Effect of 1.5 Years of Space Exposure on Tensile and Optical Properties of Spacecraft Polymers

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Presented at the  
2015 International Space Station Research and Development Conference  
July 7-9, 2015, Boston, MA
Outline

• Introduction to the space environment
• Examples of space environment induced damage
  – LDEF, ISS & Hubble Space Telescope (HST)
• Materials International Space Station Experiment (MISSE)
  – MISSE 7B Polymers Experiment
  – MISSE 7A Zenith Polymers Experiment
• Effect of 1.5 Years of Ram, Wake, Zenith and Nadir Space Exposure on Tensile Properties of Teflon
  – Samples & experimental procedures
  – Results
• The Effect of 1.5 Years of Zenith Space Exposure on Optical Properties of Spacecraft Polymers
  – Samples & experimental procedures
  – Comparison of MISSE 2 & MISSE 7 data
  – Results
In low Earth orbit (LEO) environmental threats include:

- Solar radiation (ultraviolet (UV), x-rays)
- “Solar wind” particle radiation (electrons, protons)
- Cosmic rays (energetic nuclei)
- Temperature extremes & thermal cycling
- Micrometeoroid & orbital debris (space particles)
- Atomic oxygen (reactive oxygen atoms)
Atomic Oxygen (AO)

- AO is the predominant species in LEO (≈180-650 km)
- It is formed by photodissociation of molecular oxygen (O₂) by short wavelength energetic UV radiation
- At ram impact velocities (7.66 km/s) the average impact energy is 4.5 eV
- AO oxidizes certain spacecraft materials such as polymers, resulting in gas formation - so the material erodes away...

⇒ AO is a serious threat to spacecraft survivability
Space Environment Induced Degradation

- AO undercutting erosion of the P6 Port Solar Array Al-Kapton blanket box cover (1 yr)
- AO erosion of Kapton blanket
- Debris generation
- Radiation induced darkening
- Impact site
- Long Duration Exposure Facility (LDEF) 5.8 yrs in space
- Hubble Space Telescope (HST)
- Radiation induced embrittlement & cracking of Teflon insulation (6.8 yrs)
- International Space Station (ISS) 2001

Radiation induced embrittlement & cracking of Teflon insulation (6.8 yrs)
Materials International Space Station Experiment (MISSE)

MISSE is a series of materials flight experiments consisting of trays called Passive Experiment Containers (PECs), that were exposed to the space environment on the exterior of the International Space Station (ISS).

The PECs were positioned in either a *ram/wake orientation* or a *zenith/nadir orientation*.

**Objective:**

*To test the stability and durability of materials and devices in the space environment*
PI: Phil Jenkins/Naval Research Laboratory (NRL)
Experiment type: Active & Passive
Orientation: 7A - Zenith/Nadir, 7B - Ram/Wake
ISS Location: EXPRESS Logistics Carrier 2 (ELC 2)
Deployed: November 23, 2009 (STS-129)
Retrieved: May 20, 2011 (STS-134)
Exposure: 1.49 Years
The MISSE 7B Polymers Experiment is a passive experiment that contained 44 samples flown in ram or wake flight orientations on MISSE 7B.

Objectives:

1. Determine the LEO AO erosion yield (Ey, volume loss per incident oxygen atom, cm$^3$/atom) of the polymers
2. Determine the effect of space exposure on tensile properties
3. Determine the effect of space exposure on optical properties

- 37 samples were flown in the ram orientation exposing them to a high AO fluence and radiation
  - 23 samples in Al trays
  - 14 samples in Al holders taped to the baseplate
- 7 samples were flown in the wake orientation exposing them to radiation with low AO fluence
  - All samples in Al holders taped to the baseplate
- Kapton H$^\circledR$ was flown for AO fluence determination

Pre-flight photo of the ram side if MISSE 7B with images of B7-R & NR-5 trays and taped samples
The MISSE 7A Zenith Polymers Experiment is a passive experiment that contained 25 samples flown in a zenith flight orientation on MISSE 7A

Objectives:
1. Determine the effect of solar exposure on the Ey of fluoropolymers flown in a zenith orientation under high solar radiation/low AO exposure, and compare results with those of the MISSE 7B Polymers Experiment
2. Determine the effect of space exposure on tensile properties
3. Determine the effect of space exposure on optical properties

• 25 samples were flown in the zenith orientation, exposing them to high solar radiation & grazing AO
  • 15 samples in the “Z” tray (1” x 1” samples)
  • 10 samples in Al holders taped to the baseplate

• 6 tensile samples were also flown in a nadir orientation

• Kapton H® was flown for AO fluence determination

On-orbit image of MISSE 7A & 7B with pre-flight photos of 7A taped samples and the Z tray
MISSE 7A & 7B
Environmental Exposures

Zenith
4,300 ESH
AO F= 1.6×10^{20} \text{ atoms/cm}^2

Nadir
<<2,000 ESH
AO F= \sim1.6\times10^{20} \text{ atoms/cm}^2

Wake
2,000 ESH
AO F= 2.9\times10^{20} \text{ atoms/cm}^2

Ram
2,400 ESH
AO F= 4.2\times10^{21} \text{ atoms/cm}^2

Environment data references:
1. Yi, G. T., et al., NASA TM-2013-217848
Effect of 1.5 Years of Ram, Wake, Zenith and Nadir Space Exposure on Tensile Properties of Teflon
## MISSE 7 Tensile Samples Experiment
### 19 Tensile Samples

<table>
<thead>
<tr>
<th>GRC Sample ID</th>
<th>Sample</th>
<th>Thickness (mil)</th>
<th># Samples</th>
<th>Purpose</th>
<th>MISSE Location</th>
</tr>
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<tbody>
<tr>
<td>E7</td>
<td>Back surface aluminized fluorinated ethylene propylene (Al-FEP)</td>
<td>2</td>
<td>3</td>
<td>To determine embrittlement of FEP</td>
<td>7B Ram</td>
</tr>
<tr>
<td>E23</td>
<td>Carbon paint back-surface coated FEP (C-FEP)</td>
<td>2</td>
<td>3</td>
<td>Effect of heating on the embrittlement of FEP</td>
<td>7B Ram</td>
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<tr>
<td>E6</td>
<td>Al-FEP</td>
<td>2</td>
<td>2</td>
<td>To determine embrittlement of FEP</td>
<td>7B Wake</td>
</tr>
<tr>
<td>E8</td>
<td>Expanded-polytetrafluoroethylene (ePTFE)</td>
<td>44</td>
<td>2</td>
<td>To determine embrittlement of ePTFE</td>
<td>7A Zenith</td>
</tr>
<tr>
<td>E12</td>
<td>Al-FEP</td>
<td>2</td>
<td>3</td>
<td>To determine embrittlement of FEP</td>
<td>7A Zenith</td>
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<tr>
<td>H2</td>
<td>Al-FEP</td>
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<td>3</td>
<td>To determine embrittlement of FEP</td>
<td>7A Nadir</td>
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<tr>
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<td>Al-FEP</td>
<td>2</td>
<td>3</td>
<td>To determine embrittlement of FEP</td>
<td>7A Nadir</td>
</tr>
</tbody>
</table>

### Ram Samples
- E7
- E23

### Wake Samples
- E6
- E8

### Zenith Samples
- E12
- H2
- H3

### Nadir Samples
- Pre-flight photos
Experimental Procedures

• Thickness Measurements
  – Heidenhain MT12 digital thickness gauge (±0.5 μm)
  – 5 locations on each sample
  – Used to determine cross-sectional area for stress calculations

• Tensile Properties
  – DDL Model 200Q Electromechanical Test System
  – Tensile samples were sectioned to the specifications defined in American Society for Testing and Materials (ASTM) Standard D-638 for Type V tensile specimens
  – 12.7 mm/min & 25.4 mm initial gauge length
Thickness Measurements
2 mil Aluminized-FEP (Al-FEP)

2-mil Al-FEP:

- **Nadir** and **wake** exposed samples are slightly thicker than controls, but the difference is within experimental error.
- **Zenith** exposed samples showed a very small decrease in thickness, indicating some erosion.
- **Ram** exposure resulted in by far the largest thickness loss, indicating significant atomic oxygen erosion, as expected due to highest AO fluence.

<table>
<thead>
<tr>
<th>Location</th>
<th>Thickness (mil)</th>
<th>Number of Samples</th>
<th>Number of Measurements per Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>1.970</td>
<td>20</td>
<td>5</td>
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<tr>
<td>Nadir</td>
<td>1.991</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Wake</td>
<td>1.996</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Ram</td>
<td>1.755</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Zenith</td>
<td>1.943</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>
A clear difference was observed between samples punched out parallel and normal to the roll direction.

Therefore, comparisons were only made between samples punched in the same orientation.

The “punch orientation” of the MISSE samples was not known, but was determined based on which type of stress-strain curve the samples produced.
MISSE 7 Tensile Samples Experiment
Al-FEP Tensile Data

MISSE 7 Al-FEP (Normal to Roll Direction)
Median Sample of Each Group

Stress (MPa)

Engineering Strain

Control
Nadir
Ram
Zenith
MISSE 7 Tensile Samples Experiment
Al-FEP Tensile Data

MISSE 7 Al-FEP (Parallel to Roll Direction)
Median Sample of Each Group

Stress (MPa)

Engineering Strain

- Control
- Nadir
- Wake
- Zenith
## MISSE 7 AI-FEP Tensile Data

<table>
<thead>
<tr>
<th>Roll Direction</th>
<th>Exposure</th>
<th># Samples</th>
<th>Average UTS (MPa)</th>
<th>Average E%</th>
<th>St. Dev. UTS (MPa)</th>
<th>St. Dev. E%</th>
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<tbody>
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<td>29.8</td>
<td>218.1</td>
<td>2.1</td>
<td>15.6</td>
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<td></td>
<td>Nadir</td>
<td>2</td>
<td>28.3</td>
<td>209.1</td>
<td>0.1</td>
<td>4.5</td>
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<tr>
<td></td>
<td>Wake</td>
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<td>19.0</td>
<td>121.5</td>
<td>1.0</td>
<td>19.5</td>
</tr>
<tr>
<td></td>
<td>Ram</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Zenith</td>
<td>2</td>
<td>16.3</td>
<td>69.8</td>
<td>0.1</td>
<td>1.0</td>
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<td><strong>Normal</strong></td>
<td>Control</td>
<td>12</td>
<td>25.5</td>
<td>270.9</td>
<td>2.1</td>
<td>25.0</td>
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<tr>
<td></td>
<td>Nadir</td>
<td>4</td>
<td>24.1</td>
<td>262.4</td>
<td>1.5</td>
<td>20.1</td>
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<tr>
<td></td>
<td>Wake</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Ram</td>
<td>3</td>
<td>14.9</td>
<td>80.0</td>
<td>0.6</td>
<td>9.7</td>
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<tr>
<td></td>
<td>Zenith</td>
<td>1</td>
<td>15.1</td>
<td>44.1</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**UTS**: Ultimate Tensile Strength
MISSE 7 AI-FEP

% Elongation at Failure vs. Equivalent Sun Hours (ESH)

**Parallel to Roll Direction**

- **Nadir***: 150 ESH
  - AO F = ~1.6×10^{20} atoms/cm²

- **Wake**: 2,000 ESH
  - 2.9×10^{20} atoms/cm²

- **Zenith**: 4,300 ESH
  - 1.6×10^{20} atoms/cm²

**Normal to Roll Direction**

- **Nadir***: 150 ESH
  - AO F = ~1.6×10^{20} atoms/cm²

- **Ram**: 2,400 ESH
  - 4.2×10^{21} atoms/cm²

**Nadir ESH was estimated at 150 ESH (no direct solar exposure, albedo reflected only)**
MISSE 7 Tensile Samples Experiment
AI-FEP & C-FEP Ram Samples

Heating has a major impact on the radiation induced embrittlement of FEP in space.

E7: AI-FEP
Pre-Flight
Reflections
On-orbit formed cracks

Post-Flight

Control
UTS: 25.5 MPa
Elongation: 271%

E7
UTS: 14.9 MPa
Elongation: 80%

E23: C-FEP
Control
UTS: 15.1 MPa
Elongation: 232%

E23
UTS: 0 MPa
Elongation: 0%
(Cracked on-orbit)
Tensile Strength
Expanded Polytetrafluoroethylene (ePTFE)

The ePTFE has two layers – both appear to have the same properties, but the back is smooth & the front is textured.

The back layer of control samples broke first & the front layer elongated forming a very thin fibre:

Both layers of flight samples broke nearly simultaneously & cracking was apparent on the front layer prior to break.
Tensile properties were obtained for 16 MISSE 7 tensile flight samples (3 cracked while on-orbit)

Prolonged exposure to the space environment can cause catastrophic degradation of 2-mil Al-FEP

Extent of degradation is highly dependent on exposure, determined by surface orientation:

- **Nadir**: low AO & low radiation exposure cause minimal damage
- **Wake**: low AO fluence & moderate solar exposure leads to some embrittlement
- **Ram**: high AO fluence & moderate solar exposure causes large thickness loss & significant embrittlement
- **Zenith**: high solar radiation exposure & moderate AO exposure leads to extensive embrittlement

On-orbit heating has a significant impact on radiation-induced degradation of FEP
The Effect of 1.5 Years of Zenith Space Exposure on Optical Properties of Spacecraft Polymers
Optical Procedures

- Optical properties were obtained using a Cary 5000 UV-Vis-NIR Spectrophotometer operated with an integrating sphere.
- Total and diffuse reflectance (TR, DR) and total and diffuse transmittance (TT, DT) were obtained from 250 nm to 2500 nm.
  - Data was obtained post-flight on both the flight and control samples.
- Specular reflectance (SR) and specular transmittance (ST) were computed using the following equations:
  - \( SR = TR - DR \)
  - \( ST = TT - DT \)
- An Excel macro was utilized to compute the integrated Air Mass Zero (AM0) solar absorptance (\( \alpha_s \)) using TR and TT:
  - \( \alpha_s = 1 - (TR + TT) \)
- Data from the flight and control samples were compared to determine the effect of LEO space exposure on the optical properties of the polymers.
<table>
<thead>
<tr>
<th>ID</th>
<th>Material (Abbreviation)</th>
<th>Trade Name</th>
<th>Thickness (mils)</th>
<th># of Layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z-1</td>
<td>Polytetrafluoroethylene (PTFE)</td>
<td>Chemfilm DF-100</td>
<td>5</td>
<td>1</td>
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<tr>
<td>Z-2</td>
<td>Fluorinated ethylene propylene (FEP)</td>
<td>Teflon FEP</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Z-3</td>
<td>Chlorotrifluoroethylene (CTFE)</td>
<td>Kel-F</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Z-4</td>
<td>Ethylene-tetrafluoroethylene (ETFE)</td>
<td>Tefzel ZM</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Z-5</td>
<td>Polyvinylidene fluoride (PVDF)</td>
<td>Kynar ZM</td>
<td>3</td>
<td>2</td>
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<td>Z-6</td>
<td>Ethylene-chlorotrifluoroethylene (ECTFE)</td>
<td>Halar 300</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Z-7</td>
<td>Polyvinyl fluoride (PVF)</td>
<td>Clear Tedlar</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>Z-8</td>
<td>Polyimide (PI, PMDA)</td>
<td>Kapton H</td>
<td>1</td>
<td>3</td>
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<tr>
<td>Z-9</td>
<td>Aluminized-FEP (Al-FEP)*</td>
<td>Aluminized-Teflon</td>
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<td>1</td>
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<td>Z-10</td>
<td>Silvered-FEP (Ag-FEP)*</td>
<td>Silvered-Teflon</td>
<td>5</td>
<td>1</td>
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<td>Z-11</td>
<td>Polyethylene (PE)</td>
<td>PE</td>
<td>5</td>
<td>8</td>
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<td>Z-12</td>
<td>Si/Kapton E/vapor deposited Al</td>
<td>Si/Kapton E/ VDA</td>
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<td>1</td>
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<tr>
<td>Z-14</td>
<td>Al₂O₃/FEP</td>
<td>Al₂O₃/FEP</td>
<td>2</td>
<td>1</td>
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<tr>
<td>P13</td>
<td>Polyvinyl alcohol (PVOH)</td>
<td>PVOH</td>
<td>1.5</td>
<td>12</td>
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<td>E9</td>
<td>Polypropylene (PP)</td>
<td>PP</td>
<td>20</td>
<td>1</td>
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</table>

* FEP space facing (back-surface metallized)  ** Taped sample

Z-Tray Pre-Flight

Z-Tray Post-Flight

MISSE 7A Zenith Polymers Experiment Samples

Z-4 ETFE (Tefzel)  Z-5 PVDF (Kynar)
Examples of MISSE 7 Zenith Polymer Samples
Solar Absorptance Spectra

**Teflon FEP Flight (Z-2) vs. Control Solar Absorptance**

- **Control (0.010)**
- **Flight (0.011)**

**PVF (Tedlar) Flight (Z-7) vs. Control Solar Absorptance**

- **Control (0.078)**
- **Flight (0.242)**

Z-2 FEP (Teflon) flight sample looks clear like control
Solar absorptance change is essentially zero

Z-7 PVF (Tedlar) flight sample looks yellow
Solar absorptance increase of 0.164

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## Zenith Polymers Optical Property Data

<table>
<thead>
<tr>
<th>MISSE ID</th>
<th>Material</th>
<th>Thickness (mils)</th>
<th># Layers</th>
<th>Flight vs Control</th>
<th>TR</th>
<th>DR</th>
<th>SR</th>
<th>TT</th>
<th>DT</th>
<th>ST</th>
<th>$\alpha_S$</th>
<th>$\Delta \alpha_S$</th>
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</thead>
<tbody>
<tr>
<td>Z-1</td>
<td>Polytetrafluoroethylene (PTFE), Teflon</td>
<td>5</td>
<td>1</td>
<td>Flight</td>
<td>0.135</td>
<td>0.124</td>
<td>0.011</td>
<td>0.808</td>
<td>0.339</td>
<td>0.469</td>
<td>0.057</td>
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<td>Control</td>
<td>0.144</td>
<td>0.134</td>
<td>0.010</td>
<td>0.800</td>
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<td>0.460</td>
<td>0.056</td>
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<td>Z-2</td>
<td>Fluorinated ethylene propylene (FEP), Teflon</td>
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<td>1</td>
<td>Flight</td>
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<td>0.029</td>
<td>0.020</td>
<td>0.939</td>
<td>0.028</td>
<td>0.911</td>
<td>0.011</td>
<td>0.001</td>
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<td>Control</td>
<td>0.051</td>
<td>0.019</td>
<td>0.032</td>
<td>0.939</td>
<td>0.030</td>
<td>0.909</td>
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<td>Z-3</td>
<td>Chlorotrifluoroethylene (CTFE), Kel-F</td>
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<td>2</td>
<td>Flight</td>
<td>0.113</td>
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<td>0.066</td>
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<td>0.020</td>
<td>0.824</td>
<td>0.042</td>
<td>0.021</td>
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<tr>
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<td>Control</td>
<td>0.118</td>
<td>0.012</td>
<td>0.106</td>
<td>0.861</td>
<td>0.018</td>
<td>0.843</td>
<td>0.021</td>
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<td>Z-4</td>
<td>Ethylene-tetrafluoroethylene (ETFE), Tefzel</td>
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<td>Flight</td>
<td>0.104</td>
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<td>0.475</td>
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<td>Control</td>
<td>0.107</td>
<td>0.013</td>
<td>0.093</td>
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<td>Flight</td>
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<td>0.097</td>
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<td>Control</td>
<td>0.117</td>
<td>0.106</td>
<td>0.010</td>
<td>0.820</td>
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<td>3</td>
<td>Flight</td>
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<td></td>
<td>Control</td>
<td>0.177</td>
<td>0.06</td>
<td>0.177</td>
<td>0.774</td>
<td>0.145</td>
<td>0.629</td>
<td>0.050</td>
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</tr>
<tr>
<td>Z-7</td>
<td>Polyvinyl fluoride (PVF), Clear Tedlar</td>
<td>3</td>
<td>12</td>
<td>Flight</td>
<td>0.366</td>
<td>0.343</td>
<td>0.240</td>
<td>0.392</td>
<td>0.342</td>
<td>0.051</td>
<td>0.242</td>
<td>0.164</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>Control</td>
<td>0.453</td>
<td>0.327</td>
<td>0.127</td>
<td>0.468</td>
<td>0.342</td>
<td>0.127</td>
<td>0.078</td>
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</tr>
<tr>
<td>Z-8</td>
<td>Polyimide, Kapton H</td>
<td>1</td>
<td>3</td>
<td>Flight</td>
<td>0.182</td>
<td>0.126</td>
<td>0.056</td>
<td>0.351</td>
<td>0.174</td>
<td>0.177</td>
<td>0.467</td>
<td>0.029</td>
</tr>
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<td>Control</td>
<td>0.201</td>
<td>0.030</td>
<td>0.170</td>
<td>0.361</td>
<td>0.028</td>
<td>0.333</td>
<td>0.438</td>
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<tr>
<td>Z-9</td>
<td>Aluminized-FEP (FEP/Al)</td>
<td>2</td>
<td>1</td>
<td>Flight</td>
<td>0.783</td>
<td>0.159</td>
<td>0.623</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.217</td>
<td>0.061</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>Control</td>
<td>0.844</td>
<td>0.435</td>
<td>0.409</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.156</td>
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<tr>
<td>Z-10</td>
<td>Silverized-FEP (FEP/Ag)</td>
<td>5</td>
<td>1</td>
<td>Flight</td>
<td>0.867</td>
<td>0.320</td>
<td>0.547</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.133</td>
<td>0.052</td>
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<tr>
<td></td>
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<td></td>
<td>Control</td>
<td>0.919</td>
<td>0.053</td>
<td>0.865</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.081</td>
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<tr>
<td>Z-11</td>
<td>Polyethylene (PE)</td>
<td>5</td>
<td>8</td>
<td>Flight</td>
<td>0.356</td>
<td>0.324</td>
<td>0.032</td>
<td>0.556</td>
<td>0.337</td>
<td>0.219</td>
<td>0.088</td>
<td>0.017</td>
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<tr>
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<td>Control</td>
<td>0.399</td>
<td>0.284</td>
<td>0.115</td>
<td>0.530</td>
<td>0.324</td>
<td>0.207</td>
<td>0.071</td>
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<tr>
<td>Z-12</td>
<td>Si/2 mil Kapton E/Al</td>
<td>2</td>
<td>1</td>
<td>Flight</td>
<td>0.579</td>
<td>0.037</td>
<td>0.542</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.421</td>
<td>-0.002</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Control</td>
<td>0.576</td>
<td>0.042</td>
<td>0.535</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.423</td>
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<tr>
<td>Z-14</td>
<td>$\text{Al}_2\text{O}_3$/FEP</td>
<td>2</td>
<td>1</td>
<td>Flight</td>
<td>0.117</td>
<td>0.092</td>
<td>0.026</td>
<td>0.817</td>
<td>0.022</td>
<td>0.795</td>
<td>0.066</td>
<td>0.025</td>
</tr>
<tr>
<td></td>
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<td>Control</td>
<td>0.132</td>
<td>0.045</td>
<td>0.087</td>
<td>0.826</td>
<td>0.027</td>
<td>0.799</td>
<td>0.041</td>
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<tr>
<td>Z-15</td>
<td>Polyvinyl alcohol (PVOH)</td>
<td>1.5</td>
<td>6</td>
<td>Flight</td>
<td>0.414</td>
<td>0.403</td>
<td>0.010</td>
<td>0.383</td>
<td>0.374</td>
<td>0.009</td>
<td>0.203</td>
<td>0.124</td>
</tr>
<tr>
<td></td>
<td>(Sample is cracked &amp; not flat)</td>
<td></td>
<td></td>
<td>Control</td>
<td>0.377</td>
<td>0.303</td>
<td>0.074</td>
<td>0.544</td>
<td>0.509</td>
<td>0.035</td>
<td>0.079</td>
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<tr>
<td>Z-16</td>
<td>Polypropylene (PP)</td>
<td>20</td>
<td>1</td>
<td>Flight</td>
<td>0.083</td>
<td>0.048</td>
<td>0.035</td>
<td>0.796</td>
<td>0.350</td>
<td>0.446</td>
<td>0.121</td>
<td>0.050</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>Control</td>
<td>0.086</td>
<td>0.042</td>
<td>0.045</td>
<td>0.842</td>
<td>0.356</td>
<td>0.486</td>
<td>0.071</td>
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</tbody>
</table>
## MISSE 7 vs. MISSE 2
### Solar Absorptance Changes

<table>
<thead>
<tr>
<th>MISSE Environmental Exposure</th>
<th>MISSE 2 [Waters 2009]</th>
<th>MISSE 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Orientation</td>
<td>Ram</td>
<td>Zenith</td>
</tr>
<tr>
<td>Solar Exposure (ESH)</td>
<td>6,300</td>
<td>4,300</td>
</tr>
<tr>
<td>AO Fluence (atoms/cm²)</td>
<td>(8.43 \times 10^{21})</td>
<td>(1.6 \times 10^{20})</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>F vs. C Δ (\alpha_s)</th>
<th>F vs. C Δ (\alpha_s)</th>
<th>MISSE 7 vs. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyimide, Kapton H</td>
<td>0.077</td>
<td>0.029</td>
<td>+0.048</td>
</tr>
<tr>
<td>Chlorotrifluoroethylene (CTFE), Kel-F</td>
<td>0.105</td>
<td>0.021</td>
<td>+0.084</td>
</tr>
<tr>
<td>Ethylene-tetrafluoroethylene (ETFE), Tefzel</td>
<td>0.095</td>
<td>0.072</td>
<td>+0.023</td>
</tr>
<tr>
<td>Ethylene-chlorotrifluoroethylene (ECTFE), Halar</td>
<td>0.116</td>
<td>0.189</td>
<td>-0.073</td>
</tr>
<tr>
<td>Fluorinated ethylene propylene (FEP), Teflon</td>
<td>0.004</td>
<td>0.001</td>
<td>+0.003</td>
</tr>
<tr>
<td>Polytetrafluoroethylene (PTFE), Teflon</td>
<td>-0.011</td>
<td>0.001</td>
<td>-0.012</td>
</tr>
<tr>
<td>Polyvinylidene fluoride (PVDF), Kynar</td>
<td>0.153</td>
<td>0.119</td>
<td>+0.034</td>
</tr>
<tr>
<td>Polyvinyl fluoride (PVF), Clear Tedlar</td>
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<td>0.164</td>
<td>-0.069</td>
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## MISSE 7 vs. MISSE 2
### Solar Absorptance Changes

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</tr>
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<tr>
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</tr>
</thead>
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</tbody>
</table>
Optical properties of 15 MISSE 7 Zenith Polymers Experiment flight samples were obtained post-flight and compared to control samples.

- Total, diffuse, and specular reflectance and transmittance were obtained and the AM0 solar absorptance ($\alpha_s$) for each sample was computed.

Absorptance increases varied from $\sim 0$ to 0.189:

- $\sim 0$: FEP (Z-2), PTFE (Z-1) & Si coated Kapton E (Z-12)
- 0.124: PVOH (P13), 0.164: PVF (Z-7) & 0.189: ECTFE (Z-6)

A comparison of the $\Delta \alpha_s$ of polymers flown on MISSE 2 and MISSE 7 indicated that some materials are more sensitive to AO erosion (i.e. Kapton H, CTFE & PVDF), while others are more sensitive to solar radiation degradation (i.e. PVF & ECTFE).

Samples with high increases in solar absorptance should be avoided, or protected, when considering materials for thermal control or other exterior spacecraft applications.
The MISSE 7A Zenith Polymers Experiment and MISSE 7B Polymers Experiment were successfully flown & retrieved

Tensile properties of 16 Teflon flight samples were obtained (3 cracked on-orbit) & compared with control samples

- Prolonged exposure to the space environment can cause catastrophic degradation of 2-mil Al-FEP
- Extent of degradation is highly dependent on exposure, determined by surface orientation:
  - Nadir exposure results in minimal degradation
  - Zenith exposure results in extensive embrittlement
- Temperature plays a key role in the radiation-induced degradation of FEP

Optical properties of 15 zenith flight samples were obtained post-flight and compared to control samples

- Absorptance increases varied from ~0 to 0.189
- Comparison of $\Delta \alpha_s$ of polymers flown on MISSE 2 and MISSE 7 indicate that the optical properties of some materials appear more sensitive to AO erosion, while others appear more sensitive to solar radiation degradation
Acknowledgements

We would like to express our sincere appreciation to Phil Jenkins, NRL, and Gary Pippin, (retired) Boeing, for providing the opportunity to fly these experiments as part of the MISSE 7 mission.

We would like to thank Sharon Miller, NASA Glenn, for her help and advice with the optical data. Also, Kate Snow & Joyce Li, Hathaway Brown School, for their help with the optical data. Finally, we would like to thank Patty Hunt, Hathaway Brown School, for her continual support of the NASA Glenn/HB collaboration.

This research was supported by the ISS Research Program and the MISSE-X Project.