$ th variable in the equation for erosion yield. The complete equation derivations are explained in Section 4.

## 2. MATERIALS

A list of the different materials exposed to atomic oxygen on the MISSE 2 PEACE polymer experiment is given in Table 1, along with the material abbreviation, trade name(s), and material thickness.

<sup>†</sup> It is believed that the 45° slanted edges of the aluminum sample holders contributed to a slight increase in fluence around the perimeters of the samples, causing some to erode through only around the edge; however, since this was the case for all of the samples, no further calculations needed to be done to correct for this anomalous effect.



Table 1. Materials Included in the MISSE 2 PEACE Polymers Experiment.

Material	Abbrev.	Trade Name(s)	Thickness (mils)
Acrylonitrile butadiene styrene	ABS	Cycolac	5
Allyl diglycol carbonate	ADC	CR-39, Homalite H-911	31
Amorphous fluoropolymer	AF	Teflon AF 1601	2
Cellulose acetate	CA	Clarifoil, Tenite Acetate, Dexcel	2
Chlorotrifluoroethylene	CTFE	Neoflon CTFE M-300, Kel-F	5
Crystalline polyvinylfluoride with white pigment	PVF-W	White Tedlar TWH10BS3	1
Epoxide or epoxy	EP	Hysol EA 956	88-92
Ethylene-chlorotrifluoroethylene	ECTFE	Halar	3
Ethylene-tetrafluoroethylene copolymer	ETFE	Tefzel ZM	3
Fluorinated ethylene propylene	FEP	Teflon FEP (round robin)	2
High temperature polyimide resin	PI	PMR-15	12-14
Perfluoroalkoxy copolymer resin	PFA	Teflon PFA CLP (200 CLP)	2
Poly-(p-phenylene terephthalamide)	PPD-T	Kevlar 29 fabric	2.2
Poly(p-phenylene-2,6-benzobisoxazole)	PBO	Balanced biaxial film	1
Polyacrylonitrile	PAN	Barex 210	2
Polyamide 6 or Nylon 6	PA 6	Akulon K, Ultramid B	2
Polyamide 66 or Nylon 66	PA 66	Maranyl A, Zytel	2
Polybenzimidazole	PBI	Celazole PBI	2
Polybutylene terephthalate	PBT	GE Valox 357	3
Polycarbonate	PC	PEEREX 61 (P61)	10
Polyetheretherketone	PEEK	Victrix PEEK 450	3
Polyetherimide	PEI	Ultem 1000	10
Polyethylene	PE		2
Polyethylene oxide	PEO	Alkox E-30	29
Polyethylene terephthalate	PET	Mylar A-200	2
Polyimide	PI	LaRC CP1 (CP1-300)	3
Polyimide (BPDA)	PI	Upilex-S	1
Polyimide (PMDA), sample 1	PI	Kapton H	5
Polyimide (PMDA), sample 2	PI	Kapton H	5
Polyimide (PMDA)	PI	Kapton HN	5
Polymethyl methacrylate	PMMA	Plexiglas, Lucite, Acrylite (Impact Mod.)	2
Polyoxymethylene; acetal; polyformaldehyde	POM	Delrin (natural)	10
Polyphenylene isophthalate	PPPA	Nomex Aramid Paper Type 410	2
Polypropylene	PP	Polypropylene Type C28	20
Polystyrene	PS	Trycite 1000, Trycite Dew	2
Polysulphone	PSU	Thermolux P1700-NT11, Udel P-1700	2
Polytetrafluoroethylene	PTFE	Chemfilm DF 100	2
Polyurethane	PU	Dureflex PS 8010	2
Polyvinyl fluoride	PVF	Tedlar TTR10SG3	1
Polyvinylidene fluoride	PVDF	Kynar 740	3
Pyrolytic graphite	PG		80

### 3. EXPERIMENTAL PROCEDURES

#### 3.1 Mass Loss Measurements

For both pre- and post-flight mass measurements, all samples were vacuum-desiccated at 60-100 mtorr for a minimum of four days and then weighed with a Mettler M3 Balance. Records were kept of time under vacuum, sequence of weighing, and room temperature and humidity.<sup>1-3</sup> The same sequence and procedures used for the pre-flight measurements were repeated post-flight.

#### 3.2 Density Measurements

A material's theoretical density, provided by the manufacturer, is not always accurate because of variation among different sheets of the polymer. To obtain the densities of the exact materials used in the experiment, a process known as density column measurement was used. A density gradient column was created in a 50-mL buret with solvents of either cesium chloride (CsCl) and water (H<sub>2</sub>O), for less dense polymers, or carbon tetrachloride (CCl<sub>4</sub>) and bromoform (CHBr<sub>3</sub>), for more dense polymers. Glass standards of known densities were placed in the column and allowed to settle, and then small pieces of various polymers were placed in the columns. A curve was fit to the positions and relative known densities of the glass standards. Plotting the positions of the test polymers on this curve yielded density values for each material.<sup>1-3</sup>

#### 3.3 Diameter Measurements

The MISSE 2 PEACE polymers were fabricated into one-inch (2.54-cm) diameter discs using a double bow punch cutter and an Arbor press. Although the intended diameter of the samples was precisely one inch, the samples were flown in a tray with a metal lid that slightly overlapped the edge of each polymer, so to account for the overlap as well as for slight variations in the size of the openings, 10 diameter measurements were taken of each sample tray opening at different positions using a digital micrometer. The average of these 10 measurements was used as the sample diameter. This provided a more exact value for the respective exposed diameter for each sample.<sup>1-3</sup>

#### 3.4 Sample Stacking

MISSE 1 & 2 was originally planned as a one-year mission, and enough layers of each polymer were stacked to last 1.5 years, based on estimated erosion yield data.<sup>1-3</sup> This set of layers was collectively called "flight sample part A." Retrieval of MISSE 1 & 2 was significantly delayed due to the Columbia accident; the experiments were retrieved on July 30, 2005, during Discovery's STS-114 Return to Flight mission. Because of the delay, the PEACE Polymers received nearly four years of space exposure. Fortunately, most of the polymers survived the 47-month exposure to LEO conditions because a second set of sample layers, collectively referred to as "flight sample part B," had been placed behind flight sample part A, giving a total sample thickness that, based on estimated erosion yields, would last for three years. Flight sample part A and flight sample part B of each polymer were placed together into one stack to form the entire flight sample, as shown in Figure 4.

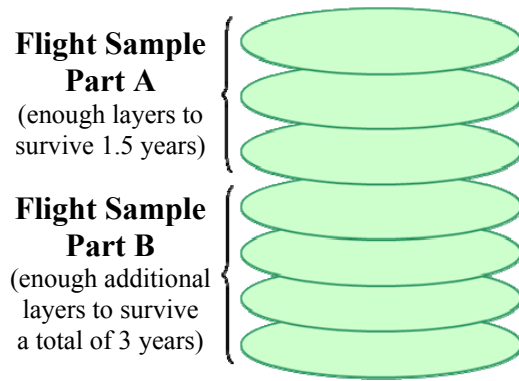


Figure 4. Illustration of the flight sample setup.

### 3.5 Mass Loss Situations

As previously mentioned, each flight sample included two sets of sample layers: part A was enough material to theoretically last for 1.5 years in space, and the additional layers of part B extended the time to three years. Each flight sample also had a corresponding identical “backup” sample (including both parts A and B) that was kept on the ground as a control. Though flight sample parts A and B were not separated during flight, they were separated for pre- and post-flight weighing. Due to mission time constraints, part B of each sample was not weighed pre-flight, and so a theoretical value for the pre-flight mass of part B was calculated: the pre-flight mass of flight sample part A,  $M_F$ , and the pre-flight mass of control sample part A,  $M_C$ , were used to calculate the average mass per layer,  $M_A$ , which was multiplied by the number  $n$  of layers in flight sample part B to get part B’s theoretical pre-flight mass,  $n \cdot M_A$ .

There were three different situations for post-flight sample weighing, so three different equations to determine mass loss were required. Mass loss ( $\Delta M$ ) is a factor in calculating the erosion yield  $E$  of a polymer (see Equation 1), and so it was also necessary to develop three different equations for fractional uncertainty of the erosion yield. The different mass loss equations were simply substituted into the equation for erosion yield, and then from each of the three resulting equations an equation for fractional uncertainty was derived to calculate the percent error for that situation.

In the first situation (see Figure 5), referred to as Situation 1, either only one sample layer was flown, or the atomic oxygen eroded through only some of the layers in flight sample part A, and all of flight sample part B was still pristine. Because flight sample part A and flight sample part B were weighed separately pre-flight, in this situation only part A needed to be weighed post-flight and compared with its pre-flight mass, so to minimize error, the terms for pre- and post-flight mass for flight sample part B were omitted from the Situation 1 mass loss equation:

$$\Delta M_1 = M_F - M_F' \quad (3)$$

where  $M_F$  is the pre-flight mass of flight sample part A and  $M_F'$  is the post-flight mass of part A. Therefore, the Situation 1 erosion yield equation is:

$$E_1 = \frac{4 \cdot (M_F - M_F')}{\pi \cdot \rho \cdot D^2 \cdot F} \quad (4)$$

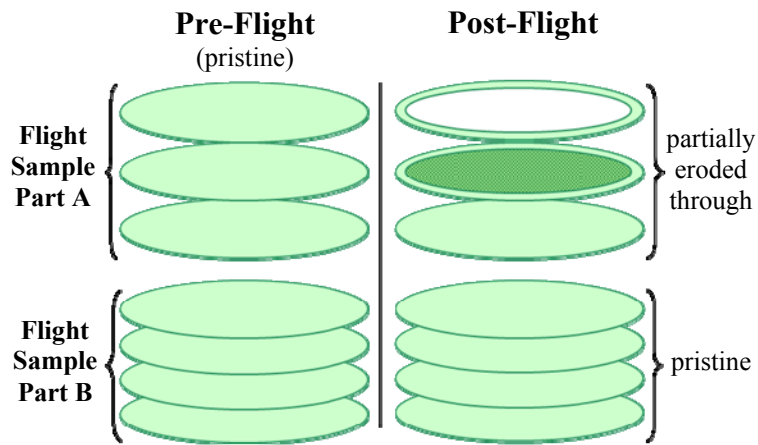


Figure 5. Illustration of Situation 1 sample erosion.

In Situation 2 (see Figure 6), atomic oxygen erosion occurred through all of the layers of flight sample part A and some of flight sample part B.

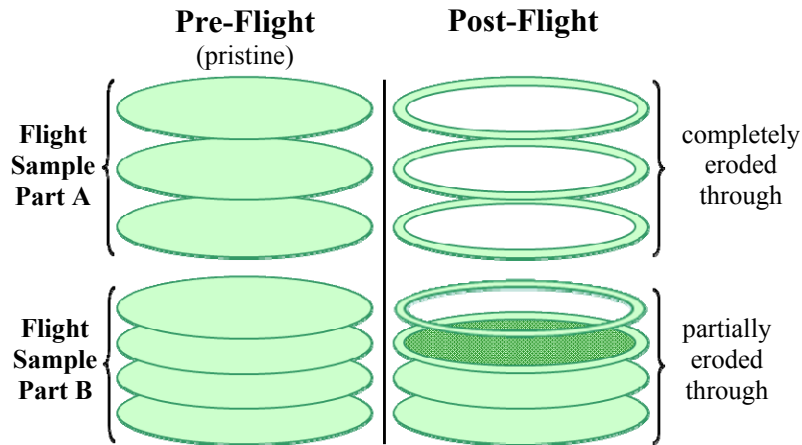


Figure 6. Illustration of Situation 2 sample erosion.

In this situation, flight sample parts A and B were able to be separated to be weighed post-flight. However, because flight sample part B was not weighed pre-flight, its theoretical pre-flight mass was used. Therefore, the Situation 2 equation for mass loss is:

$$\Delta M_2 = M_F - M_F' + n \cdot M_A - M_E' \quad (5)$$

where, again,  $M_F$  and  $M_F'$  are the pre- and post-flight mass values, respectively, of flight sample part A;  $n \cdot M_A$  is the theoretical pre-flight mass of flight sample part B; and  $M_E'$  is the post-flight mass of part B. The erosion yield equation for Situation 2 is:

$$E_2 = \frac{4 \cdot (M_F - M_F' + n \cdot M_A - M_E')}{\pi \cdot \rho \cdot D^2 \cdot F} \quad (6)$$

In Situation 3 (see Figure 7), the sample layers were stuck together and fragmented and were too fragile to separate without losing particles of the material and therefore compromising the erosion yield data.

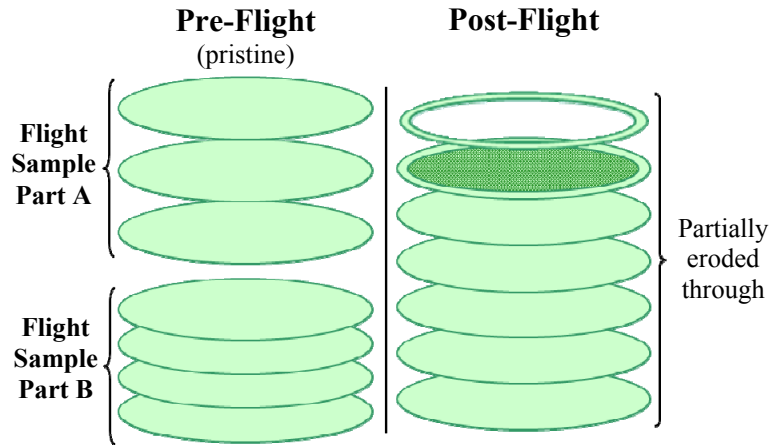


Figure 7. Illustration of Situation 3 sample erosion.

Because of this, flight sample parts A and B were weighed together post-flight. Therefore, the Situation 3 mass loss equation is:

$$\Delta M_3 = M_F + n \cdot M_A - M_S' \quad (7)$$

where  $M_F$  is the pre-flight mass of flight sample part A,  $n \cdot M_A$  is the theoretical pre-flight mass of flight sample part B, and  $M_S'$  is the post-flight mass of the entire flight sample. The Situation 3 erosion yield equation is:

$$E_3 = \frac{4 \cdot (M_F + n \cdot M_A - M_S')}{\pi \cdot \rho \cdot D^2 \cdot F} \quad (8)$$

One of the variables in the erosion yield equations is atomic oxygen fluence,  $F$ , which is itself found from an equation (the erosion yield equation (see Equation 1)) rearranged. Because this  $F$  value was also based on a series of measurements, the equation for  $F$  needed to be substituted into the erosion yield equations so that the error calculations could take into account all sources of error.

The equation for the fluence of the Kapton fluence witness samples is:

$$F_K = \frac{4 \cdot \Delta M_K}{\pi \cdot \rho_K \cdot D_K^2 \cdot E_K} \quad (9)$$

But the atomic oxygen fluence value used in the experiment was actually the average of the two  $F$  values of the two Kapton H witness samples that were flown. This needed to be taken into account as well; the expression for the average of the two fluence values is found as follows:

$$F_{AVG K} = \frac{1}{2} \left( \frac{4 \cdot \Delta M_{K1}}{\pi \cdot \rho_K \cdot D_{K1}^2 \cdot E_K} + \frac{4 \cdot \Delta M_{K2}}{\pi \cdot \rho_K \cdot D_{K2}^2 \cdot E_K} \right) = \frac{4}{2\pi \cdot \rho_K \cdot E_K} \cdot \left( \frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2} \right)$$

This expression for  $F_{AVG K}$  is then substituted into the equation for sample erosion yield:

$$E_S = \frac{4 \cdot \Delta M_S}{\pi \cdot \rho_S \cdot D_S^2 \cdot F_{AVG K}} = \frac{4 \cdot \Delta M_S}{\pi \cdot \rho_S \cdot D_S^2} \cdot \frac{2\pi \cdot \rho_K \cdot E_K}{4 \left( \frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2} \right)} = \frac{2 \cdot \Delta M_S \cdot \rho_K \cdot E_K}{\rho_S \cdot D_S^2 \cdot \left( \frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2} \right)} \quad (10)$$

Therefore, the erosion yield equations for the three situations are now:

$$E_1 = \frac{2 \cdot (M_F - M_F') \cdot \rho_K \cdot E_K}{\rho_S \cdot D_S^2 \cdot \left( \frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2} \right)} \quad (11)$$

$$E_2 = \frac{2 \cdot (M_F - M_F' + n \cdot M_A - M_E') \cdot \rho_K \cdot E_K}{\rho_S \cdot D_S^2 \cdot \left( \frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2} \right)} \quad (12)$$

$$E_3 = \frac{2 \cdot (M_F + n \cdot M_A - M_S') \cdot \rho_K \cdot E_K}{\rho_S \cdot D_S^2 \cdot \left( \frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2} \right)} \quad (13)$$

In the final equations for fractional uncertainty,  $\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}$  is replaced by the variable  $R$ .

### 3.6 Atomic Oxygen Fluence Uncertainty

Table 2 shows the values for mass loss, density, erosion yield, exposed diameter, and the corresponding uncertainty values for each of these variables, for the two Kapton fluence witness samples. The erosion yield for Kapton H polyimide was assumed to be  $3.0 \times 10^{-24} \text{ cm}^3/\text{atom}^6$  with a probable error of  $\pm 0.05 \times 10^{-24} \text{ cm}^3/\text{atom}$ , which is a standard deviation error of  $\pm 7.41 \times 10^{-26} \text{ cm}^3/\text{atom}$  (or 0.024700, a  $\pm 2.5$  percent fractional uncertainty).

Table 2. Kapton H Witness Sample Measurement and Uncertainty Values.

Kapton H Sample #	$\Delta M_K$ (g)	$\delta \Delta M_K$ (g)	$\rho_K$ (g/cm <sup>3</sup> )	$\delta \rho_K$ (g/cm <sup>3</sup> )	$D_K$ (cm)	$\delta D_K$ (cm)	$E_K$ (cm <sup>3</sup> /atom)	$\delta E_K$ (cm <sup>3</sup> /atom)	$\delta E_K/E_K$
1	0.124785	0.0000513	1.42725	0.0077	2.0986	0.00582	3.00E-24	7.41E-26	0.024700
2	0.129219	0.0000808			2.1342	0.00410			

## 4. FRACTIONAL UNCERTAINTY EQUATION DERIVATIONS AND RESULTS

The equations for fractional uncertainty in erosion yield were derived from the previous three erosion yield equations using partial derivatives. In all of the following derivations,  $\partial x$  is the partial derivative of  $x$ ,  $\delta x$  is the uncertainty of  $x$ , and  $\frac{\delta x}{x}$  is the fractional uncertainty of  $x$ . The following variable definitions apply to all of the derived equations:

- $E$  = erosion yield, cm<sup>3</sup>/atom
- $\Delta M$  = mass loss, g
- $\rho$  = density, g/cm<sup>3</sup>
- $D$  = diameter of exposed area of sample, cm
- $F$  = atomic oxygen fluence, atoms/cm<sup>2</sup>
- $M_F$  = pre-flight mass of flight sample part A, g
- $M_{F'}$  = post-flight mass of flight sample part A, g
- $n \cdot M_A$  = theoretical pre-flight mass for flight sample part B, g
- $M_{E'}$  = post-flight mass of flight sample part B, g
- $M_{S'}$  = post-flight mass of flight sample parts A and B weighed together, g

A subscript of  $K$  refers to the value corresponding to the Kapton fluence witness samples, and a subscript of  $S$  refers to the value corresponding to the flight sample in question.

### 4.1 Fractional Uncertainty Equation Derivations for Situation 1

Using Equation 11, the equation for Situation 1 erosion yield, the equation for fractional uncertainty in erosion yield for Situation 1 ( $\frac{\delta E_1}{E_1}$ ) is derived through the following process.

Term one:  $x_1 = M_F$

$$\left( \frac{1}{E_1} \cdot \frac{\partial E_1}{\partial M_F} \cdot \delta M_F \right)^2 = \left( \frac{\rho_S \cdot D_S^2 \cdot \left( \frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2} \right)}{2 \cdot (M_F - M_{F'}) \cdot \rho_K \cdot E_K} \cdot \frac{2 \cdot \rho_K \cdot E_K}{\rho_S \cdot D_S^2 \cdot \left( \frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2} \right)} \cdot \delta M_F \right)^2 = \left( \frac{\delta M_F}{\Delta M_1} \right)^2$$

Term two:  $x_2 = M_{F'}$

$$\left( \frac{1}{E_1} \cdot \frac{\partial E_1}{\partial M_{F'}} \cdot \delta M_{F'} \right)^2 = \left( \frac{\rho_S \cdot D_S^2 \cdot \left( \frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2} \right)}{2 \cdot (M_F - M_{F'}) \cdot \rho_K \cdot E_K} \cdot \frac{-2 \cdot \rho_K \cdot E_K}{\rho_S \cdot D_S^2 \cdot \left( \frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2} \right)} \cdot \delta M_{F'} \right)^2 = \left( \frac{-\delta M_{F'}}{\Delta M_1} \right)^2$$

Term three:  $x_3 = \rho_S$

$$\left( \frac{1}{E_1} \cdot \frac{\partial E_1}{\partial \rho_S} \cdot \delta \rho_S \right)^2 = \left( \frac{\rho_S \cdot D_S^2 \cdot \left( \frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2} \right)}{2 \cdot (M_F - M_{F'}) \cdot \rho_K \cdot E_K} \cdot \frac{-2 \cdot (M_F - M_{F'}) \cdot \rho_K \cdot E_K}{\rho_S^2 \cdot D_S^2 \cdot \left( \frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2} \right)} \cdot \delta \rho_S \right)^2 = \left( \frac{-\delta \rho_S}{\rho_S} \right)^2$$

Term four:  $x_4 = D_S$

$$\left( \frac{1}{E_1} \cdot \frac{\partial E_1}{\partial D_S} \cdot \delta D_S \right)^2 = \left( \frac{\rho_S \cdot D_S^2 \cdot \left( \frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2} \right)}{2 \cdot (M_F - M_{F'}) \cdot \rho_K \cdot E_K} \cdot \frac{-4 \cdot (M_F - M_{F'}) \cdot \rho_K \cdot E_K}{\rho_S \cdot D_S^3 \cdot \left( \frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2} \right)} \cdot \delta D_S \right)^2 = \left( \frac{-2 \cdot \delta D_S}{D_S} \right)^2$$

Term five:  $x_5 = \rho_K$

$$\left(\frac{1}{E_1} \cdot \frac{\partial E_1}{\partial \rho_K} \cdot \delta \rho_K\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F - M_{F'}) \cdot \rho_K \cdot E_K} \cdot \frac{2 \cdot (M_F - M_{F'}) \cdot E_K}{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)} \cdot \delta \rho_K\right)^2 = \left(\frac{\delta \rho_K}{\rho_K}\right)^2$$

Term six:  $x_6 = E_K$

$$\left(\frac{1}{E_1} \cdot \frac{\partial E_1}{\partial E_K} \cdot \delta E_K\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F - M_{F'}) \cdot \rho_K \cdot E_K} \cdot \frac{2 \cdot (M_F - M_{F'}) \cdot \rho_K}{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)} \cdot \delta E_K\right)^2 = \left(\frac{\delta E_K}{E_K}\right)^2$$

Term seven:  $x_7 = \Delta M_{K1}$

$$\left(\frac{1}{E_1} \cdot \frac{\partial E_1}{\partial \Delta M_{K1}} \cdot \delta \Delta M_{K1}\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F - M_{F'}) \cdot \rho_K \cdot E_K} \cdot \frac{-2 \cdot (M_F - M_{F'}) \cdot \rho_K \cdot E_K}{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)^2 \cdot D_{K1}^2} \cdot \delta \Delta M_{K1}\right)^2 = \left(\frac{-\delta \Delta M_{K1}}{D_{K1}^2 \cdot R}\right)^2$$

Term eight:  $x_8 = \Delta M_{K2}$

$$\left(\frac{1}{E_1} \cdot \frac{\partial E_1}{\partial \Delta M_{K2}} \cdot \delta \Delta M_{K2}\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F - M_{F'}) \cdot \rho_K \cdot E_K} \cdot \frac{-2 \cdot (M_F - M_{F'}) \cdot \rho_K \cdot E_K}{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)^2 \cdot D_{K2}^2} \cdot \delta \Delta M_{K2}\right)^2 = \left(\frac{-\delta \Delta M_{K2}}{D_{K2}^2 \cdot R}\right)^2$$

Term nine:  $x_9 = D_{K1}$

$$\left(\frac{1}{E_1} \cdot \frac{\partial E_1}{\partial D_{K1}} \cdot \delta D_{K1}\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F - M_{F'}) \cdot \rho_K \cdot E_K} \cdot \frac{-4 \cdot (M_F - M_{F'}) \cdot \Delta M_{K1} \cdot \rho_K \cdot E_K}{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)^2 \cdot D_{K1}^3} \cdot \delta D_{K1}\right)^2 = \left(\frac{-2 \cdot \Delta M_{K1} \cdot \delta D_{K1}}{D_{K1}^3 \cdot R}\right)^2$$

Term ten:  $x_{10} = D_{K2}$

$$\left(\frac{1}{E_1} \cdot \frac{\partial E_1}{\partial D_{K2}} \cdot \delta D_{K2}\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F - M_{F'}) \cdot \rho_K \cdot E_K} \cdot \frac{-4 \cdot (M_F - M_{F'}) \cdot \Delta M_{K2} \cdot \rho_K \cdot E_K}{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)^2 \cdot D_{K2}^3} \cdot \delta D_{K2}\right)^2 = \left(\frac{-2 \cdot \Delta M_{K2} \cdot \delta D_{K2}}{D_{K2}^3 \cdot R}\right)^2$$

Therefore the equation for fractional uncertainty in erosion yield for Situation 1 is:

$$\frac{\delta E_1}{E_1} = \left[ \left(\frac{\delta M_F}{\Delta M_1}\right)^2 + \left(\frac{\delta M_{F'}}{\Delta M_1}\right)^2 + \left(\frac{\delta \rho_S}{\rho_S}\right)^2 + \left(\frac{2 \cdot \delta D_S}{D_S}\right)^2 + \left(\frac{\delta \rho_K}{\rho_K}\right)^2 + \left(\frac{\delta E_K}{E_K}\right)^2 + \left(\frac{\delta \Delta M_{K1}}{D_{K1}^2 \cdot R}\right)^2 + \left(\frac{\delta \Delta M_{K2}}{D_{K2}^2 \cdot R}\right)^2 + \left(\frac{2 \cdot \Delta M_{K1} \cdot \delta D_{K1}}{D_{K1}^3 \cdot R}\right)^2 + \left(\frac{2 \cdot \Delta M_{K2} \cdot \delta D_{K2}}{D_{K2}^3 \cdot R}\right)^2 \right]^{1/2} \quad (14)$$

Table 3 shows the mass loss, density, exposed diameter, corresponding uncertainty values, and calculated fractional uncertainty for each polymer in Situation 1.



Table 3. Situation 1 Fractional Uncertainty in Erosion Yield.

Material Abbrev.	$\delta M_F$ (g)	$\delta M_{F'}$ (g)	$\Delta M$ (g)	$\rho$ (g/cm <sup>3</sup> )	$\delta\rho$ (g/cm <sup>3</sup> )	$D$ (cm)	$\delta D$ (cm)	$\delta E/E$
ABS	0.000042	0.000020	0.033861	1.0500	0.0074	2.1093	0.0058	0.027017
ADC	0.000036	0.000036	0.267295	1.3173	0.0040	2.1228	0.0033	0.025824
AF	0.000004	0.000003	0.012352	2.1463	0.0086	2.0972	0.0034	0.025975
CTFE	0.000005	0.000012	0.052949	2.1327	0.0086	2.1246	0.0030	0.025927
EP	0.000140	0.000220	0.140720	1.1150	0.0079	2.1283	0.0057	0.027020
FEP	0.000002	0.000084	0.012479	2.1443	0.0086	2.0949	0.0039	0.026890
PAN	0.000066	0.000025	0.047281	1.1435	0.0228	2.1040	0.0054	0.032801
PEO	0.000089	0.000022	0.066395	1.1470	0.0028	2.1288	0.0045	0.025948
PFA	0.000079	0.000005	0.010785	2.1383	0.0086	2.0980	0.0052	0.027248
PG	0.002890	0.000100	0.027730	2.2200	0.0074	2.1321	0.0050	0.107496
PI (Upilex-S)	0.000009	0.000003	0.038127	1.3866	0.0212	2.1225	0.0049	0.030056
PI (PMR-15)	0.000065	0.000034	0.118887	1.3232	0.0040	2.1187	0.0018	0.025696
POM	0.000041	0.000018	0.378378	1.3984	0.0233	2.1146	0.0030	0.030556
PP	0.000020	0.000003	0.072357	0.9070	0.0007	2.1211	0.0062	0.026127
PPD-T	0.000041	0.000023	0.026790	1.4422	0.0017	2.1140	0.0061	0.026193
PS	0.000058	0.000001	0.115947	1.0503	0.0079	2.1123	0.0045	0.026884
PTFE	0.000002	0.000001	0.008938	2.1503	0.0086	2.1062	0.0043	0.026089
PVF-W	0.000022	0.000012	0.004714	1.6241	0.0518	2.0860	0.0043	0.041361

#### 4.2 Fractional Uncertainty Equation Derivations for Situation 2

Using Equation 12, the equation for Situation 2 erosion yield, the equation for fractional uncertainty in erosion yield in Situation 2 ( $\frac{\delta E_2}{E_2}$ ) is derived through the following process.

One of the variables seen above in the Situation 2 equation for erosion yield,  $n \cdot M_A$ , was found from two different measurements:  $M_A$  was found by averaging the mass of each layer of that flight sample's part A and control group over the total number of layers,  $N$ . So, as with the fluence equation, the equation for  $M_A$  must be substituted into the erosion yield equation to account for all sources of error. The equation for  $M_A$  is:

$$M_A = \frac{M_F + M_C}{N}$$

$$\therefore \delta M_A = \frac{1}{N} \cdot \sqrt{\sum_{i=1}^n \left[ \left( \frac{\partial M_A}{\partial x_i} \cdot \delta x_i \right)^2 \right]} = \frac{1}{N} \cdot \sqrt{(\delta M_F)^2 + (\delta M_C)^2} \quad (15)$$

This expression for  $\delta M_A$  will be substituted into term 3 of the error equation for this situation.

Term one:  $x_1 = M_F$

$$\left( \frac{1}{E_2} \cdot \frac{\partial E_2}{\partial M_F} \cdot \delta M_F \right)^2 = \left( \frac{\rho_S \cdot D_S^2 \cdot \left( \frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2} \right)}{2 \cdot (M_F - M_{F'} + n \cdot M_A - M_{E'}) \cdot \rho_K \cdot E_K} \cdot \frac{2 \cdot \rho_K \cdot E_K}{\rho_S \cdot D_S^2 \cdot \left( \frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2} \right)} \cdot \delta M_F \right)^2 = \left( \frac{\delta M_F}{\Delta M_2} \right)^2$$

Term two:  $x_2 = M_F'$

$$\left(\frac{1}{E_2} \cdot \frac{\partial E_2}{\partial M_F'} \cdot \delta M_F'\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F - M_F' + n \cdot M_A - M_E') \cdot \rho_K \cdot E_K} \cdot \frac{-2 \cdot \rho_K \cdot E_K}{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)} \cdot \delta M_F'\right)^2 = \left(\frac{-\delta M_F'}{\Delta M_2}\right)^2$$

Term three:  $x_3 = M_A$

$$\left(\frac{1}{E_2} \cdot \frac{\partial E_2}{\partial M_A} \cdot \delta M_A\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F - M_F' + n \cdot M_A - M_E') \cdot \rho_K \cdot E_K} \cdot \frac{2n \cdot \rho_K \cdot E_K}{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)} \cdot \delta M_A\right)^2 = \left(\frac{n \cdot \delta M_A}{\Delta M_2}\right)^2$$

Term four:  $x_4 = M_E'$

$$\left(\frac{1}{E_2} \cdot \frac{\partial E_2}{\partial M_E'} \cdot \delta M_E'\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F - M_F' + n \cdot M_A - M_E') \cdot \rho_K \cdot E_K} \cdot \frac{-2 \cdot \rho_K \cdot E_K}{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)} \cdot \delta M_E'\right)^2 = \left(\frac{-\delta M_E'}{\Delta M_2}\right)^2$$

Term five:  $x_5 = \rho_S$

$$\left(\frac{1}{E_2} \cdot \frac{\partial E_2}{\partial \rho_S} \cdot \delta \rho_S\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F - M_F' + n \cdot M_A - M_E') \cdot \rho_K \cdot E_K} \cdot \frac{-2 \cdot (M_F - M_F' + n \cdot M_A - M_E') \cdot \rho_K \cdot E_K}{\rho_S^2 \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)} \cdot \delta \rho_S\right)^2 = \left(\frac{-\delta \rho_S}{\rho_S}\right)^2$$

Term six:  $x_6 = D_S$

$$\left(\frac{1}{E_2} \cdot \frac{\partial E_2}{\partial D_S} \cdot \delta D_S\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F - M_F' + n \cdot M_A - M_E') \cdot \rho_K \cdot E_K} \cdot \frac{-4 \cdot (M_F - M_F' + n \cdot M_A - M_E') \cdot \rho_K \cdot E_K}{\rho_S \cdot D_S^3 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)} \cdot \delta D_S\right)^2 = \left(\frac{-2 \cdot \delta D_S}{D_S}\right)^2$$

Term seven:  $x_7 = \rho_K$

$$\left(\frac{1}{E_2} \cdot \frac{\partial E_2}{\partial \rho_K} \cdot \delta \rho_K\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F - M_F' + n \cdot M_A - M_E') \cdot \rho_K \cdot E_K} \cdot \frac{2 \cdot (M_F - M_F' + n \cdot M_A - M_E') \cdot E_K}{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)} \cdot \delta \rho_K\right)^2 = \left(\frac{\delta \rho_K}{\rho_K}\right)^2$$

Term eight:  $x_8 = E_K$

$$\left(\frac{1}{E_2} \cdot \frac{\partial E_2}{\partial E_K} \cdot \delta E_K\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F - M_F' + n \cdot M_A - M_E') \cdot \rho_K \cdot E_K} \cdot \frac{2 \cdot (M_F - M_F' + n \cdot M_A - M_E') \cdot \rho_K}{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)} \cdot \delta E_K\right)^2 = \left(\frac{\delta E_K}{E_K}\right)^2$$

Term nine:  $x_9 = \Delta M_{K1}$

$$\left(\frac{1}{E_2} \cdot \frac{\partial E_2}{\partial \Delta M_{K1}} \cdot \delta \Delta M_{K1}\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F - M_F' + n \cdot M_A - M_E') \cdot \rho_K \cdot E_K} \cdot \frac{-2 \cdot (M_F - M_F' + n \cdot M_A - M_E') \cdot \rho_K \cdot E_K}{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)^2 \cdot D_{K1}^2} \cdot \delta \Delta M_{K1}\right)^2 = \left(\frac{-\delta \Delta M_{K1}}{D_{K1}^2 \cdot R}\right)^2$$

Term ten:  $x_{10} = \Delta M_{K2}$

$$\left( \frac{1}{E_2} \cdot \frac{\partial E_2}{\partial \Delta M_{K2}} \cdot \delta \Delta M_{K2} \right)^2 = \left( \frac{\rho_S \cdot D_S^2 \cdot \left( \frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2} \right)}{2 \cdot (M_F - M_{F'} + n \cdot M_A - M_{E'}) \cdot \rho_K \cdot E_K} \cdot \frac{-2 \cdot (M_F - M_{F'} + n \cdot M_A - M_{E'}) \cdot \rho_K \cdot E_K \cdot \delta \Delta M_{K2}}{\rho_S \cdot D_S^2 \cdot \left( \frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2} \right)^2 \cdot D_{K2}^2} \right)^2$$

$$= \left( \frac{-\delta \Delta M_{K2}}{D_{K2}^2 \cdot R} \right)^2$$

Term eleven:  $x_{11} = D_{K1}$

$$\left( \frac{1}{E_2} \cdot \frac{\partial E_2}{\partial D_{K1}} \cdot \delta D_{K1} \right)^2 = \left( \frac{\rho_S \cdot D_S^2 \cdot \left( \frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2} \right)}{2 \cdot (M_F - M_{F'} + n \cdot M_A - M_{E'}) \cdot \rho_K \cdot E_K} \cdot \frac{-4 \cdot (M_F - M_{F'} + n \cdot M_A - M_{E'}) \cdot \Delta M_{K1} \cdot \rho_K \cdot E_K \cdot \delta D_{K1}}{\rho_S \cdot D_S^2 \cdot \left( \frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2} \right)^2 \cdot D_{K1}^3} \right)^2$$

$$= \left( \frac{-2 \cdot \Delta M_{K1} \cdot \delta D_{K1}}{D_{K1}^3 \cdot R} \right)^2$$

Term twelve:  $x_{12} = D_{K2}$

$$\left( \frac{1}{E_2} \cdot \frac{\partial E_2}{\partial D_{K2}} \cdot \delta D_{K2} \right)^2 = \left( \frac{\rho_S \cdot D_S^2 \cdot \left( \frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2} \right)}{2 \cdot (M_F - M_{F'} + n \cdot M_A - M_{E'}) \cdot \rho_K \cdot E_K} \cdot \frac{-4 \cdot (M_F - M_{F'} + n \cdot M_A - M_{E'}) \cdot \Delta M_{K2} \cdot \rho_K \cdot E_K \cdot \delta D_{K2}}{\rho_S \cdot D_S^2 \cdot \left( \frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2} \right)^2 \cdot D_{K2}^3} \right)^2$$

$$= \left( \frac{-2 \cdot \Delta M_{K2} \cdot \delta D_{K2}}{D_{K2}^3 \cdot R} \right)^2$$

Therefore the equation for fractional uncertainty in erosion yield for Situation 2 is:

$$\frac{\delta E_2}{E_2} = \left[ \left( \frac{\delta M_F}{\Delta M_2} \right)^2 + \left( \frac{\delta M_{F'}}{\Delta M_2} \right)^2 + \left( \frac{\frac{n}{N} \cdot \sqrt{(\delta M_F)^2 + (\delta M_C)^2}}{\Delta M_2} \right)^2 + \left( \frac{\delta M_{E'}}{\Delta M_2} \right)^2 + \left( \frac{\delta \rho_S}{\rho_S} \right)^2 + \left( \frac{2 \cdot \delta D_S}{D_S} \right)^2 + \left( \frac{\delta \rho_K}{\rho_K} \right)^2 \right. \\ \left. + \left( \frac{\delta E_K}{E_K} \right)^2 + \left( \frac{\delta \Delta M_{K1}}{D_{K1}^2 \cdot R} \right)^2 + \left( \frac{\delta \Delta M_{K2}}{D_{K2}^2 \cdot R} \right)^2 + \left( \frac{2 \cdot \Delta M_{K1} \cdot \delta D_{K1}}{D_{K1}^3 \cdot R} \right)^2 + \left( \frac{2 \cdot \Delta M_{K2} \cdot \delta D_{K2}}{D_{K2}^3 \cdot R} \right)^2 \right]^{1/2} \quad (16)$$

Table 4 shows the mass loss, density, exposed diameter, corresponding uncertainty values, and calculated fractional uncertainty for each polymer in Situation 2.

Table 4. Situation 2 Fractional Uncertainty in Erosion Yield.

Material Abbrev.	$\delta M_F$ (g)	$\delta M_C$ (g)	$n$	$N$	$\delta M_{F'}$ (g)	$\delta M_{E'}$ (g)	$\Delta M$ (g)	$\rho$ (g/cm <sup>3</sup> )	$\delta\rho$ (g/cm <sup>3</sup> )	$D$ (cm)	$\delta D$ (cm)	$\delta E/E$
CA	0.000790	0.000433	6	14	0.000098	0.000069	0.191482	1.2911	0.0025	2.1059	0.0060	0.026573
ETFE	0.000003	0.000002	1	2	0.000003	0.000005	0.049108	1.7397	0.0029	2.1066	0.0022	0.025598
PA 66	0.000088	0.000034	3	8	0.000007	0.000019	0.065562	1.2252	0.1509	2.1185	0.0051	0.125851
PBI	0.000156	0.000141	2	4	0.000040	0.000029	0.082708	1.2758	0.0036	2.1038	0.0056	0.026275
PBO	0.000062	0.000000	5	13	0.000001	0.000004	0.056778	1.3976	0.0752	2.1268	0.0031	0.059587
PC	0.000020	0.000110	1	2	0.000002	0.000012	0.142287	1.1231	0.0079	2.1113	0.0028	0.026545
PE	0.000018	0.000004	2	8	0.000010	0.000013	0.102760	0.9180	0.0007	2.1257	0.0029	0.025620
PEEK	0.000117	0.000026	3	6	0.000001	0.000013	0.107764	1.2259	0.0457	2.1056	0.0054	0.045436
PEI	0.000018	0.000018	1	2	0.000003	0.000009	0.126853	1.2873	0.0036	2.1216	0.0053	0.026088
PI (Kapton HN)	0.000052	0.000035	1	4	0.000010	0.000012	0.121315	1.4345	0.0020	2.1313	0.0038	0.025748
PPPA	0.000162	0.000188	3	6	0.000060	0.000102	0.030549	0.7200	0.0074	2.1298	0.0055	0.028987
PSU	0.000035	0.000032	3	6	0.000012	0.000015	0.105948	1.2199	0.0221	2.1113	0.0054	0.031645
PVDF	0.000005	0.000007	1	2	0.000006	0.000001	0.066860	1.7623	0.0086	2.1108	0.0061	0.026549
PVF	0.000011	0.000011	6	13	0.000013	0.000010	0.132537	1.3792	0.0013	2.1331	0.0028	0.025612

### 4.3 Fractional Uncertainty Equation Derivations for Situation 3

Using Equation 13, the equation for Situation 3 erosion yield, the equation for fractional uncertainty in erosion yield for Situation 3 ( $\frac{\delta E_3}{E_3}$ ) is derived through the following process. Equation 15 will be used to substitute for  $\delta M_A$  in term 2 of the final equation.

Term one:  $x_1 = M_F$

$$\left(\frac{1}{E_3} \cdot \frac{\partial E_3}{\partial M_F} \cdot \delta M_F\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F + n \cdot M_A - M_S') \cdot \rho_K \cdot E_K} \cdot \frac{2 \cdot \rho_K \cdot E_K}{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)} \cdot \delta M_F\right)^2 = \left(\frac{\delta M_F}{\Delta M_3}\right)^2$$

Term two:  $x_2 = M_A$

$$\left(\frac{1}{E_3} \cdot \frac{\partial E_3}{\partial M_A} \cdot \delta M_A\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F + n \cdot M_A - M_S') \cdot \rho_K \cdot E_K} \cdot \frac{2n \cdot \rho_K \cdot E_K}{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)} \cdot \delta M_A\right)^2 = \left(\frac{n \cdot \delta M_A}{\Delta M_3}\right)^2$$

Term three:  $x_3 = M_S'$

$$\left(\frac{1}{E_3} \cdot \frac{\partial E_3}{\partial M_S'} \cdot \delta M_S'\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F + n \cdot M_A - M_S') \cdot \rho_K \cdot E_K} \cdot \frac{-2 \cdot \rho_K \cdot E_K}{\rho_S^2 \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)} \cdot \delta M_S'\right)^2 = \left(\frac{-\delta M_S'}{\Delta M_3}\right)^2$$

Term four:  $x_4 = \rho_S$

$$\left(\frac{1}{E_3} \cdot \frac{\partial E_3}{\partial \rho_S} \cdot \delta \rho_S\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F + n \cdot M_A - M_S') \cdot \rho_K \cdot E_K} \cdot \frac{-2 \cdot (M_F + n \cdot M_A - M_S') \cdot \rho_K \cdot E_K}{\rho_S^2 \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)} \cdot \delta \rho_S\right)^2 = \left(\frac{-\delta \rho_S}{\rho_S}\right)^2$$

Term five:  $x_5 = D_S$

$$\left(\frac{1}{E_3} \cdot \frac{\partial E_3}{\partial D_S} \cdot \delta D_S\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F + n \cdot M_A - M_S') \cdot \rho_K \cdot E_K} \cdot \frac{-4 \cdot (M_F + n \cdot M_A - M_S') \cdot \rho_K \cdot E_K \cdot \delta D_S}{\rho_S \cdot D_S^3 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)} \cdot \delta D_S\right)^2 = \left(\frac{-2 \cdot \delta D_S}{D_S}\right)^2$$

Term six:  $x_6 = \rho_K$

$$\left(\frac{1}{E_3} \cdot \frac{\partial E_3}{\partial \rho_K} \cdot \delta \rho_K\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F + n \cdot M_A - M_S') \cdot \rho_K \cdot E_K} \cdot \frac{2 \cdot (M_F + n \cdot M_A - M_S') \cdot E_K}{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)} \cdot \delta \rho_K\right)^2 = \left(\frac{\delta \rho_K}{\rho_K}\right)^2$$

Term seven:  $x_7 = E_K$

$$\left(\frac{1}{E_3} \cdot \frac{\partial E_3}{\partial E_K} \cdot \delta E_K\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F + n \cdot M_A - M_S') \cdot \rho_K \cdot E_K} \cdot \frac{2 \cdot (M_F + n \cdot M_A - M_S') \cdot \rho_K}{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)} \cdot \delta E_K\right)^2 = \left(\frac{\delta E_K}{E_K}\right)^2$$

Term eight:  $x_8 = \Delta M_{K1}$

$$\left(\frac{1}{E_3} \cdot \frac{\partial E_3}{\partial \Delta M_{K1}} \cdot \delta \Delta M_{K1}\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F + n \cdot M_A - M_S') \cdot \rho_K \cdot E_K} \cdot \frac{-2 \cdot (M_F + n \cdot M_A - M_S') \cdot \rho_K \cdot E_K \cdot \delta \Delta M_{K1}}{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)^2 \cdot D_{K1}^2}\right)^2 = \left(\frac{-\delta \Delta M_{K1}}{D_{K1}^2 \cdot R}\right)^2$$

Term nine:  $x_9 = \Delta M_{K2}$

$$\left(\frac{1}{E_3} \cdot \frac{\partial E_3}{\partial \Delta M_{K2}} \cdot \delta \Delta M_{K2}\right)^2 = \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F + n \cdot M_A - M_S') \cdot \rho_K \cdot E_K} \cdot \frac{-2 \cdot (M_F + n \cdot M_A - M_S') \cdot \rho_K \cdot E_K \cdot \delta \Delta M_{K2}}{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)^2 \cdot D_{K2}^2}\right)^2 = \left(\frac{-\delta \Delta M_{K2}}{D_{K2}^2 \cdot R}\right)^2$$

Term ten:  $x_{10} = D_{K1}$

$$\begin{aligned} \left(\frac{1}{E_3} \cdot \frac{\partial E_3}{\partial D_{K1}} \cdot \delta D_{K1}\right)^2 &= \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F + n \cdot M_A - M_S') \cdot \rho_K \cdot E_K} \cdot \frac{-4 \cdot (M_F + n \cdot M_A - M_S') \cdot \Delta M_{K1} \cdot \rho_K \cdot E_K \cdot \delta D_{K1}}{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)^2 \cdot D_{K1}^3}\right)^2 \\ &= \left(\frac{-2 \cdot \Delta M_{K1} \cdot \delta D_{K1}}{D_{K1}^3 \cdot R}\right)^2 \end{aligned}$$

Term eleven:  $x_{11} = D_{K2}$

$$\begin{aligned} \left(\frac{1}{E_3} \cdot \frac{\partial E_3}{\partial D_{K2}} \cdot \delta D_{K2}\right)^2 &= \left(\frac{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)}{2 \cdot (M_F + n \cdot M_A - M_S') \cdot \rho_K \cdot E_K} \cdot \frac{-4 \cdot (M_F + n \cdot M_A - M_S') \cdot \Delta M_{K2} \cdot \rho_K \cdot E_K \cdot \delta D_{K2}}{\rho_S \cdot D_S^2 \cdot \left(\frac{\Delta M_{K1}}{D_{K1}^2} + \frac{\Delta M_{K2}}{D_{K2}^2}\right)^2 \cdot D_{K2}^3}\right)^2 \\ &= \left(\frac{-2 \cdot \Delta M_{K2} \cdot \delta D_{K2}}{D_{K2}^3 \cdot R}\right)^2 \end{aligned}$$

Therefore the equation for fractional uncertainty in erosion yield for Situation 3 is:

$$\begin{aligned} \frac{\delta E_3}{E_3} &= \left[ \left(\frac{\delta M_F}{\Delta M_3}\right)^2 + \left(\frac{n}{N} \cdot \frac{\sqrt{(\delta M_F)^2 + (\delta M_C)^2}}{\Delta M_3}\right)^2 + \left(\frac{-\delta M_S'}{\Delta M_3}\right)^2 + \left(\frac{\delta \rho_S}{\rho_S}\right)^2 + \left(\frac{2 \cdot \delta D_S}{D_S}\right)^2 + \left(\frac{\delta \rho_K}{\rho_K}\right)^2 + \left(\frac{\delta E_K}{E_K}\right)^2 \right. \\ &\quad \left. + \left(\frac{\delta \Delta M_{K1}}{D_{K1}^2 \cdot R}\right)^2 + \left(\frac{\delta \Delta M_{K2}}{D_{K2}^2 \cdot R}\right)^2 + \left(\frac{2 \cdot \Delta M_{K1} \cdot \delta D_{K1}}{D_{K1}^3 \cdot R}\right)^2 + \left(\frac{2 \cdot \Delta M_{K2} \cdot \delta D_{K2}}{D_{K2}^3 \cdot R}\right)^2 \right]^{1/2} \end{aligned} \quad (17)$$

Table 5 shows the mass loss, density, exposed diameter, corresponding uncertainty values, and calculated fractional uncertainty for each polymer in Situation 3.

Table 5. Situation 3 Fractional Uncertainty in Erosion Yield.

Material Abbrev.	$\delta M_F$ (g)	$\delta M_C$ (g)	$n$	$N$	$\delta M_{S'}$ (g)	$\Delta M$ (g)	$\rho$ (g/cm <sup>3</sup> )	$\delta\rho$ (g/cm <sup>3</sup> )	$D$ (cm)	$\delta D$ (cm)	$\delta E/E$
ECTFE	0.000008	0.000004	1	4	0.000012	0.088869	1.6761	0.0059	2.1141	0.0027	0.025821
PA 6	0.000088	0.000112	4	8	0.000055	0.118376	1.1233	0.0079	2.1304	0.0033	0.026617
PBT	0.000027	0.000017	2	6	0.000049	0.036429	1.3318	0.0040	2.1296	0.0026	0.025798
PET	0.000160	0.000010	4	8	0.000033	0.125187	1.3925	0.0029	2.1240	0.0058	0.026157
PI (CP1)	0.000038	0.000038	2	4	0.000025	0.080648	1.4193	0.0167	2.1205	0.0030	0.028199
PMMA	0.000495	0.000126	5	10	0.000017	0.194588	1.1628	0.0028	2.1247	0.0034	0.025932
PU	0.000051	0.000040	4	10	0.000042	0.057227	1.2345	0.0174	2.1165	0.0039	0.029353

## 5. RESULTS AND DISCUSSION

The MISSE 2 PEACE Polymers LEO atomic oxygen erosion yield data are given in Table 6.<sup>1-3</sup> These results represent the widest variety of extremely accurately measured high atomic oxygen fluence data to date.

Including enough material in each flight sample to theoretically last for three years was crucial to the experiment's success, because although the experiment received nearly four years of atomic oxygen exposure, only one polymer (PBI) was completely eroded away. However, for five other samples (PE, ADC, PMMA, PEI, and PMR-15) the atomic oxygen did in some places erode through all layers of the flight sample. For these six samples, therefore, the calculated erosion yields are less than the actual erosion yields, because if there had been more material the mass loss would have been greater. These six erosion yield values are highlighted in Table 6. Since the samples in these cases appeared to have eroded partially or completely through at a fluence level close to the full mission fluence, the measured erosion yields of these samples were still included in the data set as estimates to develop a predictive erosion yield equation.<sup>7</sup> These samples have been re-flown in LEO for actual erosion yield determination as part of the Stressed PEACE Polymers experiment on MISSE 6.<sup>8</sup>

Table 6 also includes the uncertainty and fractional uncertainty in erosion yield for each of the MISSE 2 PEACE Polymers samples. The highest fractional uncertainty was for PA 66,  $\pm 12.59$  percent, and the lowest fractional uncertainty was for Tefzel ZM,  $\pm 2.56$  percent. The average fractional uncertainty in erosion yield was very small,  $\pm 3.30$  percent.

Table 6. MISSE 2 PEACE Polymers Experiment Fractional Uncertainty Data Summary.

Material	Abbrev.	Trade Name(s)	Fractional Uncertainty in Erosion Yield	Uncertainty in Erosion Yield	Erosion Yield (cm <sup>3</sup> /atom)
Acrylonitrile butadiene styrene	ABS	Cyclocac	0.027017	2.96E-26	1.09 ± 0.03 E-24
Allyl diglycol carbonate	ADC	CR-39, Homalite H-911	0.025824	1.76E-25	>6.80 E-24
Amorphous fluoropolymer	AF	Teflon AF 1601	0.025975	5.13E-27	1.98 ± 0.05 E-25
Cellulose acetate	CA	Clarifoil, Tenite Acetate, Dixel	0.026573	1.34E-25	5.05 ± 0.13 E-24
Chlorotrifluoroethylene	CTFE	Neoflon CTFE M-300, Kel-F	0.025927	2.15E-26	8.31 ± 0.22 E-25
Crystalline polyvinylfluoride with white pigment	PVF-W	White Tedlar TWH10BS3	0.041361	4.17E-27	1.01 ± 0.04 E-25
Epoxide or epoxy	EP	Hysol EA 956	0.027020	1.14E-25	4.21 ± 0.11 E-24
Ethylene-chlorotrifluoroethylene	ECTFE	Halar	0.025821	4.63E-26	1.79 ± 0.05 E-24
Ethylene-tetrafluoroethylene copolymer	ETFE	Tefzel ZM	0.025598	2.46E-26	9.61 ± 0.25 E-25
Fluorinated ethylene propylene	FEP	Teflon FEP (round robin)	0.026890	5.39E-27	2.00 ± 0.05 E-25
High temperature polyimide resin	PI	PMR-15	0.025696	7.77E-26	>3.02 E-24
Perfluoroalkoxy copolymer resin	PFA	Teflon PFA CLP (200 CLP)	0.027248	4.72E-27	1.73 ± 0.05 E-25
Poly-(p-phenylene terephthalamide)	PPD-T	Kevlar 29 fabric	0.026193	1.64E-26	6.28 ± 0.16 E-25
Poly(p-phenylene-2,6-benzobisoxazole)	PBO	(balanced biaxial film)	0.059587	8.08E-26	1.36 ± 0.08 E-24
Polyacrylonitrile	PAN	Barex 210	0.032801	4.63E-26	1.41 ± 0.05 E-24
Polyamide 6 or Nylon 6	PA 6	Akulon K, Ultramid B	0.026617	9.33E-26	3.51 ± 0.09 E-24
Polyamide 66 or Nylon 66	PA 66	Maranyl A, Zytel	0.125851	2.27E-25	1.80 ± 0.23 E-24
Polybenzimidazole	PBI	Celazole PBI	0.026275	5.81E-26	>2.21 E-24
Polybutylene terephthalate	PBT	GE Valox 357	0.025798	2.35E-26	9.11 ± 0.24 E-25
Polycarbonate	PC	PEEREX 61 (P61)	0.026545	1.14E-25	4.29 ± 0.11 E-24
Polyetheretherketone	PEEK	Victrex PEEK 450	0.045436	1.36E-25	2.99 ± 0.14 E-24
Polyetherimide	PEI	Ultem 1000	0.026088	8.63E-26	>3.31 E-24
Polyethylene	PE		0.025620	9.59E-26	>3.74 E-24
Polyethylene oxide	PEO	Alkox E-30	0.025948	5.01E-26	1.93 ± 0.05 E-24
Polyethylene terephthalate	PET	Mylar A-200	0.026157	7.87E-26	3.01 ± 0.08 E-24
Polyimide	PI	LaRC CP1 (CP1-300)	0.028199	5.38E-26	1.91 ± 0.05 E-24
Polyimide (BPDA)	PI	Upilex-S	0.030056	2.77E-26	9.22 ± 0.28 E-25
Polyimide (PMDA)	PI	Kapton H	0.024700	7.41E-26	3.00 ± 0.07 E-24
Polyimide (PMDA)	PI	Kapton H	0.024700	7.41E-26	3.00 ± 0.07 E-24
Polyimide (PMDA)	PI	Kapton HN	0.025748	7.24E-26	2.81 ± 0.07 E-24

Table 6. cont. MISSE 2 PEACE Polymers Experiment Fractional Uncertainty Data Summary.

Material	Abbrev.	Trade Name(s)	Fractional Uncertainty in Erosion Yield	Uncertainty in Erosion Yield	Erosion Yield (cm <sup>3</sup> /atom)
Polymethyl methacrylate	PMMA	Plexiglas, Lucite, Acrylite (Impact Mod.)	0.025932	1.45E-25	>5.60 E-24
Polyoxymethylene; acetal; polyformaldehyde	POM	Delrin (natural)	0.030556	2.79E-25	9.14 ± 0.28 E-24
Polyphenylene isophthalate	PPPA	Nomex Aramid Paper Type 410	0.028987	4.10E-26	1.41 ± 0.04 E-24
Polypropylene	PP	C28	0.026127	7.00E-26	2.68 ± 0.07 E-24
Polystyrene	PS	Trycite 1000, Trycite Dew	0.026884	1.00E-25	3.74 ± 0.10 E-24
Polysulphone	PSU	Thermolux P1700-NT11, Udel P-1700	0.031645	9.31E-26	2.94 ± 0.09 E-24
Polytetrafluoroethylene	PTFE	Chemfilm DF 100	0.026089	3.69E-27	1.42 ± 0.04 E-25
Polyurethane	PU	Dureflex PS 8010	0.029353	4.59E-26	1.56 ± 0.05 E-24
Polyvinyl fluoride	PVF	Tedlar TTR10SG3	0.025612	8.17E-26	3.19 ± 0.08 E-24
Polyvinylidene fluoride	PVDF	Kynar 740	0.026549	3.41E-26	1.29 ± 0.03 E-24
Pyrolytic graphite	PG		0.107496	4.46E-26	4.15 ± 0.45 E-25

## 6. SUMMARY

The purpose of the MISSE 2 PEACE Polymers experiment was to obtain the atomic oxygen erosion yields of a wide variety of polymeric materials exposed to the LEO space environment for a long period of time.<sup>1-3</sup> The MISSE 2 PEACE Polymers experiment is unique in that it included the widest variety of polymers exposed to identical LEO conditions and received a high fluence of atomic oxygen exposure ( $8.43 \times 10^{21}$  atoms/cm<sup>2</sup>). Because of this, the experiment provides very valuable erosion yield data for spacecraft design purposes.<sup>1-3</sup> It is therefore extremely important to know how accurate the atomic oxygen erosion yield data are. To address this, the error in each polymer's experimental erosion yield value was calculated using equations for fractional uncertainty derived from the equation used to find erosion yield. Because three different situations were required for post-flight sample weighing, a factor in calculating the erosion yield  $E$  of a polymer, three different equations were derived for determining the fractional uncertainty of the erosion yield values.

The uncertainty and fractional uncertainty in erosion yield for each of the MISSE 2 PEACE Polymers samples have been determined. The highest fractional uncertainty was for PA 66, ±12.59 percent, and the lowest fractional uncertainty was for Tefzel ZM, ±2.56 percent. The average fractional uncertainty in erosion yield was very small, ±3.30 percent. The results listed in Table 6 represent the widest variety of extremely accurately measured high atomic oxygen fluence data to date.



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<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b> Atomic oxygen erosion of polymers in low Earth orbit (LEO) poses a serious threat to spacecraft performance and durability. To address this, 40 different polymer samples and a sample of pyrolytic graphite, collectively called the PEACE (Polymer Erosion and Contamination Experiment) Polymers, were exposed to the LEO space environment on the exterior of the International Space Station (ISS) for nearly 4 years as part of the Materials International Space Station Experiment 1 & 2 (MISSE 1 & 2). The purpose of the PEACE Polymers experiment was to obtain accurate mass loss measurements in space to combine with ground measurements in order to accurately calculate the atomic oxygen erosion yields of a wide variety of polymeric materials exposed to the LEO space environment for a long period of time. Error calculations were performed in order to determine the accuracy of the mass measurements and therefore of the erosion yield values. The standard deviation, or error, of each factor was incorporated into the fractional uncertainty of the erosion yield for each of three different situations, depending on the post-flight weighing procedure. The resulting error calculations showed the erosion yield values to be very accurate, with an average error of $\pm 3.30$ percent.					
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