# Materials International Space Station Experiment-9 (MISSE-9) Polymers and Composites Experiment

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## Abstract

Spacecraft in low Earth orbit (LEO) are subjected to harsh environmental conditions, including radiation (cosmic rays, ultraviolet, x-ray, and charged particle radiation), micrometeoroids and orbital debris, temperature extremes, thermal cycling, and atomic oxygen (AO). These environmental exposures can result in erosion, embrittlement and optical property degradation, threatening spacecraft performance and durability. To increase our understanding of effects such as AO erosion and radiation induced embrittlement of spacecraft materials, NASA Glenn has developed a series of experiments flown as part of the Materials International Space Station Experiment (MISSE) missions on the exterior of the International Space Station (ISS). These experiments have provided critical LEO space environment durability data such as AO erosion data for many materials and mechanical properties changes after long term space exposure. In continuing these studies, a new experiment called the Polymers and Composites Experiment has been selected for flight on the MISSE-Flight Facility (MISSE-FF). The Polymers and Composites Experiment will be flown as part of the MISSE-9 mission, the inaugural mission of MISSE-FF manifested on SpaceX-14. This experiment includes 138 samples being flown in ram, wake or zenith orientations for space environmental durability assessment. The primary objective is to determine the LEO AO erosion yield, $E_y$ (the volume loss per incident oxygen atom ($cm^3$/atom)), of polymers, composites, and coated samples, as a function of solar irradiation and AO fluence. In addition, epoxy samples with varying levels of ZnO powder are included to study the effect of filler quantity on AO erosion. An AO Scattering Chamber is included to help improve the understanding of AO scattering mechanisms for improved AO undercutting modeling. Indium tin oxide (ITO) coated samples are included to validate the durability of ITO conductive coatings in LEO. Tensile samples of Teflon fluorinated ethylene propylene (FEP) of varying thicknesses and back-surface coatings will be flown in wake and zenith orientations to study radiation embrittlement versus thickness, and the effect of heating on FEP embrittlement. Finally, shape memory composite and cosmic ray shielding samples will be flown for LEO durability assessment. This paper presents an overview of the MISSE-9 Polymers and Composites Experiment.

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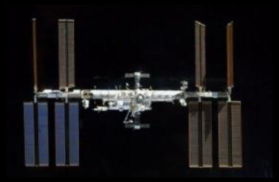
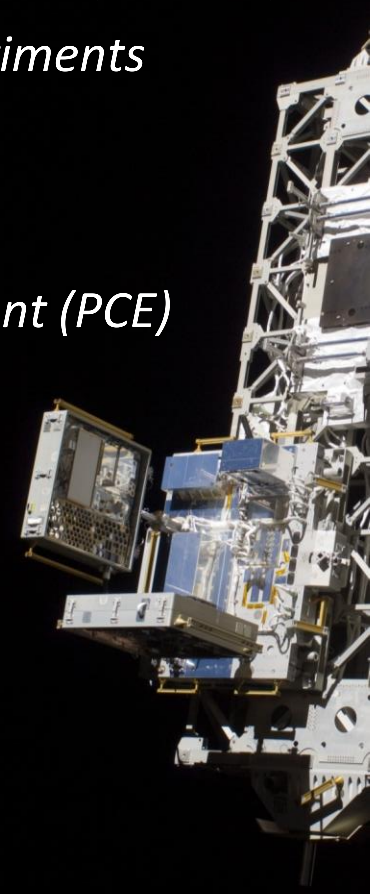
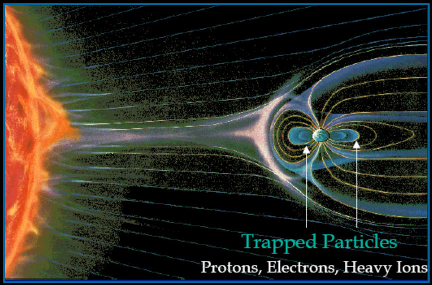
*Presented at the 42th Committee on Space Research (COSPAR) Scientific Assembly*
*July 14-22, 2018 in Pasadena, CA*

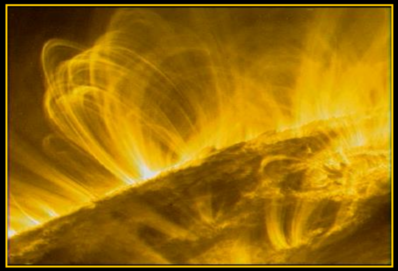
# Outline

- Introduction to the space environment
  - *Examples of spacecraft damage*
- Materials International Space Station Experiment (MISSE)
  - *Overview of Glenn’s MISSE 1-8 polymers flight experiments*
- MISSE-Flight Facility (MISSE-FF)
  - *Introduction to MISSE-FF*
  - *Glenn’s MISSE-9 Polymers and Composites Experiment (PCE)*
    - *Ram, Wake & Zenith*
- MISSE-9 PCE Summary





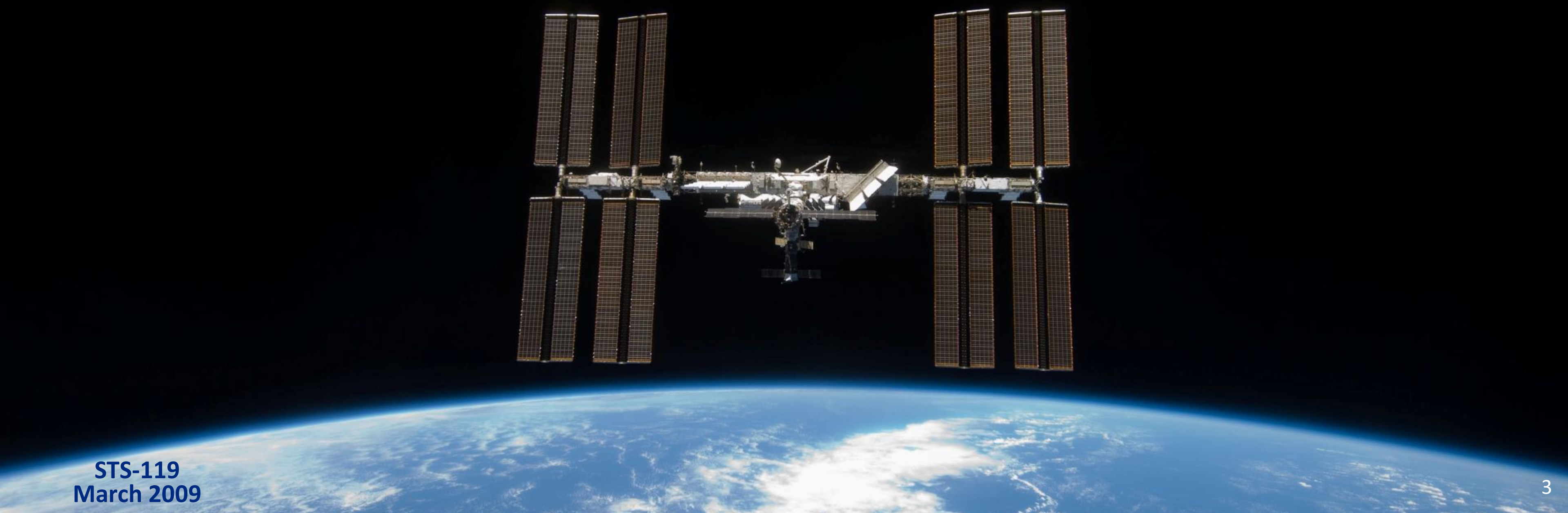

# The Space Environment



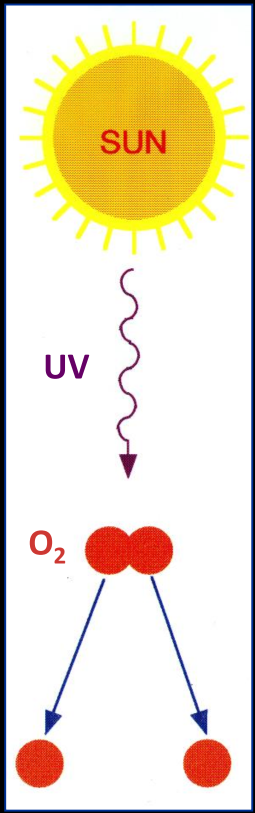
*Materials on the exterior of spacecraft are exposed to many harmful environmental threats*

In low Earth orbit (LEO) environmental threats include:

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



# Atomic Oxygen (AO)

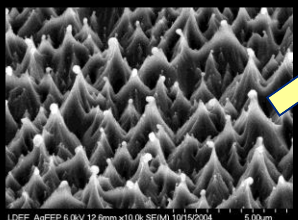


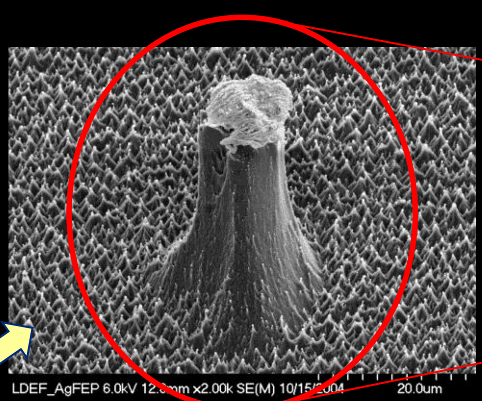

Atomic Oxygen

- AO is the predominant species in LEO (≈200-650 km)
- It is formed by photodissociation of molecular oxygen ($O_2$) by short wavelength energetic UV radiation
- At ram impact velocities (17,000 mph) the average impact energy is 4.5 eV
- AO oxidizes certain materials (such as polymers) with resulting gas formation - so *the material erodes away...*

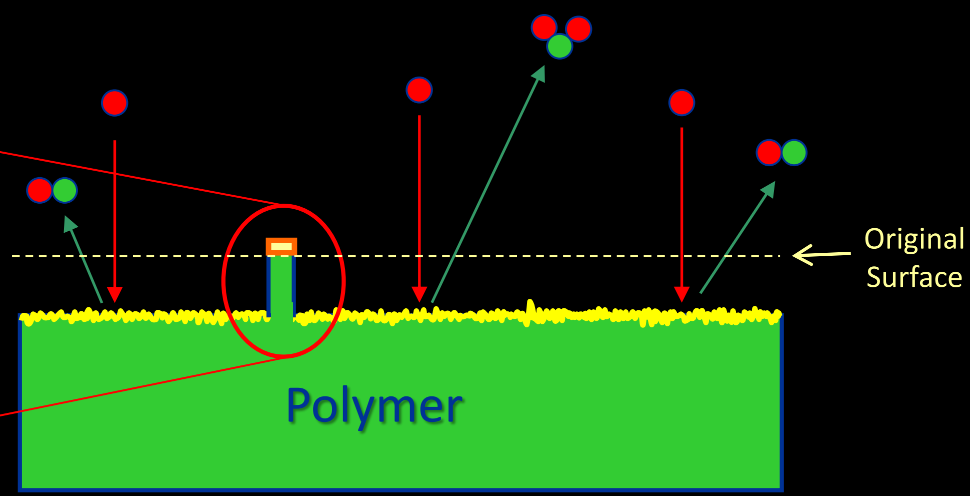
⇒ *AO is a serious threat to spacecraft survivability*

Ram AO erosion causes "cone" formation



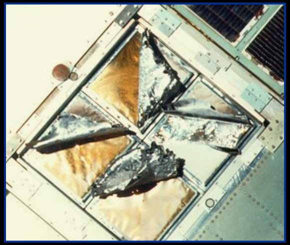


2000X



# Space Environment Induced Degradation

Radiation induced darkening

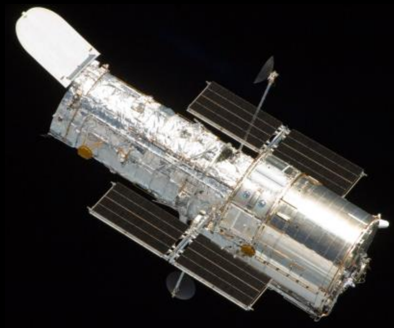


Structural degradation

Pre-flight

Post-flight

AO erosion of Kapton blanket

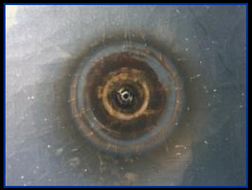


Hubble Space Telescope (HST)

Radiation induced embrittlement & cracking of Teflon insulation (6.8 yrs)

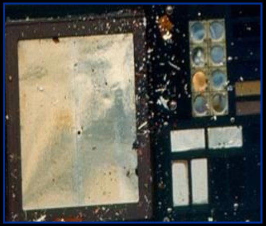
Long Duration Exposure Facility **(LDEF)**

*5.8 yrs in space*



Impact site

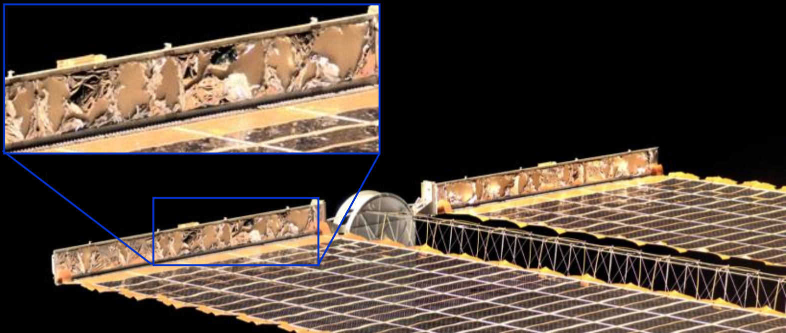
Debris generation



International Space Station (ISS)

2001

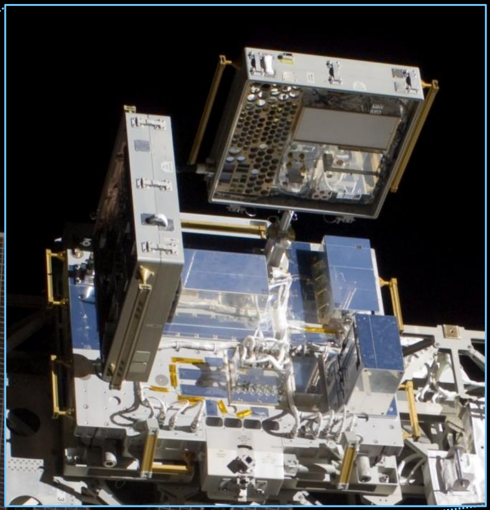
AO undercutting erosion of the P6 Port Solar Array Al-Kapton blanket box cover (1 yr)



# Materials International Space Station Experiment (MISSE)

The MISSE 1-8 missions consisted of a series of materials flight experiments flown in 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 *ram/wake* or *zenith/nadir* orientations providing different environmental exposures.



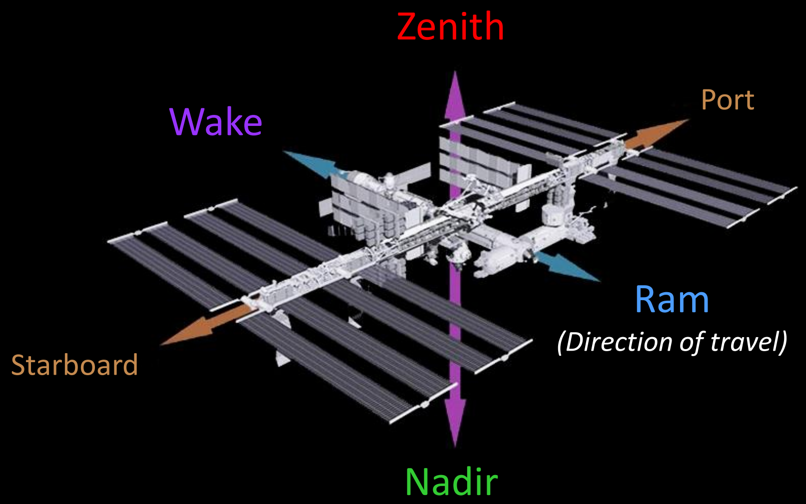
*Objective:*
*To test the stability and durability of materials and devices in the space environment*

MISSE 7A & 7B
*November 2009*
STS-129

# Flight Orientations
# & Environmental Exposures

**Ram:**
- *Facing the direction of travel (i.e. forward pointing or leading edge)*
- *Highest AO & moderate solar exposure*

**Wake:**
- *Facing away from the direction of travel (i.e. aft pointing or trailing edge)*
- *Essentially no AO & moderate solar exposure*

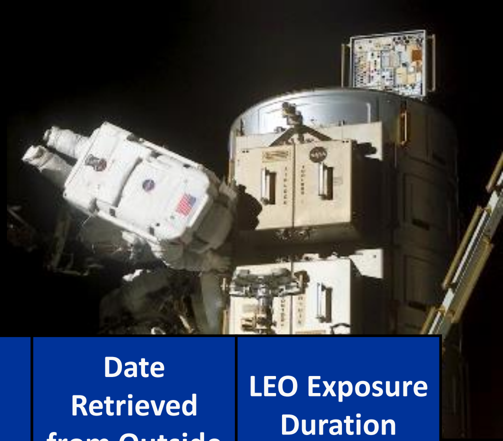



**Zenith:**
- *Direction facing away from Earth (i.e. directly above)*
- *Grazing AO & highest solar exposure*

**Nadir:**
- *Direction facing towards Earth (i.e. straight down)*
- *Grazing AO & lowest solar exposure*

# MISSE 1-8

## Mission Summary



| MISSE PEC | Launch Mission | Date Placed Outside ISS | Location on ISS | Tray Orientation | Retrieval Mission | Date Retrieved from Outside of ISS | LEO Exposure Duration (years) |
|---|---|---|---|---|---|---|---|
| 1 & 2 | STS-105 | 8/16/2001 | PEC 1: High Pressure Gas Tank (HPGT)<br>PEC 2: Quest Airlock | Ram & Wake | STS-114 | 7/30/2005 | **3.95** |
| 3 & 4 | STS-121 | 8/3/2006* | PEC 3: HPGT<br>PEC 4: Quest Airlock | Ram & Wake | STS-118 | 8/18/2007 | **1.04** |
| 5 | STS-114 | 8/3/2005 | Aft P6 Trunion Pin Handrail | Zenith & Nadir | STS-115 | 9/15/2006 | **1.12** |
| 6A & 6B | STS-123 | 3/22/2008 | Columbus Laboratory | Ram & Wake | STS-128 | 9/1/2009 | **1.45** |
| 7A & 7B | STS-129 | 11/23/2009 | EXPRESS Logistics Carrier 2 (ELC 2) on the S3 Truss | 7A: Zenith & Nadir<br>7B: Ram & Wake | STS-134 | 5/20/2011 | **1.49** |
| 8 & ORMatE-III R/W | STS-134 | 8: 5/20/2011<br>ORMatE-III R/W: 7/12/2011** | EXPRESS Logistics Carrier 2 (ELC 2) on the S3 Truss | 8: Zenith & Nadir<br>ORMatE-III R/W: Ram & Wake | SpaceX-3 Dragon | 7/9/2013 | MISSE 8: **2.14**<br>ORMatE-III: **2.00** |

** Deployed during Expedition 13*

*** Deployed during STS-135*

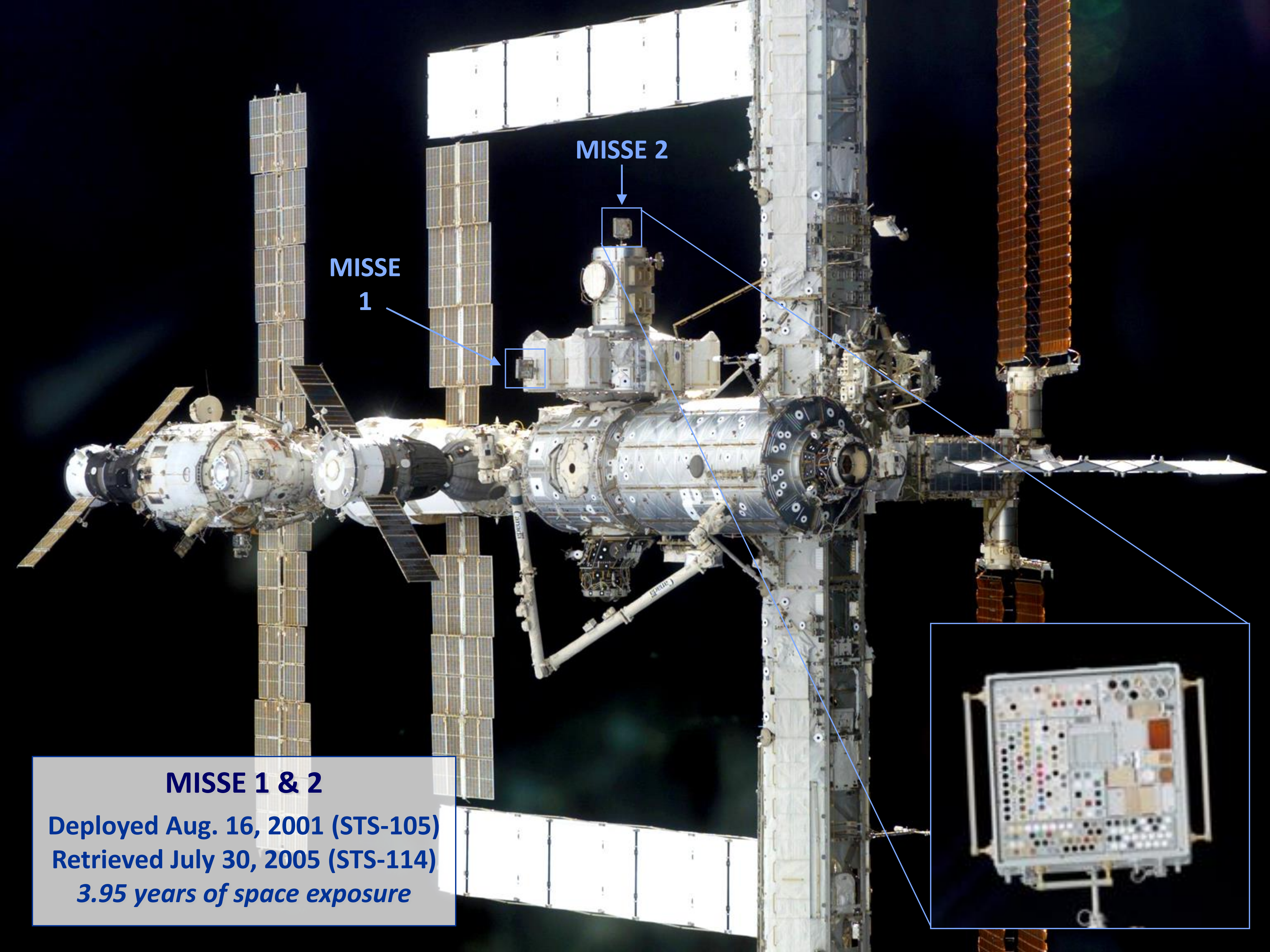
*ORMatE-III R/W: Optical Reflector Materials Experiment III Ram/Wake*

# MISSE 1-8

## Polymer Experiments

### 6 experiments with 195 flight samples

| MISSE Mission | Experiment | # Samples | Mission Orientation | Duration (yrs) | Experiment Objective | Active/ Passive |
|---|---|---|---|---|---|---|
| 2 | Polymers Experiment (PEACE) | 41 | 2 Ram | 4.0 | Determine the AO erosion yield ($E_y$) of a wide variety of polymers | P |
| 6A & 6B | Stressed Polymers Experiment | 36 | 6A Ram | 1.5 | To determine if the AO Ey is dependent upon stress, plus evaluate thin film stacking effects on $E_y$ | P |
| 7A & 7B | Zenith Polymers Experiment | 25 | 7A Zenith | 1.5 | To determine the effect of solar exposure on the AO $E_y$ of fluoropolymers (high solar/low AO exposure) | P |
| | Nadir Tensile Sample Experiment | 6 | 7A Nadir | | To determine the effect of LEO radiation (charged particle & albedo radiation) on the embrittlement of Al-FEP | P |
| | Polymer Experiment | 45 | 7B Ram<br>7B Wake | | For AO $E_y$ determination and to determine if AO erosion of high & low ash containing polymers is dependent on fluence | P |
| 8B & 8A | Polymers Experiment | 42 | 8B Ram<br>8B Wake<br>8A Zenith | 8A: 2.1<br>8B: 2.0 | To characterize the degradation of polymers & other spacecraft materials flown in ram, wake & zenith orientations | P |


MISSE 2
MISSE 1
MISSE 1 & 2
Deployed Aug. 16, 2001 (STS-105)
Retrieved July 30, 2005 (STS-114)
3.95 years of space exposure

# The MISSE 2 Polymers Experiment

*Objective: To determine the AO erosion yield (Ey) of a wide variety of polymers exposed for an extended period of time to the LEO AO space environment*

Pre-flight

**MISSE 2**

**Deployed Aug. 16, 2001 (STS-105)**

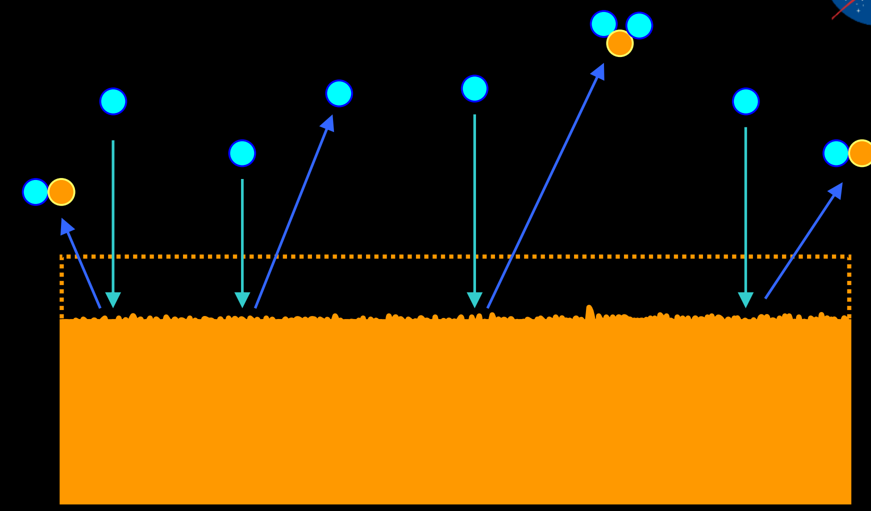
**Retrieved July 30, 2005 (STS-114)**

***4 years of space exposure***

# Atomic Oxygen Erosion Yield ($E_y$)

(Also called Reaction Efficiency or Recession Rate)

$E_y$ is the volume loss per incident oxygen atom ($cm^3$/atom)



## Ey based on Mass Loss Measurements

**Erosion Yield ($E_y$) of Sample**

$$E_y = \frac{\Delta M_s}{A_s \rho_s F_k}$$

where:
- $\Delta M_s$ = Mass loss of polymer sample (g)
- $A_s$ = Area of polymer sample ($cm^2$)
- $\rho_s$ = Density of sample ($g/cm^3$)
- $F_k$ = AO fluence measured by Kapton H witness samples ($atom/cm^2$)

**Atomic Oxygen Fluence**

$$F_k = \frac{\Delta M_k}{A_k \rho_k E_k}$$

where:
- $\Delta M_k$ = Mass loss of Kapton H witness (g)
- $A_k$ = Area of Kapton H witness ($cm^2$)
- $\rho_k$ = Density of Kapton H sample (1.427 $g/cm^3$)
- $E_k$ = Erosion yield of Kapton H ($3.0 \times 10^{-24}$ $cm^3$/atom)

# MISSE 2 Polymers Experiment


**Pre-flight**

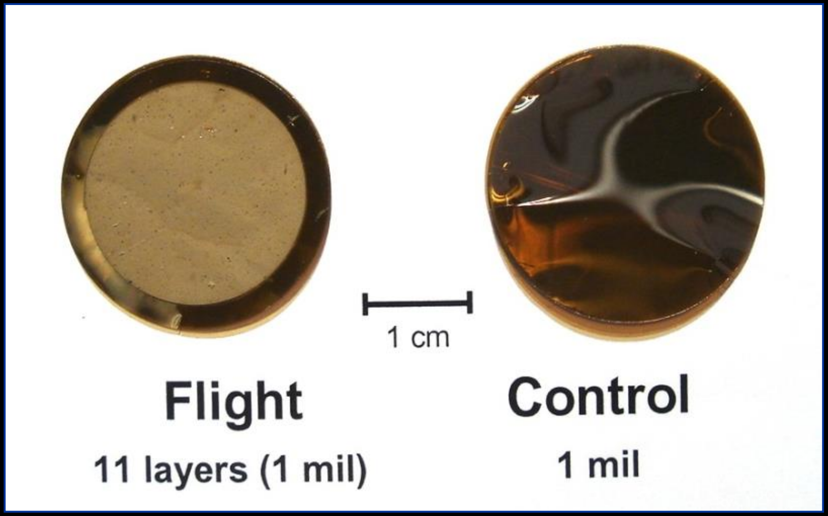

**Post-flight**

# Polyimide (PMDA)
# Upilex-S

**2-E5-32**

*Post-flight photos*

*In flight tray*

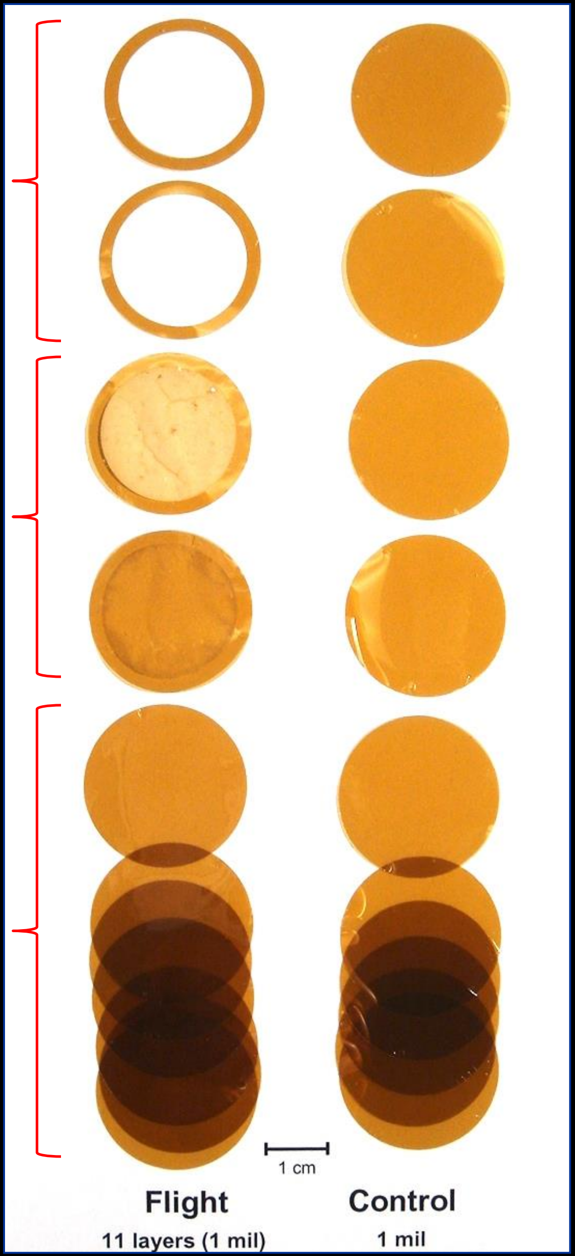



*Out of tray*

*Complete erosion*

*Partial erosion*

*No erosion*



# MISSE 2 Polymers Erosion Yield Data

| Polymer Abbreviation | $E_y$ ($cm^3$/atom) | $E_y$ Uncertainty (%) | Polymer Abbreviation | $E_y$ ($cm^3$/atom) | $E_y$ Uncertainty (%) |
|---|---|---|---|---|---|
| ABS | 1.09E-24 | 2.7 | PEI | *> 3.31E-24** | 2.6 |
| CA | 5.05E-24 | 2.7 | PA 6 | 3.51E-24 | 2.7 |
| PPD-T (Kevlar) | 6.28E-25 | 2.6 | PA 66 | 1.80E-24 | 12.6 |
| PE | *> 3.74E-24** | 2.6 | PI (CP1) | 1.91E-24 | 2.8 |
| PVF (Tedlar) | 3.19E-24 | 2.6 | PI (Kapton H) | 3.00E-24 | 2.7 |
| PVF (White Tedlar) | 1.01E-25 | 4.1 | PI (Kapton HN) | 2.81E-24 | 2.6 |
| POM (Delrin) | 9.14E-24 | 3.1 | PI (Upilex-S) | 9.22E-25 | 3.0 |
| PAN | 1.41E-24 | 3.3 | PI (PMR-15) | *> 3.02E-24** | 2.6 |
| ADC (CR-39) | *> 6.80E-24** | 2.6 | PBI | *> 2.21E-24** | 2.6 |
| PS | 3.74E-24 | 2.7 | PC | 4.29E-24 | 2.7 |
| PMMA | *> 5.60E-24** | 2.6 | PEEK | 2.99E-24 | 4.5 |
| PEO | 1.93E-24 | 2.6 | PET (Mylar) | 3.01E-24 | 2.6 |
| PBO (Zylon) | 1.36E-24 | 6.0 | CTFE (Kel-f) | 8.31E-25 | 2.6 |
| EP | 4.21E-24 | 2.7 | ECTFE (Halar) | 1.79E-24 | 2.6 |
| PP | 2.68E-24 | 2.6 | ETFE (Tefzel) | 9.61E-25 | 2.6 |
| PBT | 9.11E-25 | 2.6 | FEP | 2.00E-25 | 2.7 |
| PSU | 2.94E-24 | 3.2 | PTFE | 1.42E-25 | 2.6 |
| PU | 1.56E-24 | 2.9 | PFA | 1.73E-25 | 2.7 |
| PPPA (Nomex) | 1.41E-24 | 2.9 | AF | 1.98E-25 | 2.6 |
| PG | 4.15E-25 | 10.7 | PVDF (Kynar) | 1.29E-24 | 2.7 |

*$E_y$ > this value because sample stack was partially, or fully, eroded through

Ave. uncertainty: 3.30%

# MISSE 2 PEACE Polymers Experiment
## Results & Benefits

*Post-flight photo of MISSE 2 PEACE*

### Results:

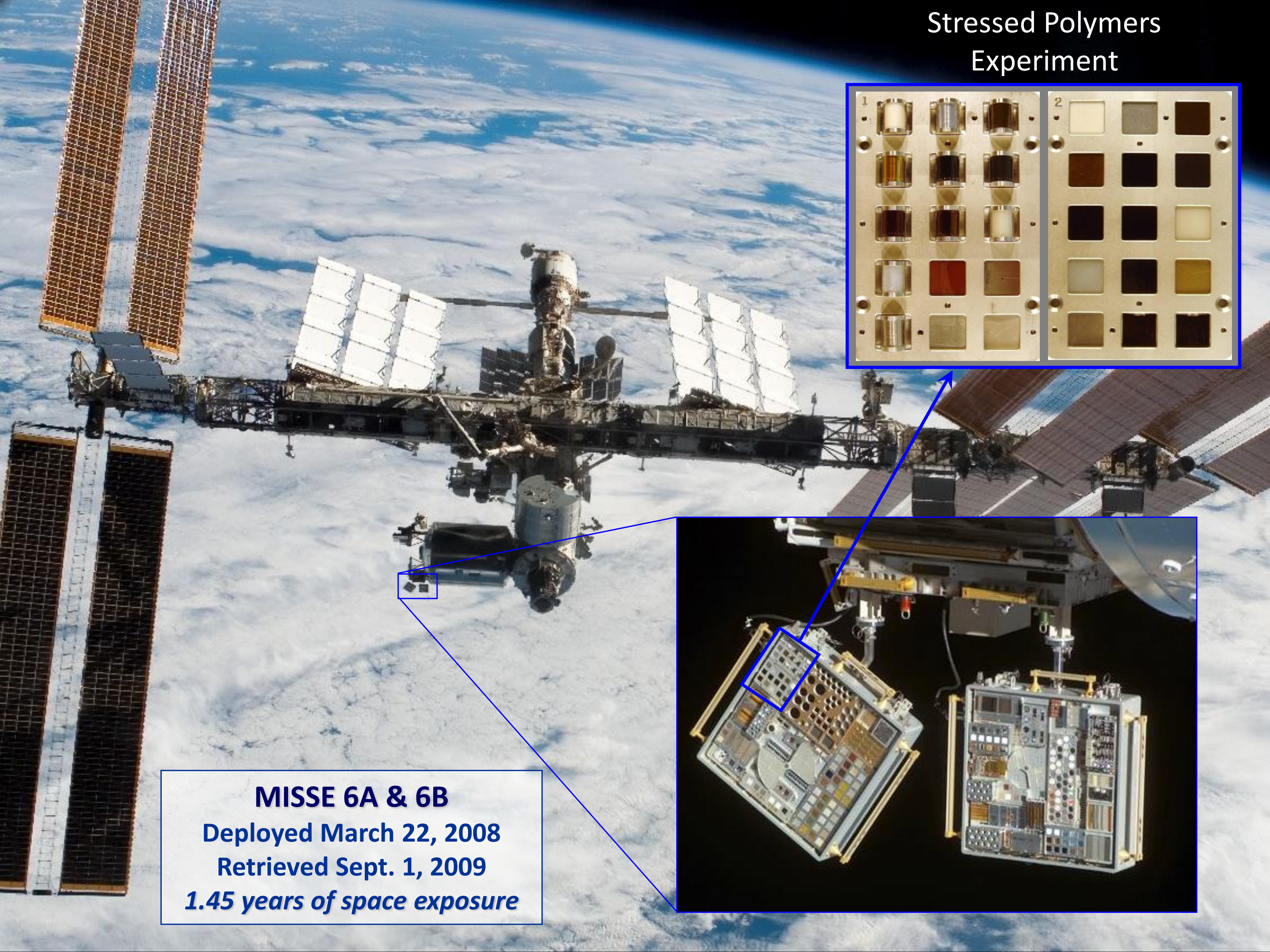
- LEO AO $E_y$ data of 38 polymers & pyrolytic graphite obtained
- Flight data used for ground-to-space correlations for AO ashers
- An *AO Erosion Predictive Tool* was developed using the flight data


*More accurate ground testing*

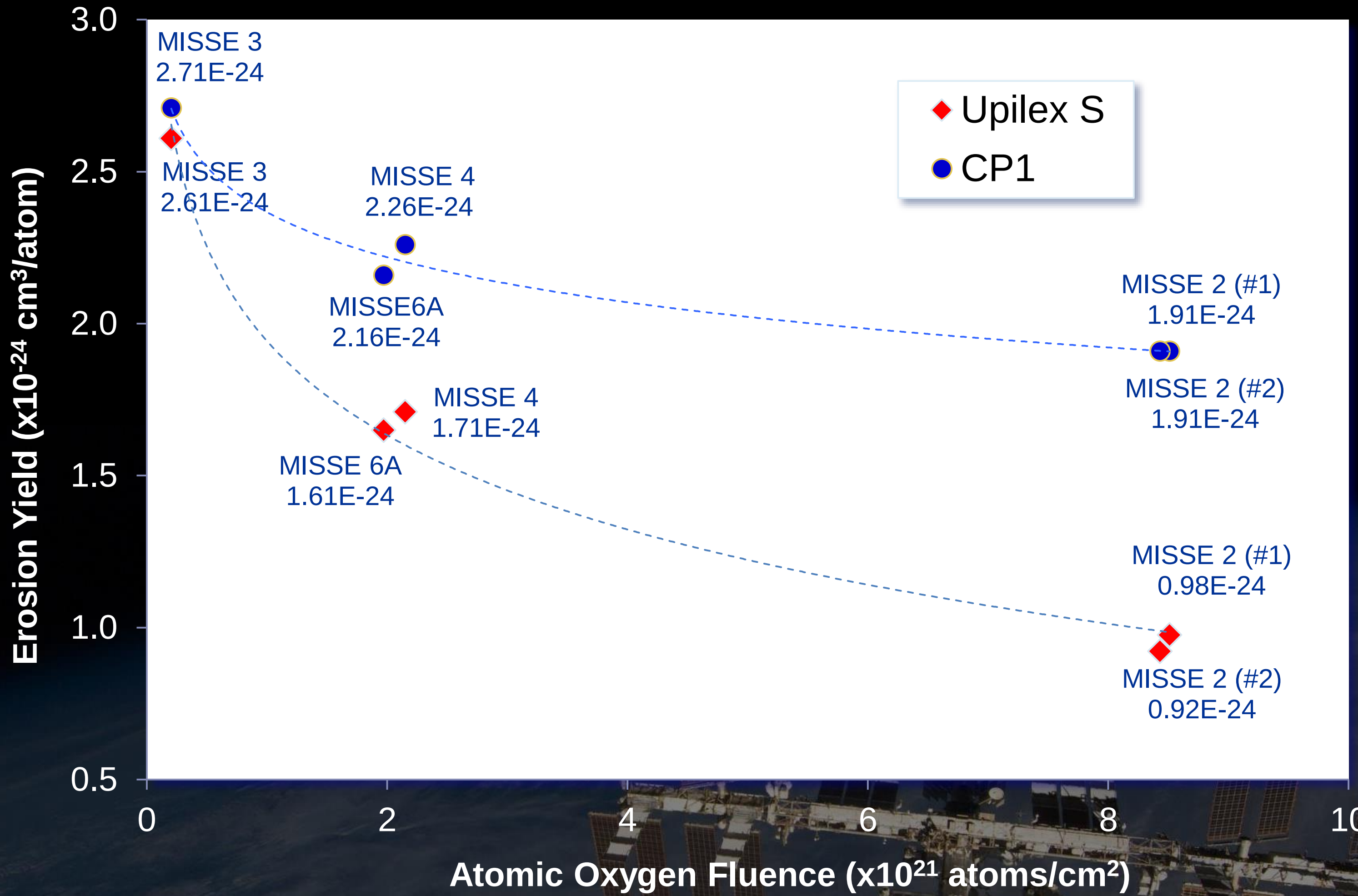
### Benefits:

- MISSE 2 & Predictive Tool $E_y$ data has been highly requested (65+) & the data has directly impacted spacecraft materials design, including:
  - *Operational Land Imager (OLI) for Landsat Program*
  - *Global Precipitation Measurement-Microwave Imager (GMI) for the Global Precipitation Measurement (GPM)*
  - *Joint Polar Satellite System (JPSS)*
  - *Radiation Budget Instrument (RBI)*
  - *Stratospheric Aerosol and Gas Experiment (SAGE) III on the ISS*
  - *Restore-L, Robotic Servicing Mission (Landsat 7 refueling mission)*
  - *Space Test Program's Standard Interface Vehicle (STP-SIV)*
  - *WorldView-2 & Worldview-3*
  - *DOD program (star tracker)*
- Flight data enables more accurate ground-laboratory testing
- NASA Technical Standards Handbook "Spacecraft Polymers Atomic Oxygen Durability Handbook" (**NASA-HDBK-6024**) has been written based on the flight data

*WorldView-3*


Stressed Polymers
Experiment
MISSE 6A & 6B
Deployed March 22, 2008
Retrieved Sept. 1, 2009
1.45 years of space exposure

# Upilex-S and CP1 (Clear Polyimide)
## Erosion Yield Vs. AO Fluence

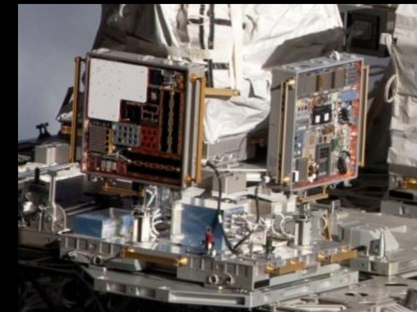


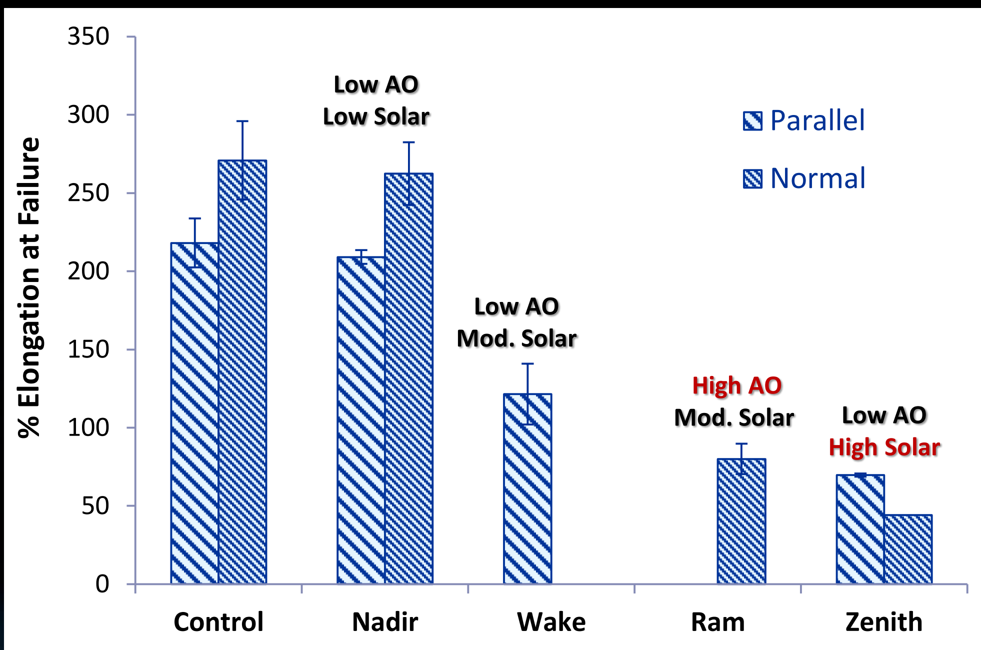

⇒ *Flying the same polymer on various MISSE missions provides important information on erosion dependence on environmental exposure*

⇒ *An objective of MISSE-9 PCE is to obtain $E_y$ vs. AO fluence data for additional spacecraft polymers*


MISSE 7A & 7B
Deployed Nov. 23, 2009
Retrieved May 20, 2011
1.49 years of space exposure

# MISSE 7
## Al-FEP
## % Elongation at Failure vs. Environmental Exposure



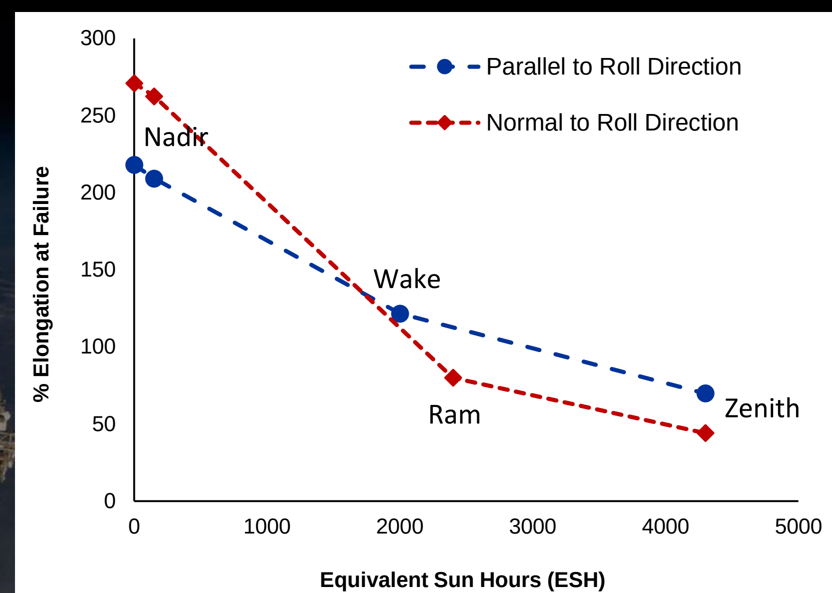



**Nadir**
150 ESH*
AO F= ~$1.6\times10^{20}$ atoms/cm$^2$

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

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

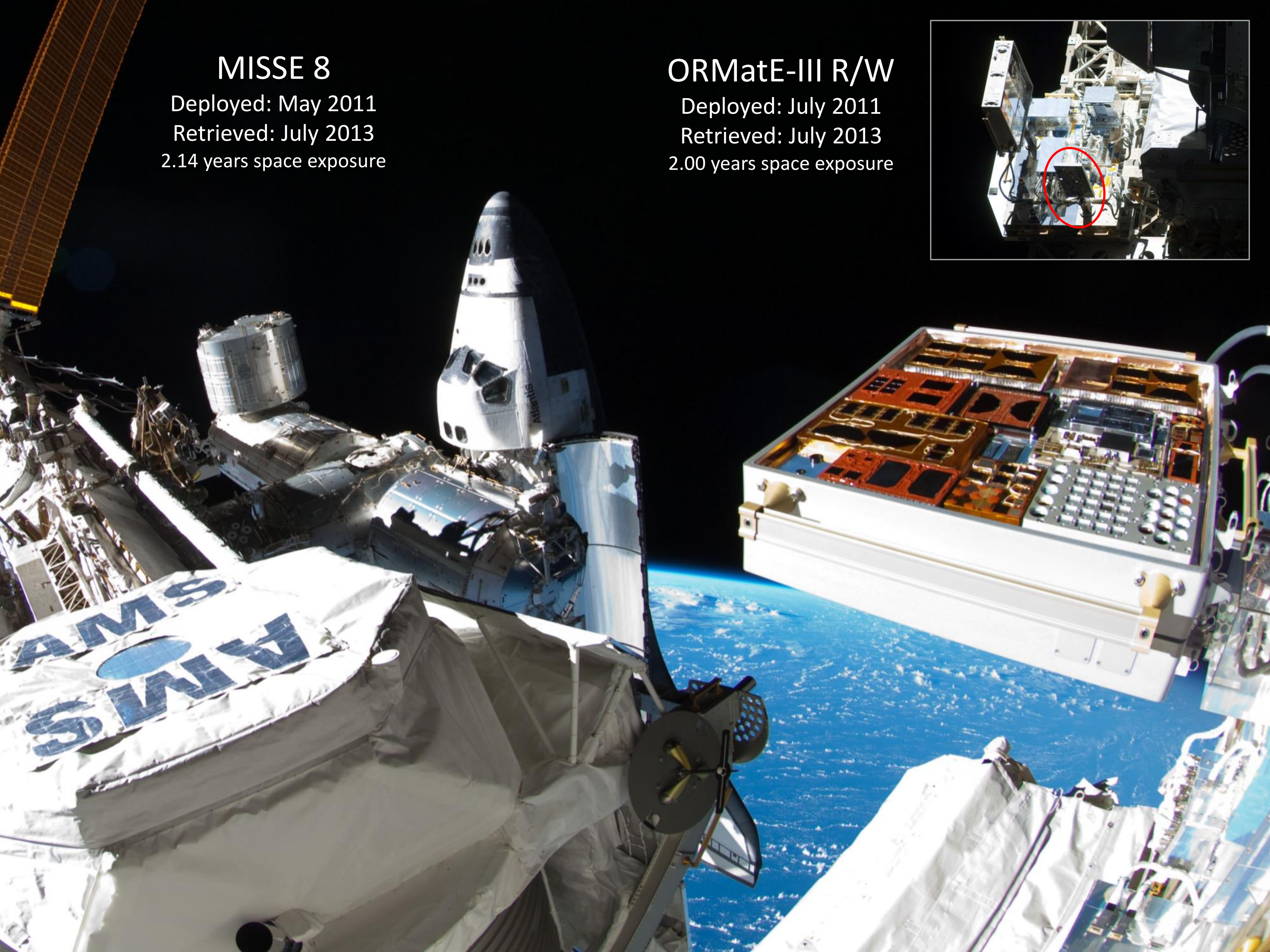
**Zenith**
4,300 ESH
AO F= $1.6\times10^{20}$ atoms/cm$^2$




***Parallel:*** *Tensile samples sectioned parallel to the manufacture roll direction*
***Normal:*** *Tensile samples sections normal to the manufacture roll direction*

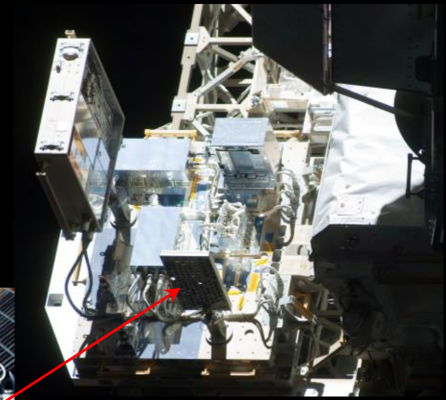
*Al-FEP: Aluminized-Teflon fluorinated ethylene propylene*

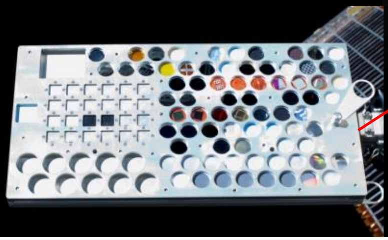
**Nadir ESH was estimated at 150 ESH (no direct solar exposure, albedo reflected only)*


MISSE 8
Deployed: May 2011
Retrieved: July 2013
2.14 years space exposure
ORMatE-III R/W
Deployed: July 2011
Retrieved: July 2013
2.00 years space exposure
AMS
AMS

# MISSE 8

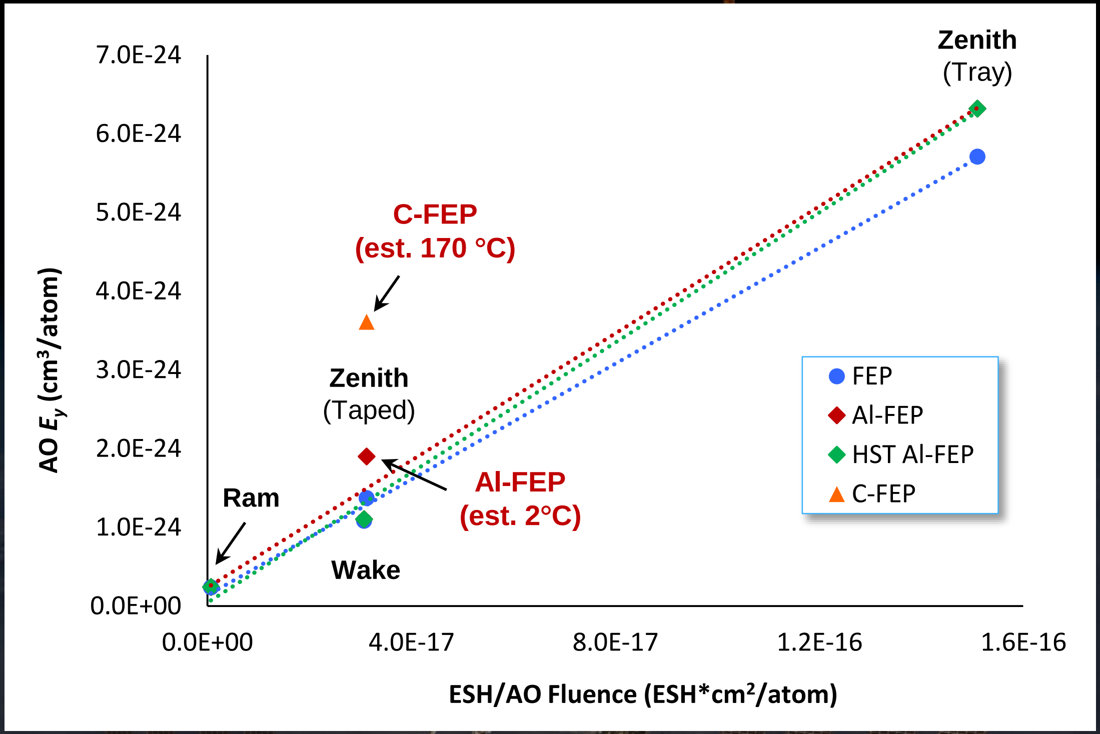
## Teflon FEP AO $E_y$ vs. Equivalent Sun Hours (ESH)/AO Fluence





ORMatE-III
Wake Surface

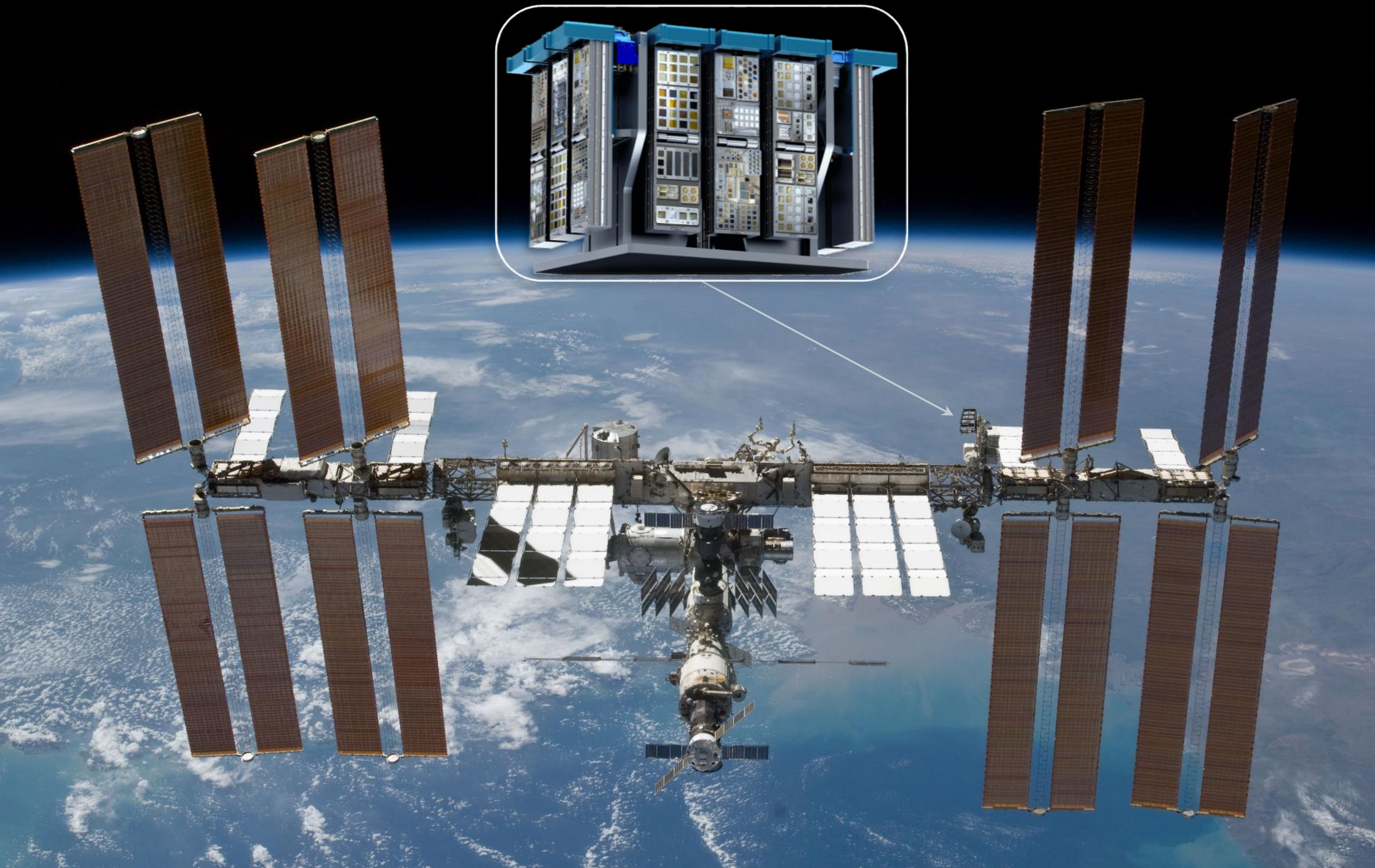
- *Excellent correlation of AO $E_y$ to ESH/AO fluence ratio:*
  - *Shows the effect of solar radiation and/or heating due to solar exposure on erosion of FEP*
- *C-FEP (170 ℃) has a significantly higher $E_y$ than Al-FEP (2 ℃) for the same exposure:*
  - *Heating has a major impact on the Ey of FEP in the zenith orientation*

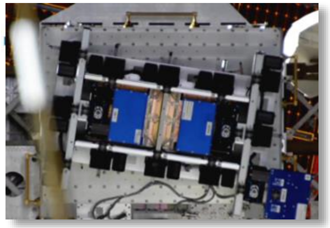



FEP: Fluorinated ethylene propylene
C-FEP: Carbon back-surface painted FEP
Al-FEP: Aluminized-Teflon FEP
HST Al-FEP: Hubble Space Telescope retrieved Al-FEP

# Polymers and Composites Experiment (PCE)

MISSE 9 inaugural mission of the MISSE-Flight Facility (MISSE-FF)





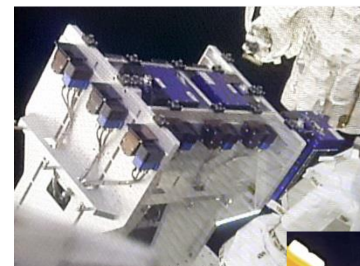
# Materials International Space Station Experiment-Flight Facility (MISSE-FF)

Alpha Space Test & Research Alliance, LLC

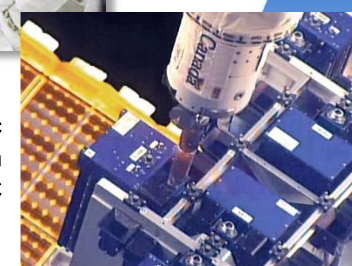
http://www.alphaspace.com/

- MISSE-FF is ISS's new permanent external material science platform that is modular and robotically serviceable
  - *Provides ram, wake, zenith and nadir exposures*
  - *Launched aboard SpaceX CRS-14 on April 2, 2018*
  - *Robotically installed on ELC-2 Site 3 on April 8, 2018*
  - *The MISSE-9 experiments were deployed on April 19, 2018*
- Modular design allows MISSE Sample Carriers (MSCs) with experiments to be added/replaced at different times
  - *MSC duration: 6 months - 3 years (1 year typical)*
- Supports active experiments with downlink of data
- Active environmental sensors provides environmental data over time in each flight orientation
  - *Standard: Temperature, contamination, UV (for NASA PI's)*
  - *Service Fee: AO, UV (non-NASA PI), TID*
- High-resolution cameras provide monthly sample images
- Remote control provides sample protection & on-demand images

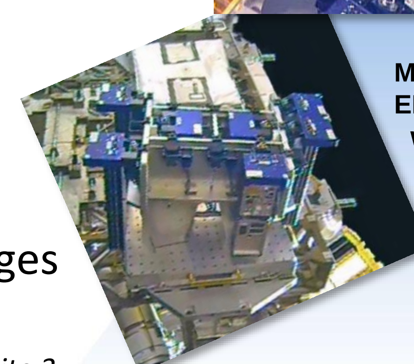
**MISSE Sample Carrier (MSC)**



**MISSE-FF being moved to ELC-2**



**Robotic insertion of a MSC**



**MISSE-FF at ELC-2 Site 3 with the 5 MSCs open**

*MISSE illustration courtesy of Alpha Space*

*ELC-2 Site 3: Express Logistics Carrier-2, Payload Site 3*

# MISSE-9
# Polymers and Composites Experiment (PCE)

**Principal Investigator (PI):** Kim de Groh (GRC)

**Primary Collaborator:** Bruce Banks (SAIC/GRC)

**Sample Collaborators:** Loredana Santo & Fabrizio Quadrini (University of Rome “Tor Vergata”), Jenny Devaud & John Fleming (Ball Aerospace), Larry Drzal (Michigan State University), Henry de Groh (NASA Glenn) & Maryann Meador (NASA Glenn)

## Primary Objectives:

1. *Determine the low Earth orbit (LEO) atomic oxygen (AO) erosion yield ($E_y$) of spacecraft polymers and composites as a function of solar irradiation and AO fluence*
2. *Determine optical and tensile property degradation of spacecraft polymers in LEO*
3. *Determine AO fluence and contamination for MISSE-9 ram, wake & zenith orientations*
4. *Determine functionality and durability of cosmic ray shielding (CRS) & shape memory composite (SMC) samples*
5. *Use the flight data to improve AO predictive models (erosion and scattering)*

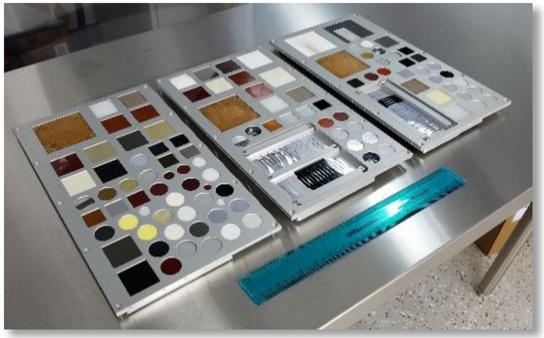
## Experiment Description:

- Passive experiment with 138 samples flown in ram, wake & zenith orientations
  - 39 Ram, 52 Wake (38 tensile) & 47 Zenith (24 tensile)
- Pre-flight & post-flight data will be measured in ground-facilities

## Expected Results:

- LEO $E_y$ values as a fct of AO fluence, solar exposure & inorganic content
- Changes in optical, thermal and tensile properties
- AO fluence and contamination data in ram, wake and zenith directions

**PCE (138 flight samples)**
**39 Ram, 52 Wake & 47 Zenith**



**Pre-flight photo**

# MISSE-9 PCE Ram Samples

39 Samples

- 32 Circular (C)
- 7 Square (S)

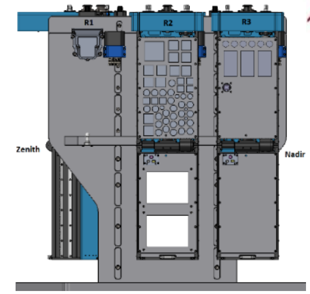
| MISSE-9 ID | Material | Abbrev. | # Layers | Total thickness (inch) | C or S | Size (inch) |
|---|---|---|---|---|---|---|
| M9R-C1 | Polyimide (PMDA) (Kapton H) | Kapton H | 2 | 0.010 | C | 1 |
| M9R-C2 | Polyimide (PMDA) (Kapton H) | Kapton H | 2 | 0.010 | C | 0.8 |
| M9R-C3 | Polyimide (PMDA) (Kapton H) | Kapton H | 2 | 0.010 | C | 0.65 |
| M9R-C4 | Polyimide (PMDA) (Kapton H) | Kapton H | 2 | 0.010 | C | 0.5 |
| M9R-C5 | Polyimide (PMDA) (Kapton HN) | Kapton HN | 2 | 0.010 | C | 1 |
| M9R-C6 | Alumina slide | $Al_2O_3$ | 1 | 0.063 | C | 1 |
| M9R-C7 | Polyoxymethylene (Delrin acetal) | POM | 2 | 0.020 | C | 1 |
| M9R-C8 | Polyoxymethylene (Delrin acetal) | POM | 2 | 0.020 | C | 0.8 |
| M9R-C9 | Polyoxymethylene (Delrin acetal) | POM | 2 | 0.020 | C | 0.65 |
| M9R-C10 | Polyoxymethylene (Delrin acetal) | POM | 2 | 0.020 | C | 0.5 |
| M9R-C11 | Epoxy (Locktite Heavy Duty) | Epoxy | 1 | 0.118 | C | 1 |
| M9R-C12 | 2.9% ZnO powder filled epoxy (Locktite) | ZnO-Epoxy | 1 | 0.125 | C | 1 |
| M9R-C13 | 6.3% ZnO powder filled epoxy (Locktite) | ZnO-Epoxy | 1 | 0.125 | C | 1 |
| M9R-C14 | 9.78% ZnO powder filled epoxy (Locktite) | ZnO-Epoxy | 1 | 0.101 | C | 1 |
| M9R-C15 | Fluorinated ethylene propylene (Teflon FEP) | FEP | 1 | 0.005 | C | 1 |
| M9R-C16 | Aluminized-Teflon (FEP/Al)* | Al-FEP | 1 | 0.005 | C | 1 |
| M9R-C17 | Silver-Teflon (FEP/Ag/Inconel)* | Ag-FEP | 1 | 0.005 | C | 1 |
| M9R-C18 | Carbon painted (India Ink) Teflon (FEP/C/FEP)* | C-FEP | 1 | 0.015 | C | 1 |
| M9R-C19 | Polyimide (PMDA) (Kapton H) | Kapton H | 2 | 0.010 | C | 1 |
| M9R-C20 | Polytetrafluoroethylene (Chemfilm DF 100) | PTFE | 1 | 0.005 | C | 1 |
| M9R-C21 | Crystalline polyvinylfluoride, white pigment (white Tedlar) | PVF-W | 1 | 0.002 | C | 1 |
| M9R-C22 | Highly Oriented Pyrolytic Graphite | HOPG | 1 | 0.041 | C | 1 |
| M9R-C23 | Polyimide (BPDA) (Upilex-S) | Upilex-S | 2 | 0.002 | C | 1 |
| M9R-C24 | Polyimide (CP1) | CP1 | 2 | 0.006 | C | 1 |
| M9R-C25 | Polyethylene terephthalate (Mylar) | PET | 4 | 0.008 | C | 1 |
| M9R-C26 | Polyethylene | PE | 5 | 0.010 | C | 1 |
| M9R-C27 | Magnesium Fluoride | $MgF_2$ | 1 | 0.108 | C | 1 |
| M9R-C28 | Cyanate ester graphite fiber composite (RS3-M55J 6K) | RS3-M55J 6K | 1 | 0.062 | C | 1 |
| M9R-C29 | Sodium silicate/RS3-M55J 6K | $Na_2Si_3O_7$/RS3-M55J 6K | 1 | 0.064 | C | 1 |
| M9R-C30 | Polyimide aerogel | Polyimide Aerogel | 1 | 0.125 | C | 1 |
| M9R-C31 | Carbon nanotube (CNT) paper | Buckypaper | 3 | 0.005 | C | 1 |
| M9R-C32 | Graphene nanoplatelets (GnP) paper | GnP paper | 1 | 0.010 | C | 1 |
| M9R-S1 | Polyimide (PMDA) (Kapton H) | Kapton H | 2 | 0.010 | S | 1 |
| M9R-S2 | Z307 (black paint)/aluminum | Z307/Al | 1 | 0.035 | S | 1 |
| M9R-S3 | Ball Infrared Black (BIRB) paint/aluminum | BIRB/Al | 1 | 0.100 | S | 1 |
| M9R-S4 | Carbon nanotube (CNT) coated SiC w/ 0.5 mil Kapton cover | Kapton H/ CNT/SiC | 1 | 0.130 | S | 1 |
| M9R-S5 | Indium tin oxide coated Kapton HN/aluminum | ITO/Kapton HN/Al | 1 | 0.002 | S | 1 |
| M9R-S6 | Indium tin oxide coated silver-Teflon | ITO/FEP/ Ag/Inconel | 1 | 0.005 | S | 1 |
| M9R-S7 | Atomic Oxygen Scattering Chamber (30° angle) | AO Scatter Chamber | 1 | 0.275 | S | 1 |

*FEP layer is space facing

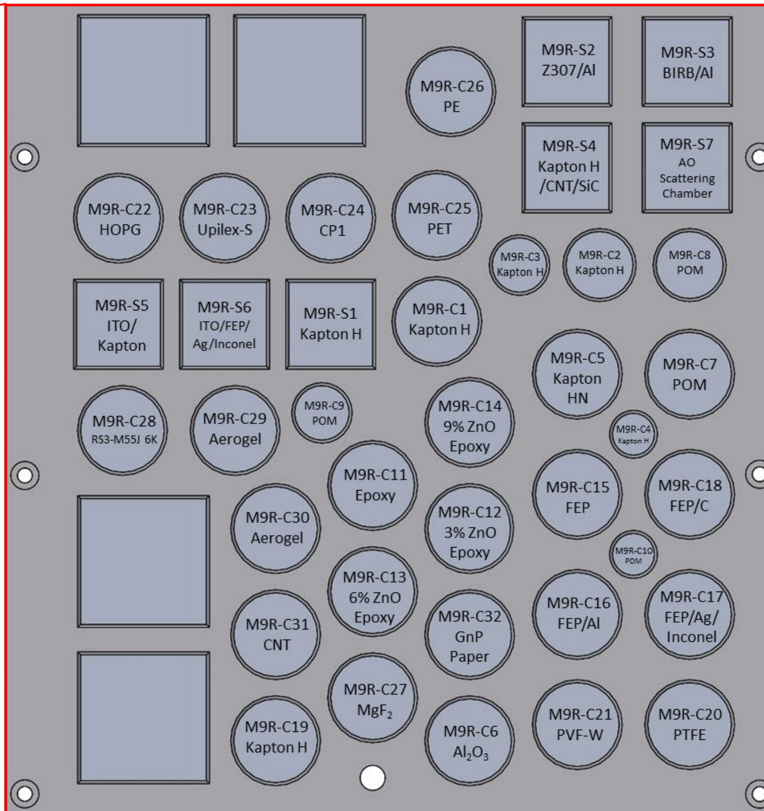
# MISSE-9 PCE Ram Samples

## 39 samples: 32 circular (0.5 – 1-inch) & 7 square (1-inch)

**MSC R2**




**R2 mount side deck**

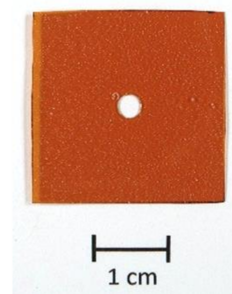



*Drawings courtesy of Alpha Space*

# Overview of PCE Ram Samples

## (High AO & moderate solar exposure)

- **Ram Samples:**
  - Kapton H for MISSE-9 ram AO fluence determination
  - $Al_2O_3$ slides for MISSE-9 ram contamination determination
  - Samples for LEO AO $E_y$ and optical property durability:
    - *Polymers*
    - *Composites*
    - *Black paint (BIRB & Z307) coated samples*
    - *Buckypaper & graphene nanoplatelets (GnP) paper*
    - *Carbon nanotube (CNT) coatings*
    - *Polyimide aerogel*
    - *$MgF_2$*
    - *ITO/FEP and ITO/Kapton HN (also for electrical property durability)*
  - Samples of varying diameters to study the effect of the sample holder on $E_y$ (sample holder chamfer edge effect on $E_y$)
  - Samples with varying % of inorganic filler to determine filler effect on $E_y$
  - AO Scattering Chamber (30° angle base) for AO scattering characterization
  - Previously flown polymers for $E_y$ vs. AO fluence, $E_y$ vs. solar exposure and $E_y$ vs. ESH/AO fluence
  - C-FEP vs. Al-FEP to study passive heating effects on $E_y$ of radiation exposed FEP




**AO Scattering Chamber**
**NaCl/Kapton H**

**Blue:** Environment data
**Black:** New sample data
**Green:** AO $E_y$ vs. environment data
**Red:** Heating effects data

# MISSE-9 PCE Wake
## 1-inch Samples
### (14 1-inch Samples: 10 Circular & 4 square)

| MISSE-9 ID | Material | Abbrev. | Thickness (inch) | C or S |
|---|---|---|---|---|
| M9W-C1 | Polyimide (PMDA) (Kapton H) | Kapton H | 0.005 | C |
| M9W-C2 | Polyimide (PMDA) (Kapton HN) | Kapton HN | 0.005 | C |
| M9W-C3 | Alumina slide | $Al_2O_3$ | 0.063 | C |
| M9W-C4 | Fluorinated ethylene propylene (Teflon FEP) | FEP | 0.005 | C |
| M9W-C5 | Aluminized-Teflon (FEP/Al)* | Al-FEP | 0.005 | C |
| M9W-C6 | Silver-Teflon (FEP/Ag/Inconel)* | Ag-FEP | 0.005 | C |
| M9W-C7 | Carbon painted (India Ink) Teflon (FEP/C/FEP)* | C-FEP | 0.015 | C |
| M9W-C8 | Polyvinyl chloride | PVC | 0.005 | C |
| M9W-C9 | Cosmic ray shielding (CRS) sample** | CRS | 0.039 | C |
| M9W-C10 | Shape memory composite (SMC) sample** | SMC | 0.236 | C |
| M9W-S1 | Indium tin oxide coated Kapton HN/aluminum | ITO/Kapton HN/Al | 0.002 | S |
| M9W-S2 | Indium tin oxide coated silver-Teflon | ITO/FEP/Ag/Inconel | 0.005 | S |
| M9W-S3 | Indium tin oxide coated silver-Teflon | ITO/FEP/Ag/Inconel | 0.005 | S |
| M9W-S4 | Carbon nanotube (CNT) coated SiC | CNT/SiC | 0.130 | S |

*FEP layer is space facing; C: Circular; S: Square

** University of Rome Tor Vergata samples

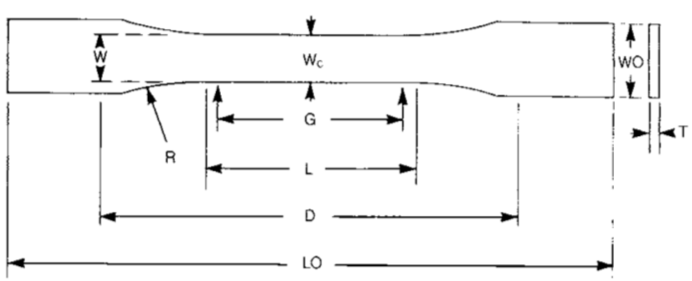
# MISSE-9 PCE Wake
# Tensile Samples (38)

| MISSE-9 ID | Material | Abbrev. | Thickness (inch) | Number of Samples |
|---|---|---|---|---|
| M9W-T1 to T5 | Aluminized-Teflon (FEP/Al)* - Parallel | Al-FEP | 0.002 | 5 |
| M9W-T6 to T10 | Aluminized-Teflon (FEP/Al)* - Normal | Al-FEP | 0.002 | 5 |
| M9W-T11 to T15 | Aluminized-Teflon (FEP/Al)* - Parallel | Al-FEP | 0.005 | 5 |
| M9W-T16 to T20 | Aluminized-Teflon (FEP/Al)* - Normal | Al-FEP | 0.005 | 5 |
| M9W-T21 to T24 | Silver-Teflon (FEP/Ag/Inconel)* - Parallel | Ag-FEP | 0.005 | 4 |
| M9W-T25 to T29 | Carbon painted (India Ink) Teflon (FEP/C)* - Parallel | C-FEP | 0.002 | 5 |
| M9W-T30 to T34 | Carbon painted (India Ink) Teflon (FEP/C)* - Parallel | C-FEP | 0.005 | 5 |
| M9W-T35 to T38 | Aluminized-Teflon (Al/FEP) - Parallel (Al space facing) | Al/FEP | 0.002 | 4 |

*FEP is space facing

| | | | # Tensile Samples | 38 |
|---|---|---|---|---|

D 638 – 08

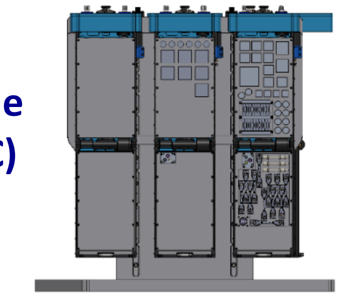



TYPES I, II, III & V

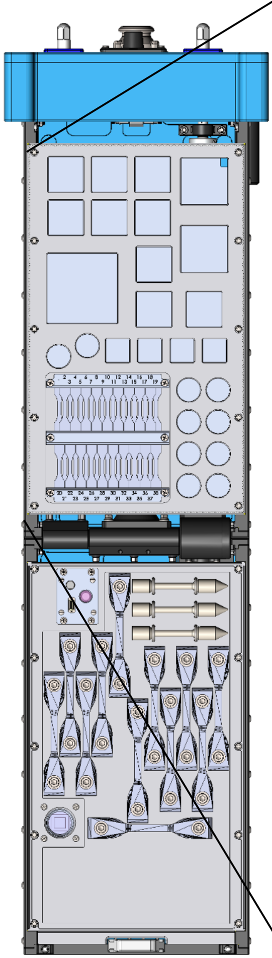

| ASTM D638-08 Type V Specimen Dimensions | |
|---|---|
| W—Width of narrow section | 3.18 mm (0.125 in.) |
| L—Length of narrow section | 9.53 mm (0.375 in.) |
| WO—Width overall, min | 9.53 mm (0.375 in.) |
| LO—Length overall, min | 63.5 mm (2.5 in.) |
| G—Gage length | 7.62 mm (0.300 in.) |
| D—Distance between grips | 25.4 mm (1.00 in.) |
| R—Radius of fillet | 12.7 mm (0.500 in.) |

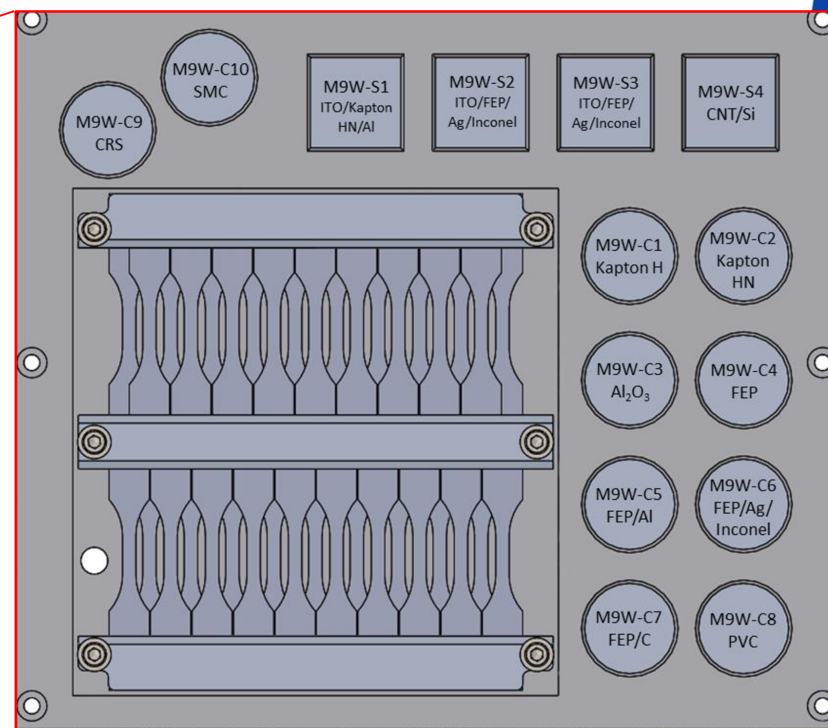
# MISSE-9 PCE Wake Samples

## 52 samples: 38 tensile & 14 1-inch



**MISSE Sample Carrier (MSC) W3**




**W3 mount side deck**

*Drawings courtesy of Alpha Space*

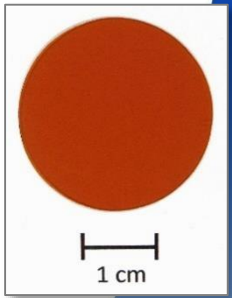
# Overview of PCE Wake Samples

## (Very little AO & moderate solar exposure)

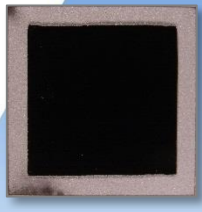
- **Wake 1-inch Samples:**
  - Kapton H for MISSE-9 wake AO fluence determination
  - $Al_2O_3$ slides for wake contamination determination
  - Samples for optical property durability:
    - *Polyvinyl chloride (PVC)*
    - *Carbon nanotube (CNT) coatings*
    - *ITO/FEP and ITO/Kapton HN (also for electrical property durability)*
  - Cosmic ray shielding (CRS) sample for functionality and durability
  - Shape memory composite (SMC) sample for functionality and durability
  - FEP for $E_y$ vs. ESH/AO fluence
    - FEP, Al-FEP & Ag-FEP
  - C-FEP vs. Al-FEP to study passive heating effects on $E_y$ of radiation exposed FEP

- **Wake Tensile Samples:**
  - Tensile samples to study LEO radiation embrittlement
    - *2 mil vs. 5 mil Al-FEP to study film thickness effects on embrittlement*
    - *Al-FEP vs. Ag-FEP to compare mechanical property degradation*
    - *Effect of roll direction (parallel vs. normal) on embrittlement of FEP*
    - *C-FEP vs. Al-FEP to study passive heating effects on embrittlement of radiation exposed FEP*

**Blue:** Environment data
**Black:** New sample data
**Green:** AO $E_y$ vs. environment data
**Purple:** Verify previous data
**Red:** Heating effects data



Kapton H


Carbon nanotube (CNT) coated SiC

# MISSE-9 PCE Zenith
## 1-inch Samples
### (23 Samples: 18 Circular & 5 square)

| MISSE-9 ID | Material | Abbrev. | Thickness (inch) | C or S |
|---|---|---|---|---|
| M9Z-C1 | Polyimide (PMDA) (Kapton H) | Kapton H | 0.005 | C |
| M9Z-C2 | Polyimide (PMDA) (Kapton HN) | Kapton HN | 0.005 | C |
| M9Z-C3 | Alumina slide | $Al_2O_3$ | 0.063 | C |
| M9Z-C4 | Fluorinated ethylene propylene (Teflon FEP) | FEP | 0.005 | C |
| M9Z-C5 | Aluminized-Teflon (FEP/Al)* | Al-FEP | 0.005 | C |
| M9Z-C6 | Silver-Teflon (FEP/Ag/Inconel)* | Ag-FEP | 0.005 | C |
| M9Z-C7 | Back-surface carbon painted Teflon (FEP/C/FEP)* | C-FEP | 0.015 | C |
| M9Z-C8 | Ethylene-chlorotrifluoroethylene (Halar) | ECTFE | 0.003 | C |
| M9Z-C9 | Polytetrafluoroethylene (Teflon PTFE) | PTFE | 0.005 | C |
| M9Z-C10 | Chlorotrifluoroethylene (Kel-F) | CTFE | 0.005 | C |
| M9Z-C11 | Ethylene-tetrafluoroethylene (Tefzel ZM) | ETFE | 0.003 | C |
| M9Z-C12 | Polyvinylidene fluoride (Kynar) | PVDF | 0.003 | C |
| M9Z-C13 | Polyethylene | PE | 0.002 | C |
| M9Z-C14 | Polyvinylfluoride (clear Tedlar) | PVF | 0.001 | C |
| M9Z-C15 | Crystalline polyvinylfluoride w/white pigment (white Tedlar) | PVF-W | 0.002 | C |
| M9Z-C16 | Polyimide (BPDA) (Upilex-S) | Upilex-S | 0.001 | C |
| M9Z-C17 | Shape memory composite (SMC) sample** | SMC | 0.236 | C |
| M9Z-C18 | Magnesium Fluoride | $MgF_2$ | 0.108 | C |
| M9Z-S1 | Z307 (black paint)/aluminum | Z307/Al | 0.035 | S |
| M9Z-S2 | Ball Infrared Black (BIRB) paint/aluminum | BIRB/Al | 0.100 | S |
| M9Z-S3 | Carbon nanotube (CNT) coated SiC | CNT/SiC | 0.130 | S |
| M9Z-S4 | EpoCNT (carbon nanotube in epoxy matrix)/aluminum | EpoCNT/Al | 0.064 | S |
| M9Z-S5 | Indium tin oxide coated silver-Teflon | ITO/FEP/Ag/Inconel | 0.005 | S |

*FEP layer is space facing; C: Circular; S: Square
** University of Rome Tor Vergata samples

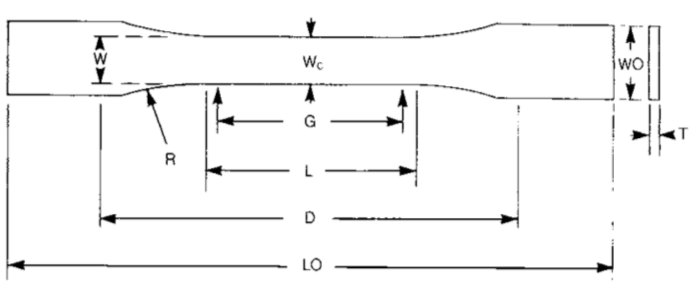
# MISSE-9 PCE Zenith
# Tensile Samples (24)

| MISSE-9 ID | Material | Abbrev. | Thickness (inch) | Number of Samples |
|---|---|---|---|---|
| M9Z-T1 to T4 | Aluminized-Teflon (FEP/Al)* - Parallel | Al-FEP | 0.002 | 4 |
| M9Z-T5 to T8 | Aluminized-Teflon (FEP/Al)* - Normal | Al-FEP | 0.002 | 4 |
| M9Z-T9 to T12 | Aluminized-Teflon (FEP/Al)* - Parallel | Al-FEP | 0.005 | 4 |
| M9Z-T13 to T16 | Aluminized-Teflon (FEP/Al)* - Normal | Al-FEP | 0.005 | 4 |
| M9Z-T17 to T20 | Carbon painted (India Ink) Teflon (FEP/C)* - Parallel | C-FEP | 0.002 | 4 |
| M9W-T21 to T24 | Aluminized-Teflon (Al/FEP) - Parallel (Al space facing) | Al/FEP | 0.002 | 4 |

*FEP is space facing

# Tensile Samples 24

**D 638 – 08**

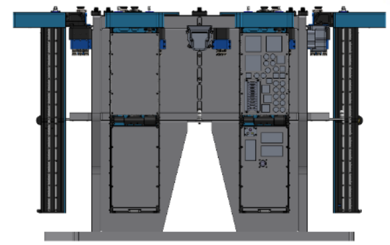



TYPES I, II, III & V

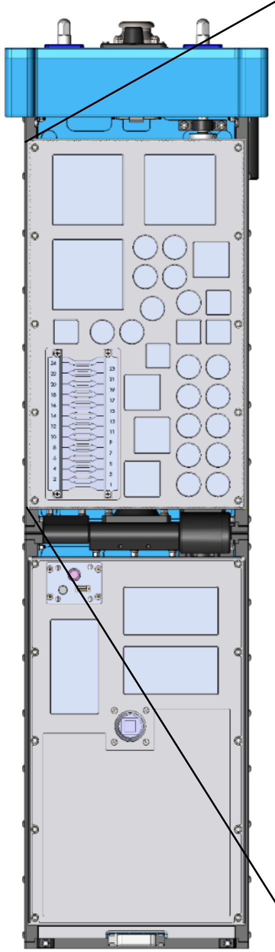

| ASTM D638-08 Type V Specimen Dimensions | |
|---|---|
| W—Width of narrow section | 3.18 mm (0.125 in.) |
| L—Length of narrow section | 9.53 mm (0.375 in.) |
| WO—Width overall, min | 9.53 mm (0.375 in.) |
| LO—Length overall, min | 63.5 mm (2.5 in.) |
| G—Gage length | 7.62 mm (0.300 in.) |
| D—Distance between grips | 25.4 mm (1.00 in.) |
| R—Radius of fillet | 12.7 mm (0.500 in.) |

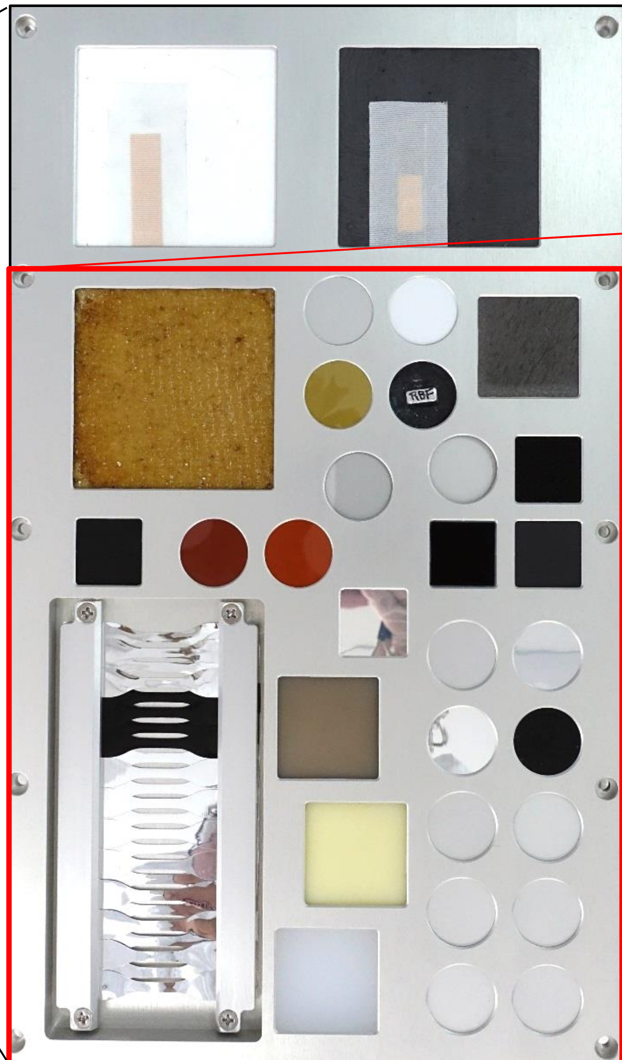
# MISSE-9 PCE Zenith Samples

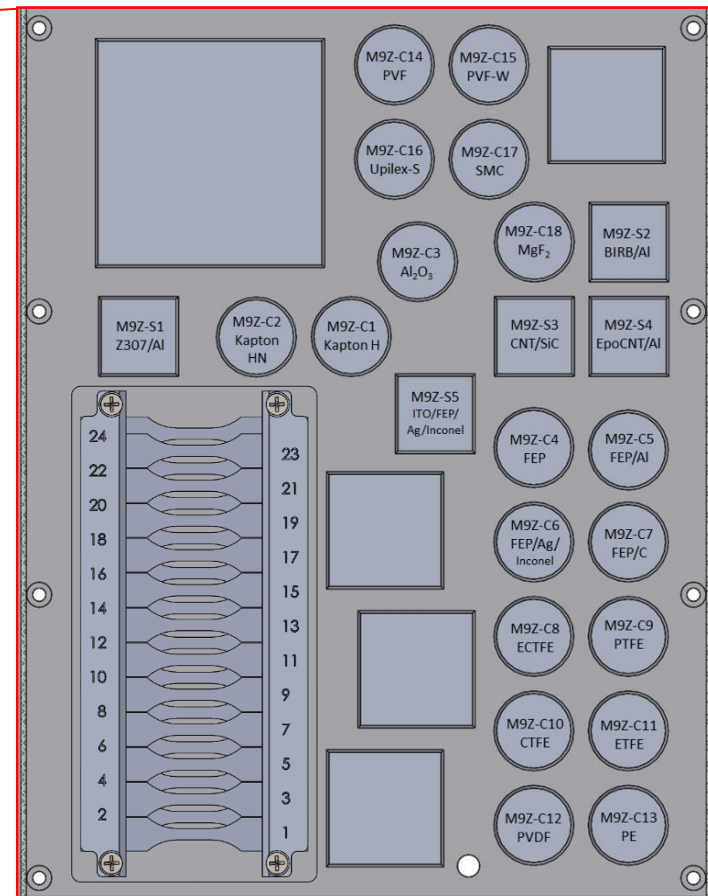
## 47 samples: 24 tensile & 23 1-inch



**MSC Z3**








**Z3 mount side deck**

*Drawings courtesy of Alpha Space*

# Overview of PCE Zenith Samples

## (Grazing AO & high solar exposure)

- **Zenith 1-inch Samples:**
  - Kapton H for MISSE-9 zenith AO fluence determination
  - $Al_2O_3$ slides for MISSE-9 zenith contamination determination
  - Shape memory composite (SMC) sample for functionality and durability
  - Samples for AO $E_y$ and optical property durability:
    - *$MgF_2$*
    - *Carbon nanotube (CNT) coatings*
    - *Black paint (BIRB & Z307) coated samples*
    - *ITO/FEP (also for electrical property durability)*
  - Previously flown polymers for $E_y$ vs. ESH/AO fluence:
    - *Fluoropolymers*
    - *Upilex-S, Kapton HN, White Tedlar, PE*
  - C-FEP vs. Al-FEP to study passive heating effects on $E_y$ of radiation exposed FEP

Z307/Al

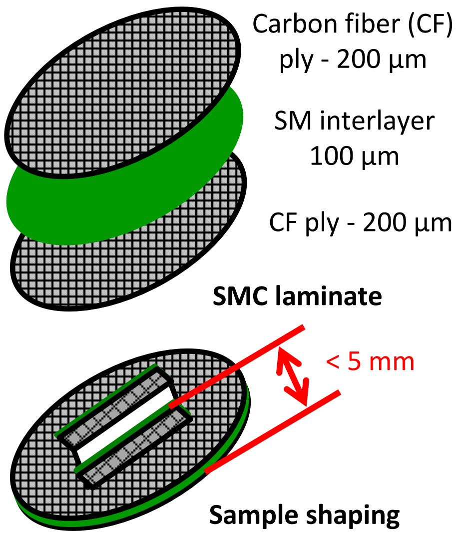
**Blue:** Environment data
**Black:** New sample data
**Green:** AO $E_y$ vs. environment data
**Purple:** Verify previous data
**Red:** Heating effects data

- **Zenith Tensile Samples:**
  - Tensile samples to study LEO radiation embrittlement
    - *2 mil vs. 5 mil Al-FEP to study film thickness effects on embrittlement*
    - *Al-FEP vs. Ag-FEP to compare mechanical property degradation*
    - *Effect of roll direction (parallel vs. normal) on embrittlement of FEP*
    - *C-FEP vs. Al-FEP to study passive heating effects on embrittlement of radiation exposed FEP*

# University of Rome Tor Vergata

## M.inO.S. (Materials in Open Space) Samples

### Shape Memory Composites (SMC)



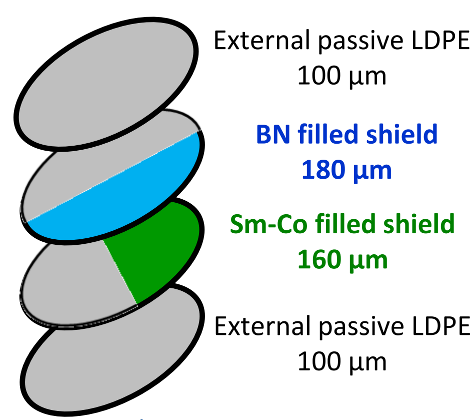

M.inO.S.

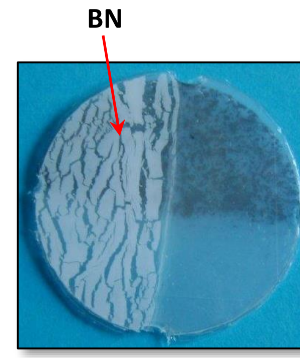
*Materials in Open Space*

The SMC samples are made with 2 composite plies and 1 shape memory interlayer:

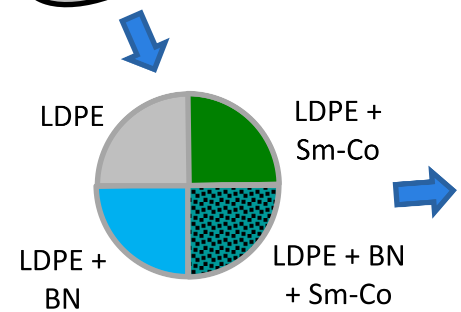
- *Evaluate on-orbit sample recovery due to Solar heating, or heat transfer from the platform*
- *Evaluate the aging effect of space exposure on **shape memory behavior**, mass loss & material degradation (cross-linking, chain polymer break, delamination, and embrittlement)*

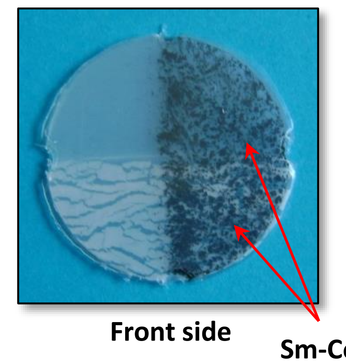
### Cosmic Ray Shielding (CRS)




Backside



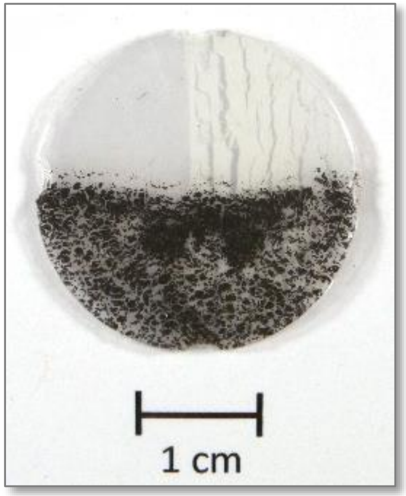




Front side

The CRS sample is a combination of low density polyethylene (LDPE) film and inorganic particles:

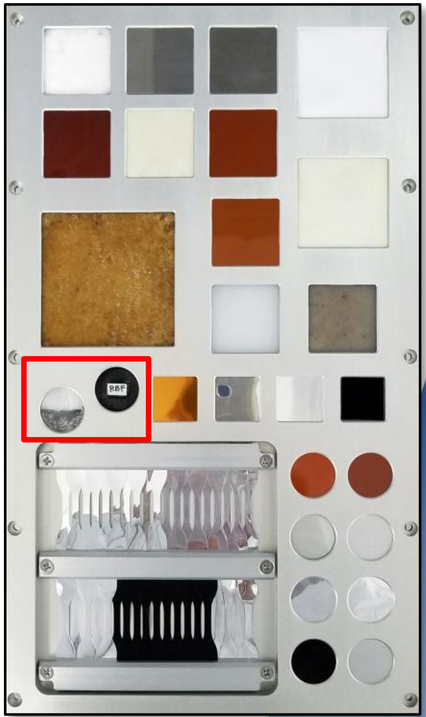
- *Samarium cobalt (Sm-Co) & boron nitride (BN) powders*
- *New shielding material for spacesuits (i.e. flexible) and possibly spacecraft*

# University of Rome Tor Vergata
## MISSE-9 Wake Samples




M9W-C9
Cosmic ray shielding
(CRS) sample


M9W-C10
Shape memory composite
(SMC) sample



MSC W3


M9W-C9 & M9W-C10
(with Al block in place for pre-flight tests)

M9W-C9 & M9W-C10
(with Al block removed for flight)

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## MISSE-9 Zenith Sample


**M9Z-C17**
Shape memory composite (SMC) sample
(with Al block in place for pre-flight tests)

M9Z-C17
(with Al block removed for flight)
*Photo credit: Alpha Space*

M9Z-C17
(with Al block removed for flight)
*Photo credit: Alpha Space*

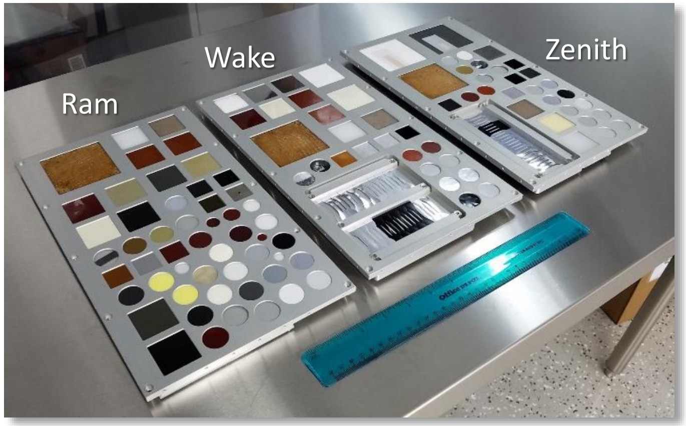
**MSC Z3**

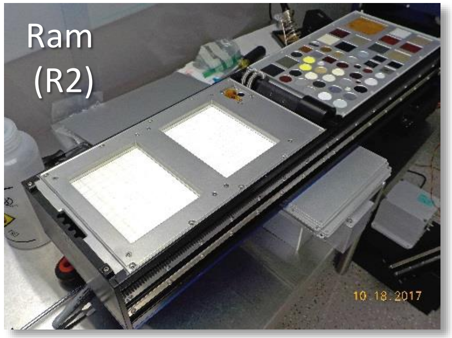
# Polymer and Composites Experiment (PCE)

## Integration of the PCE samples into the MISSE-9 Decks

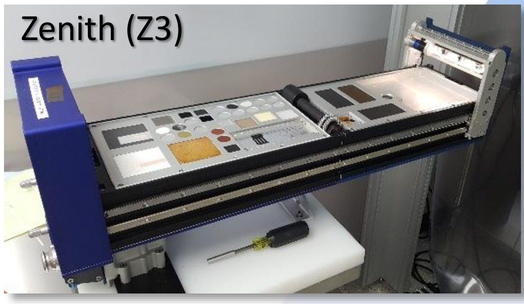
R2 W3 Z3

Alpha Space, Houston
August 4, 2017







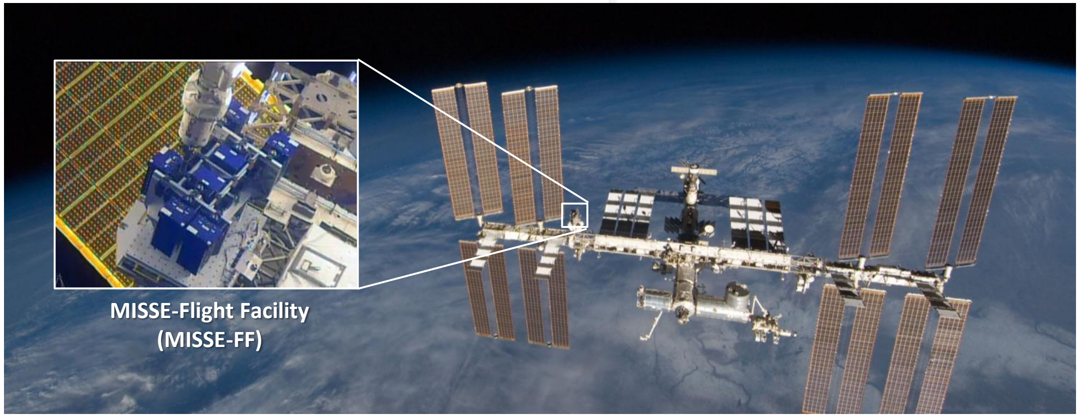

*Pre-flight full MSC photos courtesy of Alpha Space*

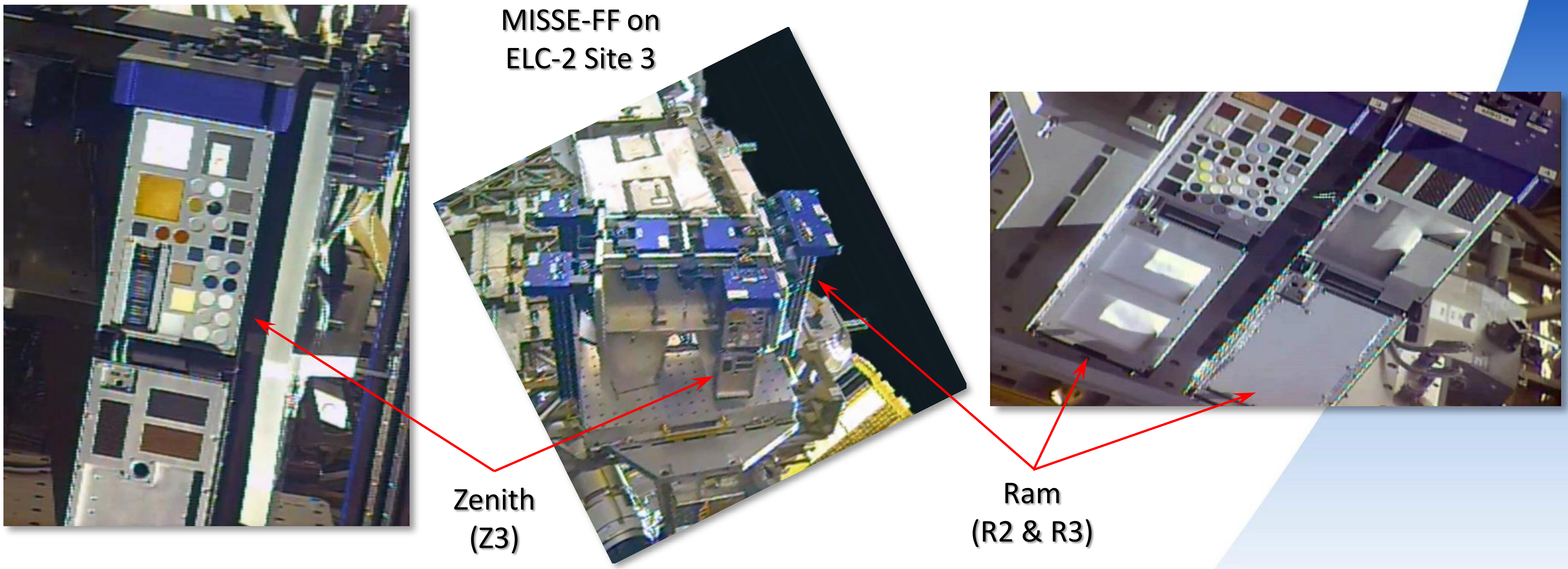
# MISSE-Flight Facility

## MISSE-9 deployed on April 19, 2018 for a 1 year mission

**MISSE-FF launched aboard SpaceX CRS-14 on April 2, 2018**

**Robotically installed on ELC-2 Site 3 on April 8, 2018**




*MISSE-FF illustration courtesy of Alpha Space*

# Polymer and Composites Experiment (PCE)
## Ram (R2) Pre-flight & On-Orbit Images

Pre-flight Image

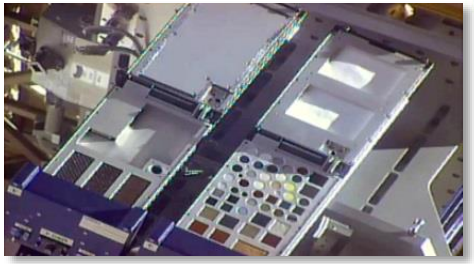
On-Orbit Image Composite

On-orbit images taken April 23, 2018

*On-orbit sample photos courtesy of NASA and Alpha Space*

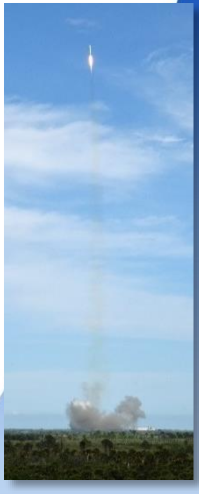
# MISSE-9 PCE Summary

- The **Polymers and Composites Experiment (PCE)** is part of MISSE-9, the inaugural mission of the MISSE-Flight Facility (MISSE-FF)



PCE ram samples on-orbit

- **Passive experiment:**
  - 138 samples being flown in ram, wake & zenith orientations:
    - ***Ram (39):*** *32 - circular (0.5" - 1.0") & 7 - 1" square*
    - ***Wake (52):*** *38 - tensile samples + 14 - 1" samples*
    - ***Zenith (47):*** *24 - tensile samples + 23 - 1" samples*
  - Pre-flight & post-flight data will be measured in ground-facilities
- **Mission summary:**
  - *MISSE-9 & MISSE-FF launched to ISS on April 2 as part of the SpaceX CRS-14 mission*
  - *MISSE-FF was robotically transferred to ELC-2 Site 3 on April 8, 2018*
  - *MISSE-9 experiments were successfully deployed April 19, 2018 for a 1 year mission*



SpaceX CRS-14 launch

- **Expected results include:**
  - Monthly high resolution on-orbit photographs of flight samples
  - AO fluence and contamination data in ram, wake and zenith directions
  - LEO AO $E_y$ values as a function of AO fluence, solar irradiation & inorganic content
  - Changes in optical, thermal and tensile properties
  - Performance and durability of cosmic ray shielding materials & shape memory composites
- **Expected impacts:**

  *This experiment will provide critical space environmental durability data for LEO and low Mars orbit mission spacecraft enabling:*
  - Improved predictions of materials and component lifetimes in space
  - Improvements to Glenn's AO $E_y$ Predictive Tool and AO Monte Carlo Model
  - A revision of NASA Technical Standards Spacecraft Polymers Atomic Oxygen Durability Handbook

# Acknowledgements

Glenn's MISSE research has been supported by various projects over the past 18 years including the ISS Research Program, the MISSE-X Project, the MISSE Informatics Project and currently Glenn Center Funds