



# Durability of Polymers in the Space Environment

Kim K. de Groh  
NASA Glenn Research Center



MISSE-Flight Facility  
(MISSE-FF)



*195<sup>th</sup> Technical Meeting of The Rubber Division of the American Chemical Society (ACS)  
April 30, 2019, Independence, Ohio*



# Kim K. de Groh

Sr. Materials Research Engineer  
NASA Glenn Research Center  
Environmental Effects and Coatings Branch  
[kim.k.degroh@nasa.gov](mailto:kim.k.degroh@nasa.gov)



- B.S. in Materials Science, Michigan State University (1985)
- M.S. in Materials Science, Michigan State University (1987)
- Joined the space environment durability group at NASA in 1989
  - *Conduct research on the environmental durability of spacecraft materials in the space environment*



- *Married to Henry de Groh*
  - *Sr. Materials Engineer  
NASA Glenn Research Center*
- *Two sons:*
  - *Henry, BA in Philosophy,  
Miami University (2018)*
  - *Dan, Senior in Commercial Music Production  
at the University of Cincinnati*
- *We live in Hinckley, Ohio*

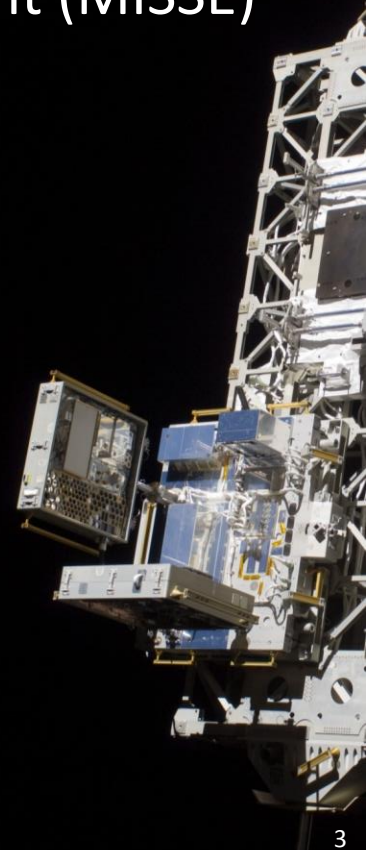


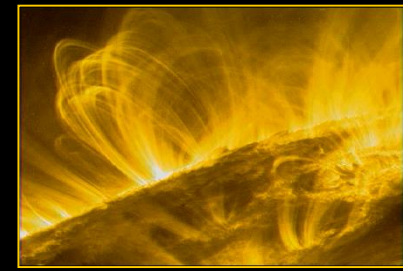
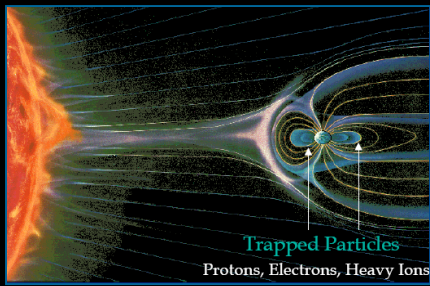


# Outline



- Introduction to the space environment
  - *Overview of atomic oxygen (AO)*
  - *Examples of space environment induced spacecraft damage*
- Materials International Space Station Experiment (MISSE)
  - *Overview of Glenn's MISSE 1-8 polymers flight experiments*
  - *20 year collaboration with Hathaway Brown School (HB)*
- MISSE-Flight Facility (MISSE-FF)
  - *Introduction to MISSE-FF*
  - *MISSE-9 Polymers and Composites Experiment (PCE)*
  - *MISSE-10 Polymers and Composites Experiment-2 (PCE-2)*
  - *MISSE-12 Polymers and Composites Experiment-3 (PCE-3)*



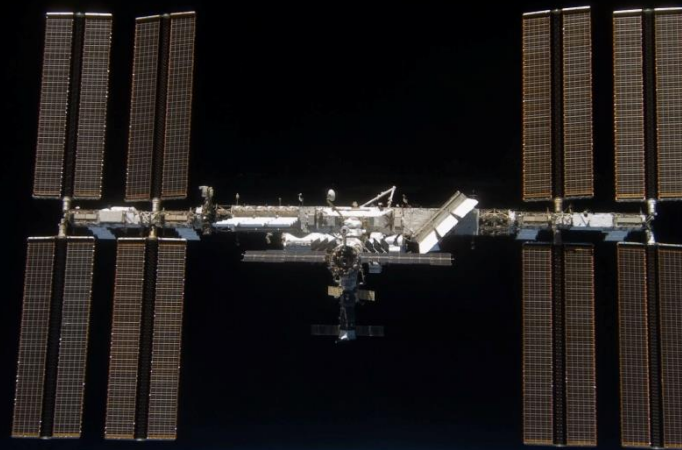


# The Space Environment

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

In low Earth orbit (LEO) environmental threats include:

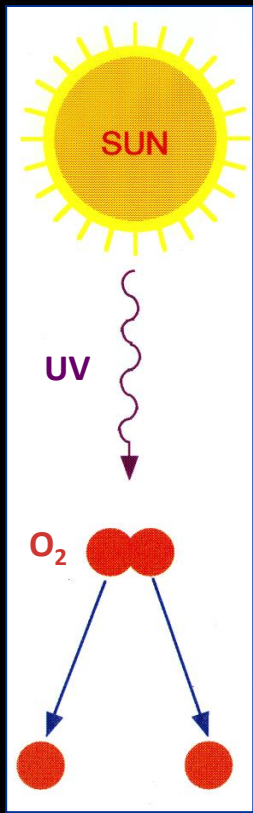
- Solar radiation (ultraviolet (UV), x-rays)
- Charged particle radiation (electrons, protons)
- Cosmic rays (energetic nuclei)
- Temperature extremes & thermal cycling
- Micrometeoroids & orbital debris (space particles)
- Atomic oxygen (AO) (reactive oxygen atoms)



# Low Earth Orbit Atomic Oxygen



# Atomic Oxygen (AO)

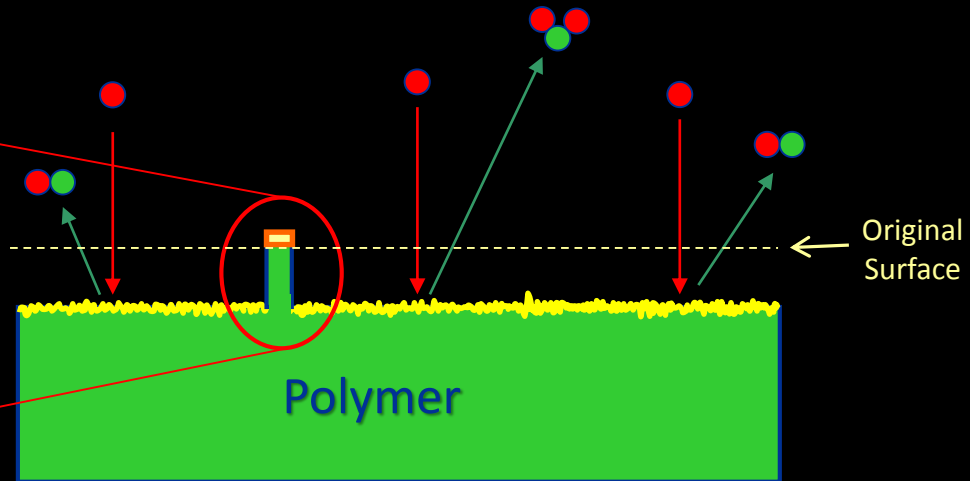
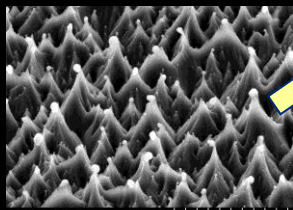
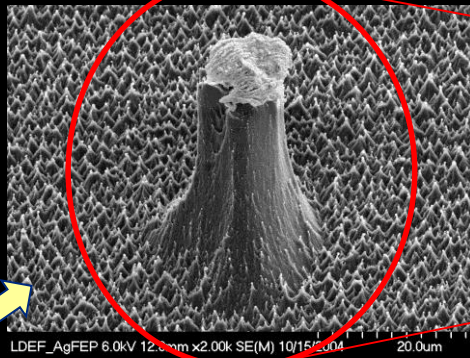


- AO is the predominant species in LEO ( $\approx 200\text{-}650$  km)
- It is formed by photodissociation of molecular oxygen ( $\text{O}_2$ ) by short wavelength energetic UV radiation
- At ram impact velocities (17,000 mph) the average impact energy is 4.5 eV
- AO oxidizes certain materials (such as polymers) with resulting gas formation - so *the material erodes away...*

$\Rightarrow$  *AO is a serious threat to spacecraft survivability*

Atomic Oxygen

Ram AO erosion causes "cone" formation



# Atomic Oxygen Erosion on the Long Duration Exposure Facility (LDEF)

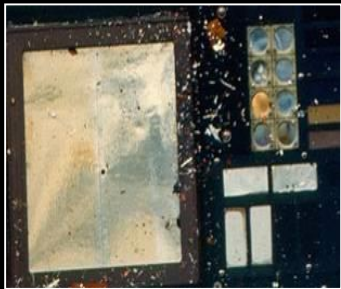
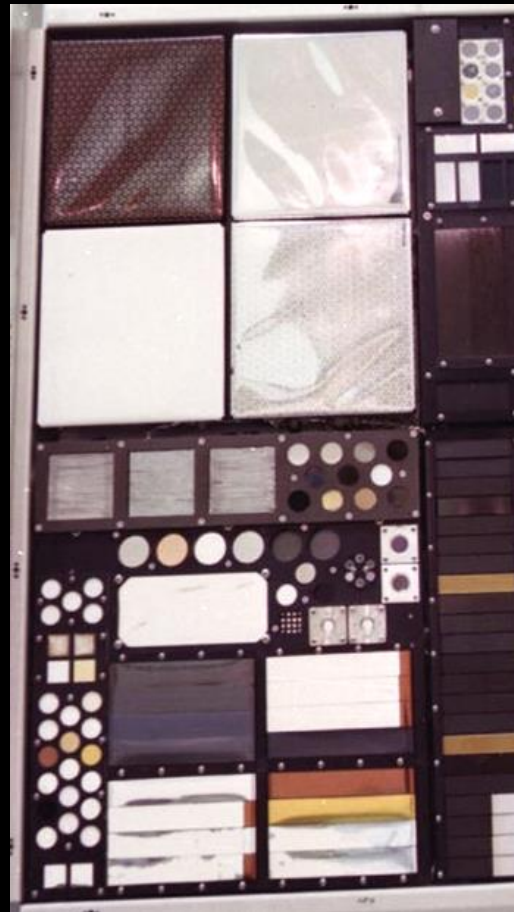


*5.8 years of space exposure*

*Ram AO F=  $8.99 \times 10^{21}$  atoms/cm<sup>2</sup>*

Pre-flight

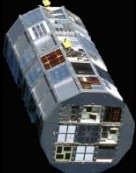
Post-flight



AO debris generation

AO erosion of numerous materials

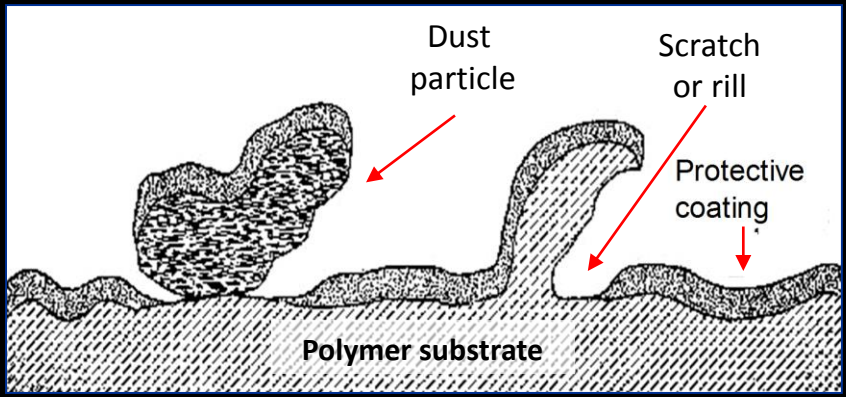
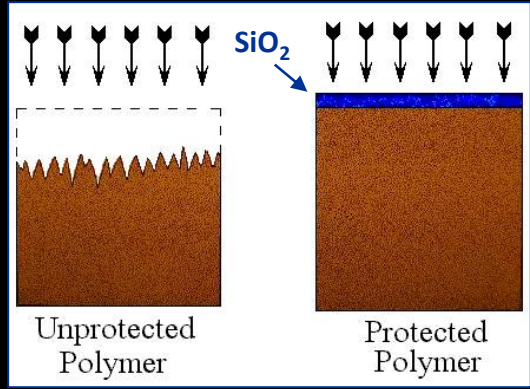
LDEF Tray D09



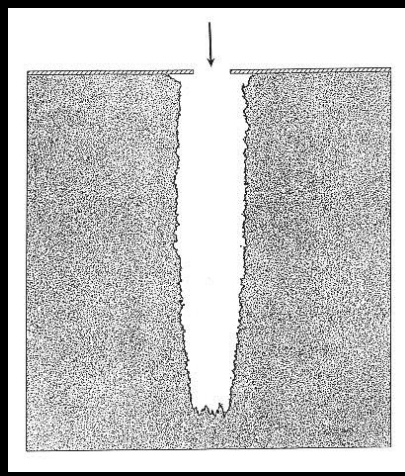
# AO Protective Coatings & Undercutting Erosion



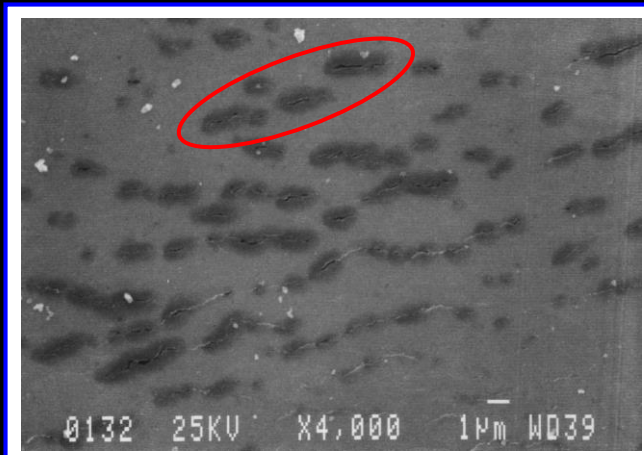
## Protective Coating Defects



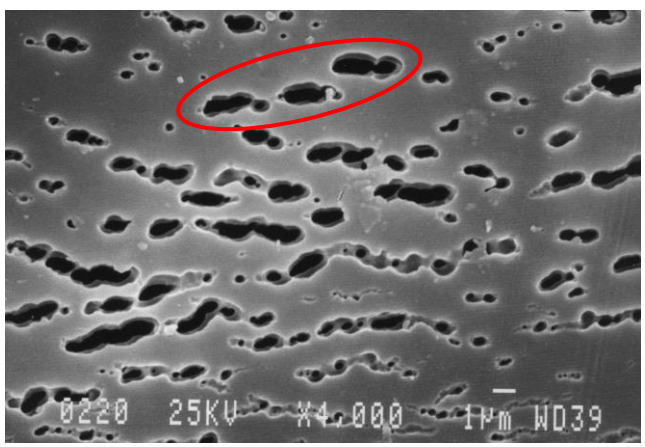
## Directed Ram AO undercutting



## LDEF Al-Kapton Multilayer Insulation (MLI) Blanket

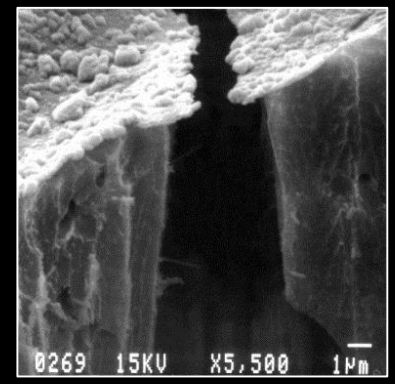


With Al coating



With Al coating removed

## Undercutting in LDEF Al/Cr/Graphite Epoxy

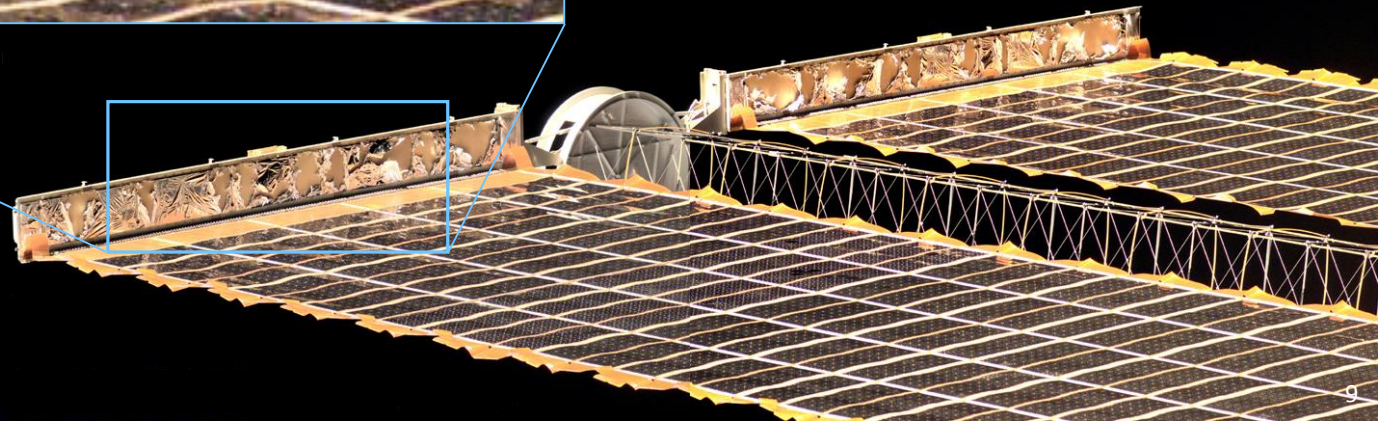
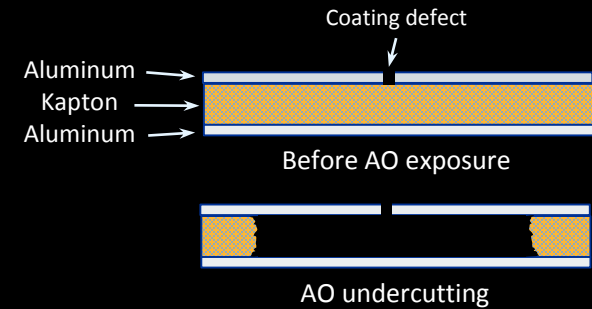
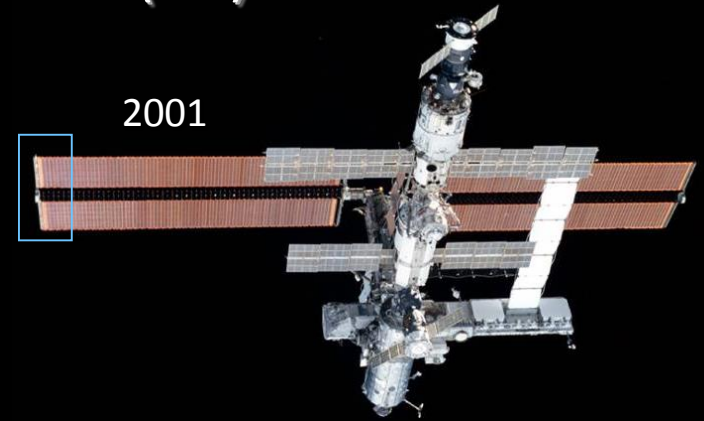




# Space Environment Induced Degradation International Space Station (ISS)



AO undercutting erosion of the ISS  
P6 Port Solar Array Al-Kapton blanket box cover  
after only 1 year of space exposure





# Solar & Charged Particle Radiation

# Space Environment Induced Degradation

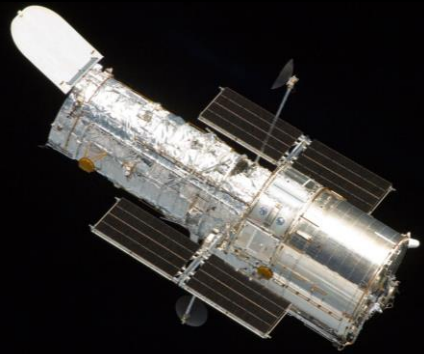
## Hubble Space Telescope (HST)



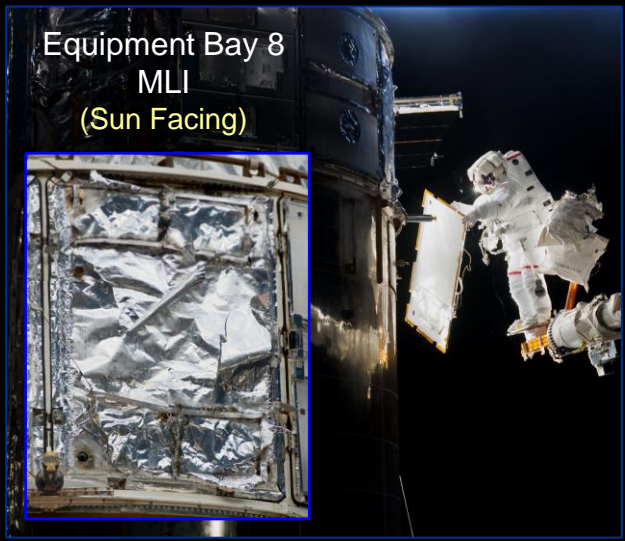
Radiation induced embrittlement & cracking of HST Teflon multilayer insulation (MLI)



Servicing Mission 2 (SM2)  
6.8 years of space exposure



Servicing Mission 4 (SM4)  
19 years of space exposure



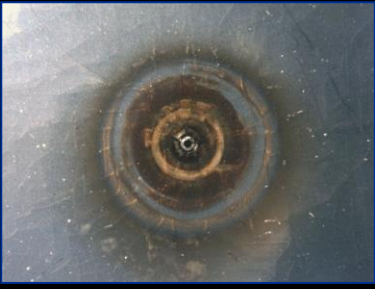
SM4 replacement of severely degraded Bay 8 MLI  
19 years of space exposure



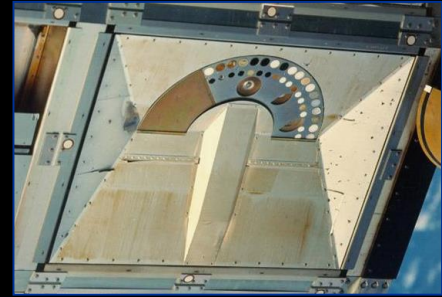
# Space Environment Induced Degradation

## Long Duration Exposure Facility (LDEF)

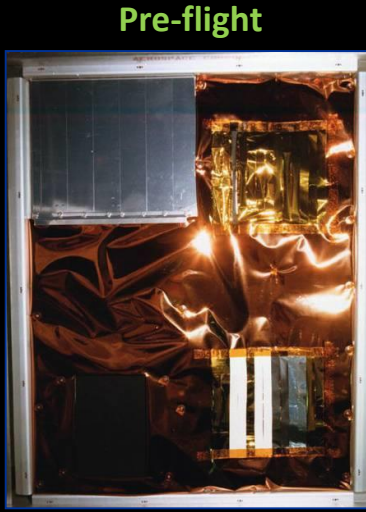
5.8 years in space



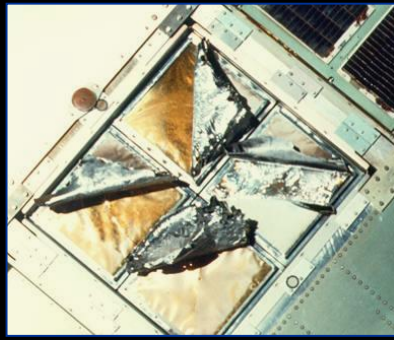
Impact site



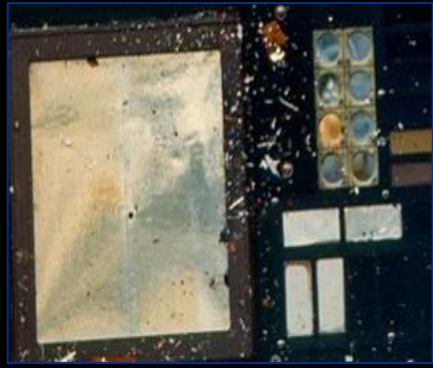
Radiation induced darkening



AO erosion of Kapton blanket



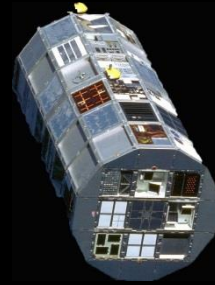
Structural degradation



Debris generation



# Space Environmental Effects Flight Experiments Skylab to MISSE-FF



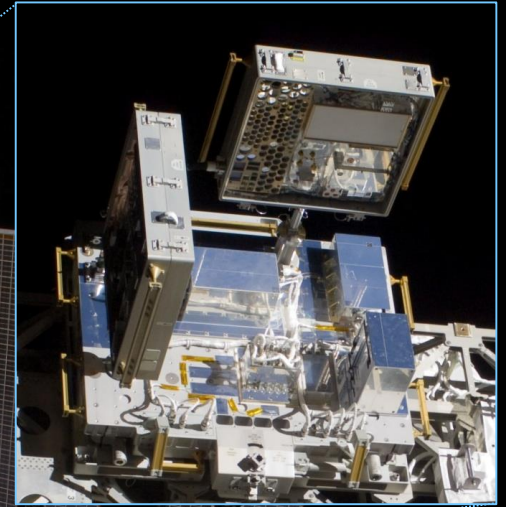


# Materials International Space Station Experiment (MISSE)



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:

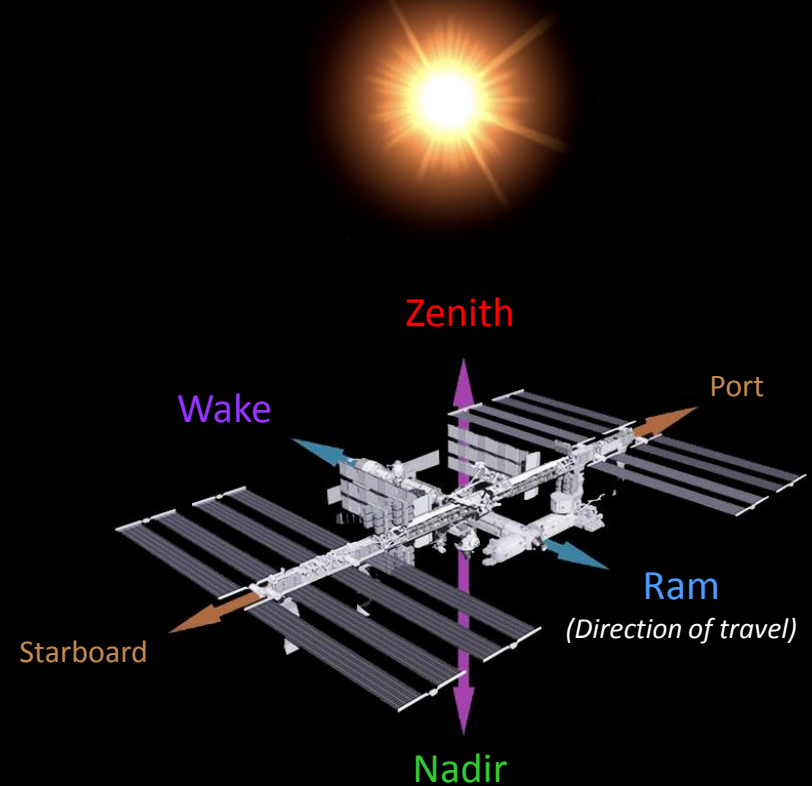
- Facing away from the direction of travel  
(i.e. aft pointing or trailing edge)
- Essentially no AO & moderate solar exposure

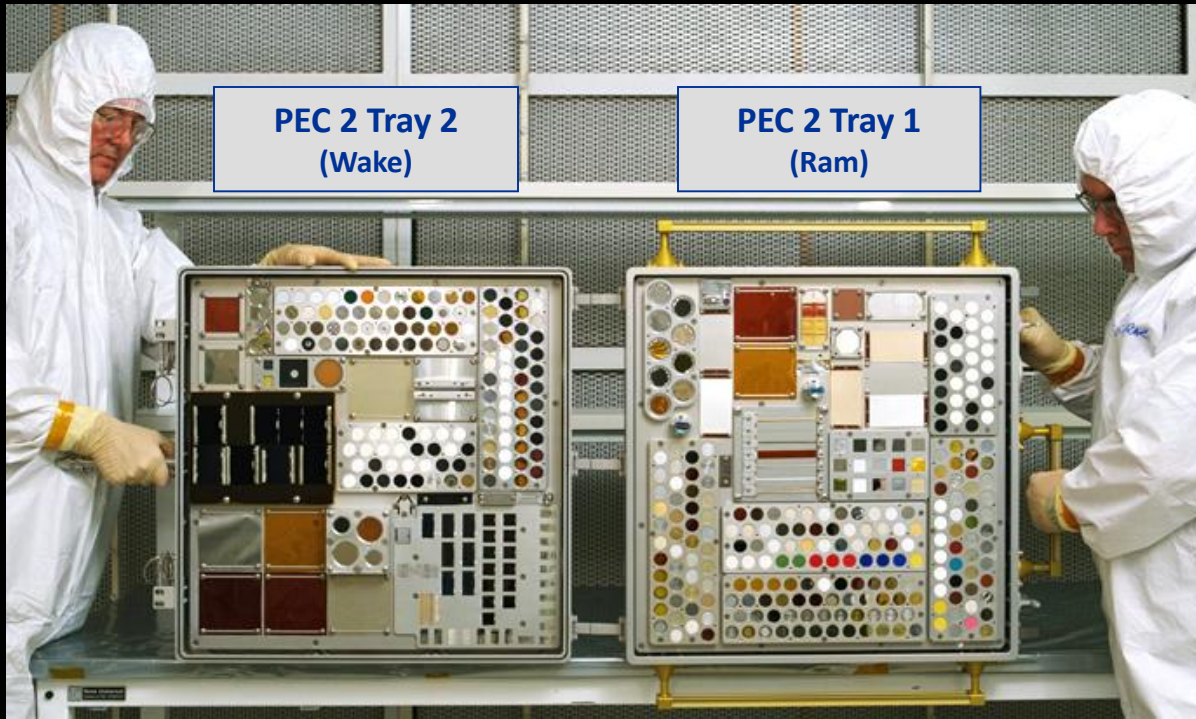
## Zenith:

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

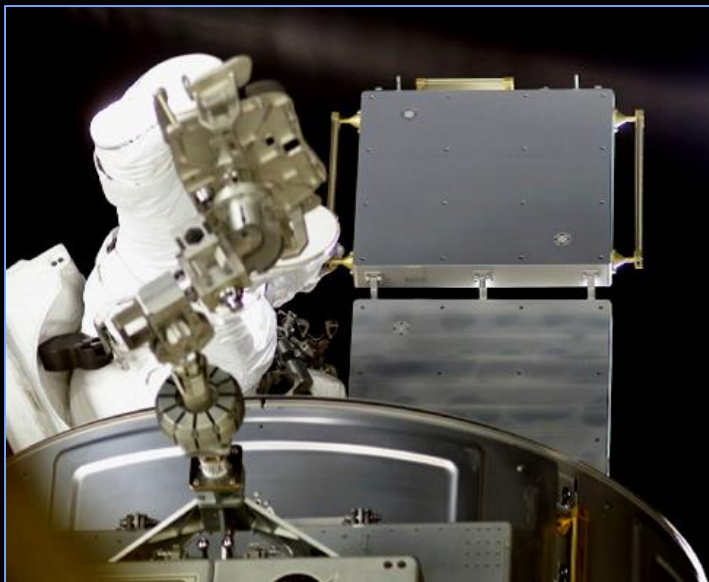
## Nadir:

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





**MISSE**  
Experiment  
Integration,  
Shuttle  
launch &  
EVA  
Attachment



Patrick Forrester  
& PEC 2  
August 16, 2001

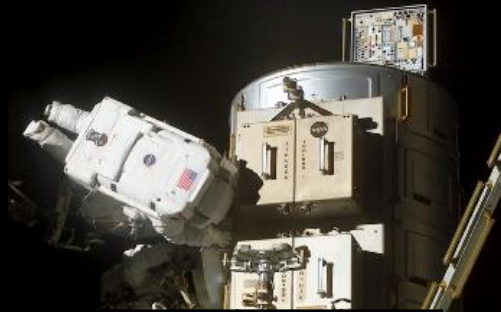






# MISSE 1-8

## 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) PEC 2: Quest Airlock	Ram & Wake	STS-114	7/30/2005	<b>3.95</b>
3 & 4	STS-121	8/3/2006*	PEC 3: HPGT PEC 4: Quest Airlock	Ram & Wake	STS-118	8/18/2007	<b>1.04</b>
5	STS-114	8/3/2005	Aft P6 Trunion Pin Handrail	Zenith & Nadir	STS-115	9/15/2006	<b>1.12</b>
6A & 6B	STS-123	3/22/2008	Columbus Laboratory	Ram & Wake	STS-128	9/1/2009	<b>1.45</b>
7A & 7B	STS-129	11/23/2009	EXPRESS Logistics Carrier 2 (ELC 2) on the S3 Truss	7A: Zenith & Nadir 7B: Ram & Wake	STS-134	5/20/2011	<b>1.49</b>
8 & ORMatE-III R/W	STS-134	8: 5/20/2011 ORMatE-III R/W: 7/12/2011**	EXPRESS Logistics Carrier 2 (ELC 2) on the S3 Truss	8: Zenith & Nadir ORMatE-III R/W: Ram & Wake	SpaceX-3 Dragon	7/9/2013	MISSE 8: <b>2.14</b> ORMatE-III: <b>2.00</b>

\* Deployed during Expedition 13

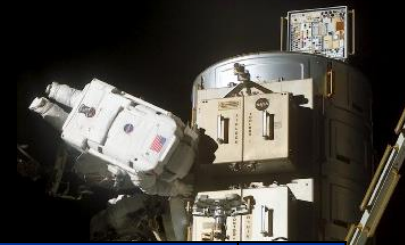
\*\* Deployed during STS-135

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



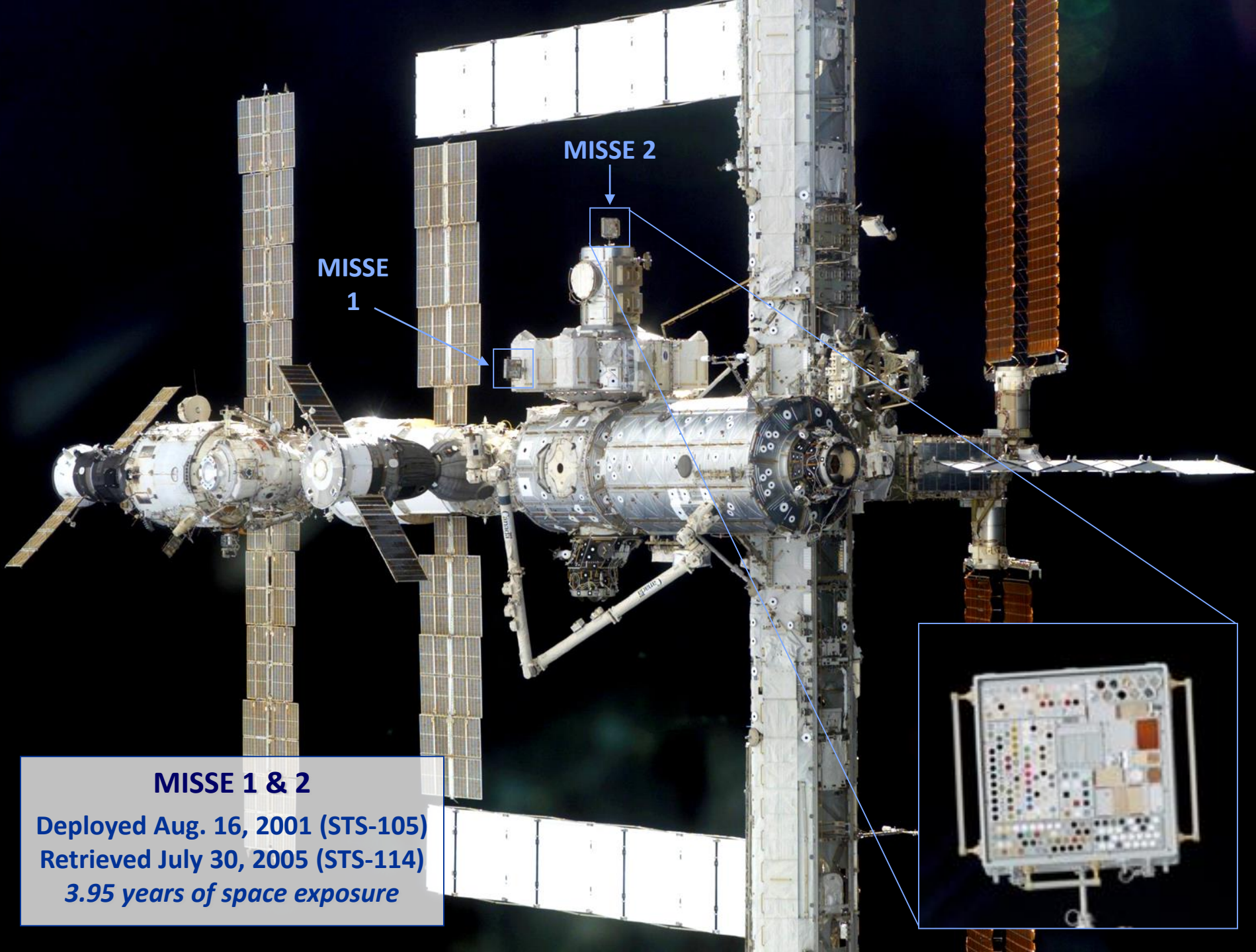
# MISSE 1-8 Experiment Summary

13 experiments with 318 flight samples



MISSE Mission	Experiment	# Samples	Mission Orientation	Duration (yrs)	Experiment Objective	Active/Passive
2	Polymers Experiment (PEACE)	41	2 Ram	3.95	Determine the AO erosion yield (Ey) of a wide variety of polymers	P
	Spacecraft Silicones	4				P
4	Spacecraft Silicones	4	4 Ram	1.04	To determine changes in optical properties and nanomechanical hardness for ground-testing	P
5	Spacecraft Silicones	3	5 Nadir	1.12		Determine AO Ey and radiation induced embrittlement of a wide variety of polymers with low solar radiation
	Polymers Experiment (PEACE)	49			Determine space environmental durability of fluorinated polymers (w/ Boeing, NASA MSFC & Montana State Univ.)	P
	Team Cooperative* (Fluorinated Polymers)	20				
6A & 6B	Stressed Polymers Experiment	36	6A Ram	1.45	To determine if the AO Ey is dependent upon stress, plus evaluate thin film stacking effects on Ey	P
	Scattered Space Atomic Oxygen Experiment (SSAOE)	13	6B Ram		Actively measure direct ram & scattered AO erosion and passively measure angular distribution of scattered AO	A/P
	Polymer Strain Experiment*	6	6B Wake		To measure radiation-induced strain in thin film polymers as a function of exposure time on-orbit	A
7A & 7B	Zenith Polymers Experiment	25	7A Zenith	1.49	To determine the effect of solar exposure on the AO Ey of fluoropolymers (high solar/low AO exposure)	P
	Nadir Tensile Sample Experiment	6	7A Nadir		To determine the effect of LEO radiation (charged particle and albedo radiation) on the embrittlement of Al-FEP	P
	Polymer Experiment	45	7B Ram & 7B Wake		For AO Ey determination and to determine if AO erosion of high & low ash containing polymers is dependent on fluence	P
	Flexural Stress Effects Experiment	24	7B Wake		To examine the role of surface flexural stress on space environment induced polymer degradation	P
8 & ORMatE-III	Polymers Experiment	42	ORMatE-III Ram & Wake & 8 Zenith	8: 2.14 O-III: 2.00	To characterize the degradation of polymers & other spacecraft materials flown in ram, wake & zenith orientations	P

\*Co-investigator



MISSE 2

MISSE 1

## MISSE 1 & 2

Deployed Aug. 16, 2001 (STS-105)

Retrieved July 30, 2005 (STS-114)

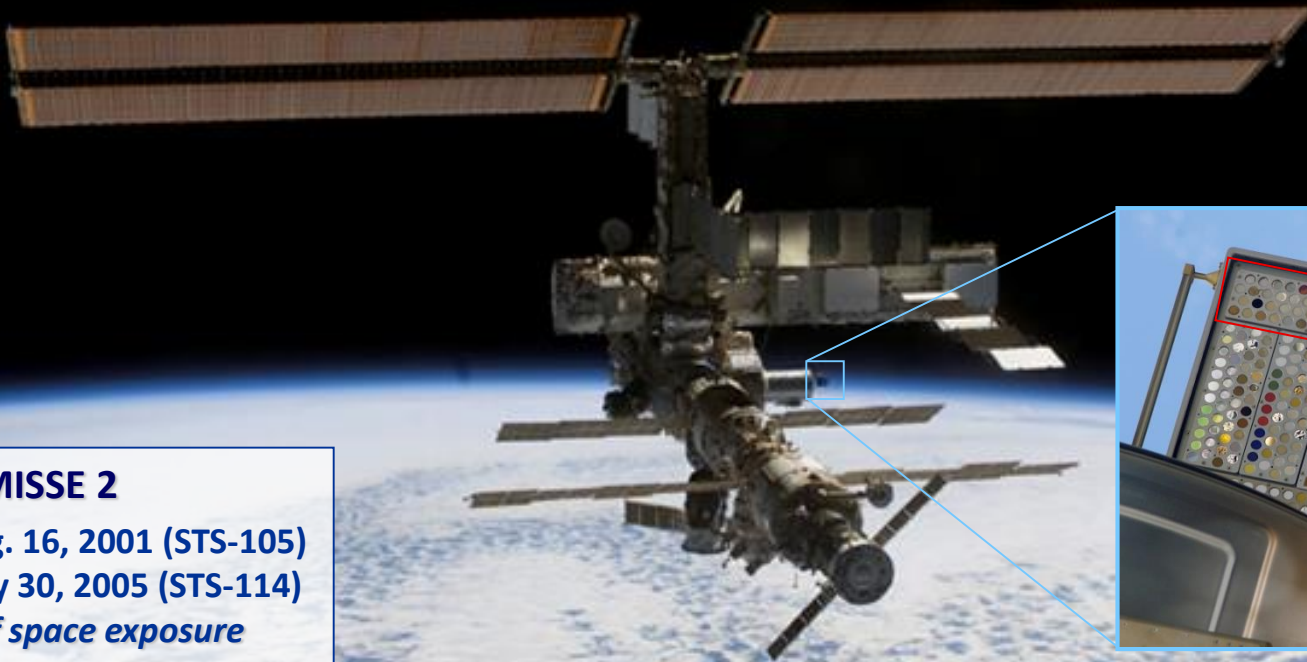
*3.95 years of space exposure*



# MISSE 2 Polymers Experiment

*Objective: To determine the AO erosion yield ( $E_v$ ) 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)

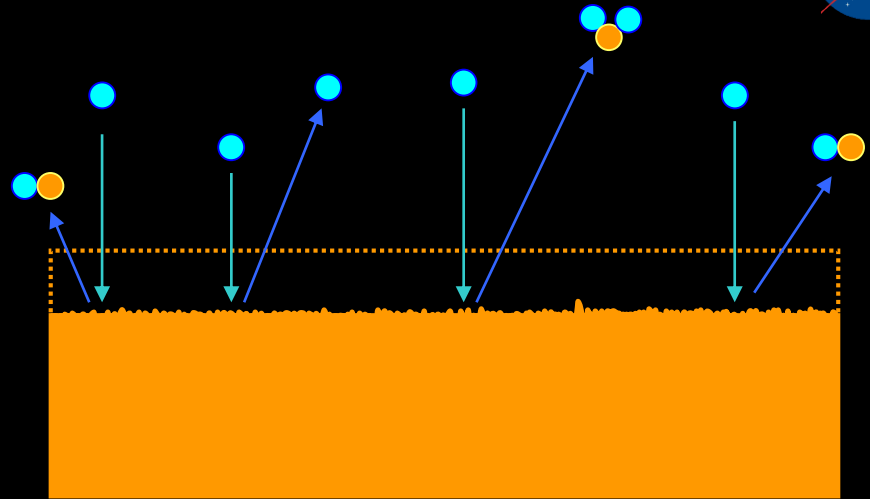
Retrieved July 30, 2005 (STS-114)

*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 ( $\text{cm}^3/\text{atom}$ )



## Erosion Yield ( $E_y$ ) 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 ( $\text{cm}^2$ )  
 $\rho_s$  = Density of sample ( $\text{g}/\text{cm}^3$ )  
 $F_k$  = AO fluence measured by Kapton H witness samples ( $\text{atom}/\text{cm}^2$ )

### 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 ( $\text{cm}^2$ )  
 $\rho_k$  = Density of Kapton H sample ( $1.427 \text{ g}/\text{cm}^3$ )  
 $E_k$  = Erosion yield of Kapton H ( $3.0 \times 10^{-24} \text{ cm}^3/\text{atom}$ )

# MISSE 2 Polymers Experiment



Pre-flight



Post-flight (4 years of space exposure)

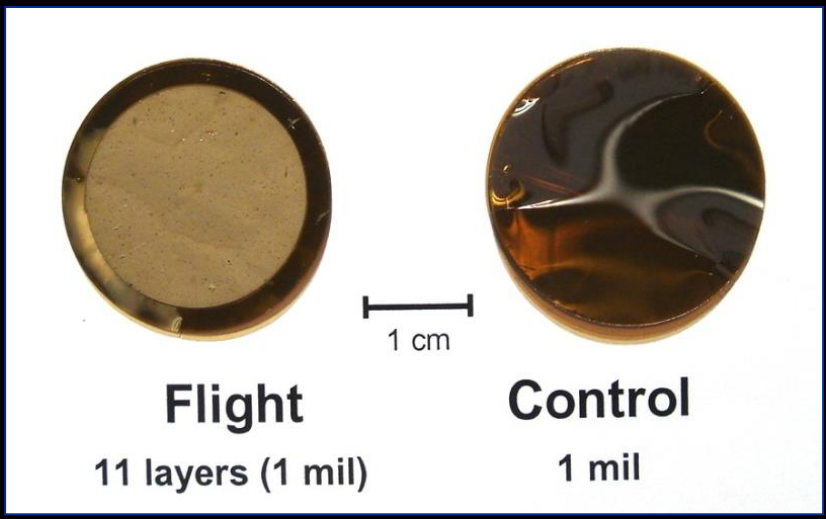
Polyimide (PMDA)  
Upilex-S

2-E5-32

*Post-flight photos*



*In flight tray*



**Flight**

11 layers (1 mil)

**Control**

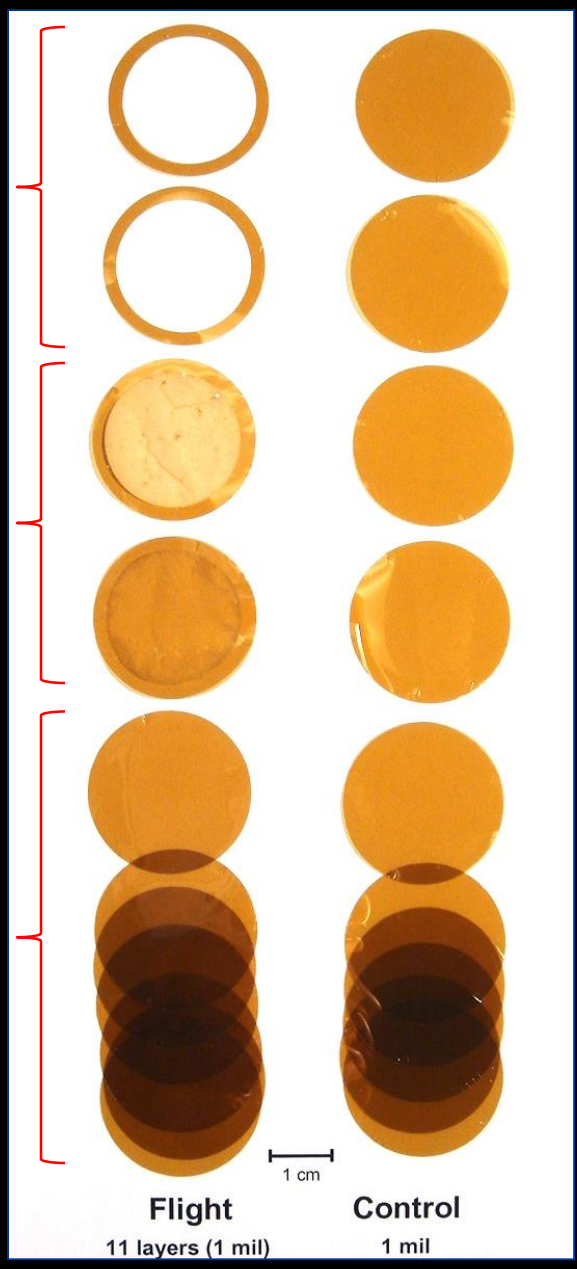
1 mil

*Out of tray*

*Complete erosion*

*Partial erosion*

*No erosion*



**Flight**

11 layers (1 mil)

**Control**

1 mil



# MISSE 2 Polymers Erosion Yield Data



Polymer Abbreviation	$E_y$ (cm <sup>3</sup> /atom)	$E_y$ Uncertainty (%)	Polymer Abbreviation	$E_y$ (cm <sup>3</sup> /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%



# LEO Directed Ram AO Exposure Erosion Textures

## MISSE 2

AO F =  $8.43 \times 10^{21}$  atoms/cm<sup>2</sup>

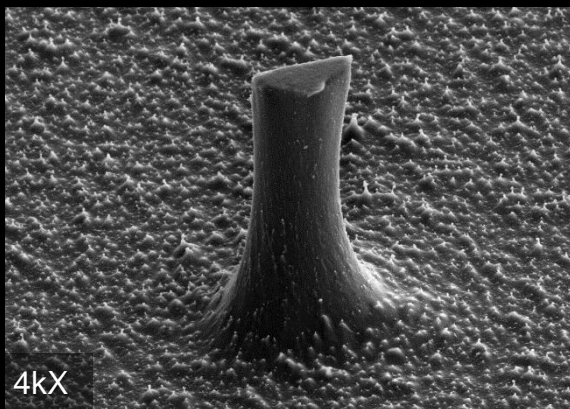
Polytetrafluoroethylene (PTFE)

$E_y = 1.42 \times 10^{-25}$  atoms/cm<sup>2</sup>



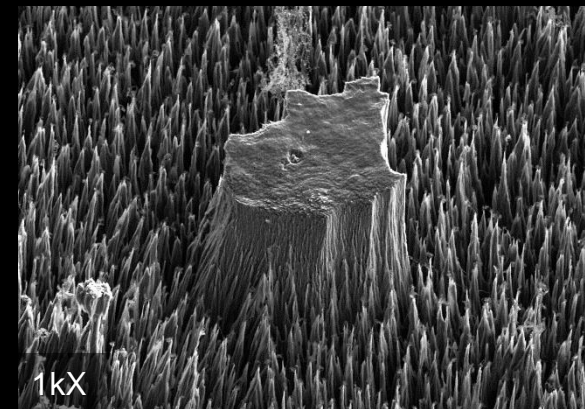
Teflon FEP/Al

$E_y = 2.11 \times 10^{-25}$  atoms/cm<sup>2</sup>



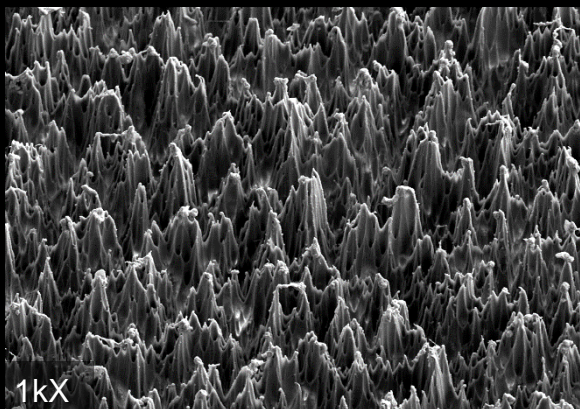
Pyrolytic Graphite (PG)

$E_y = 4.15 \times 10^{-25}$  atoms/cm<sup>2</sup>



Chlorotrifluoroethylene

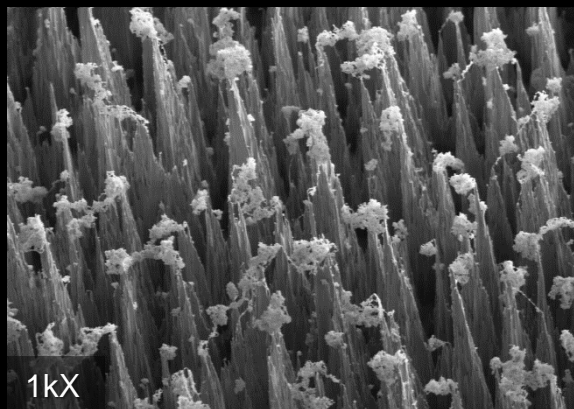
$E_y = 8.31 \times 10^{-25}$  atoms/cm<sup>2</sup>



Kapton H polyimide

$E_y = 3.00 \times 10^{-24}$  atoms/cm<sup>2</sup>

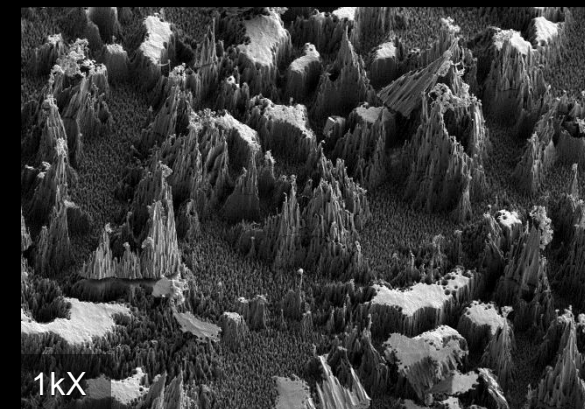
2nd eroded layer (5 mil thick)



Polyvinyl fluoride

$E_y = 3.19 \times 10^{-24}$  atoms/cm<sup>2</sup>

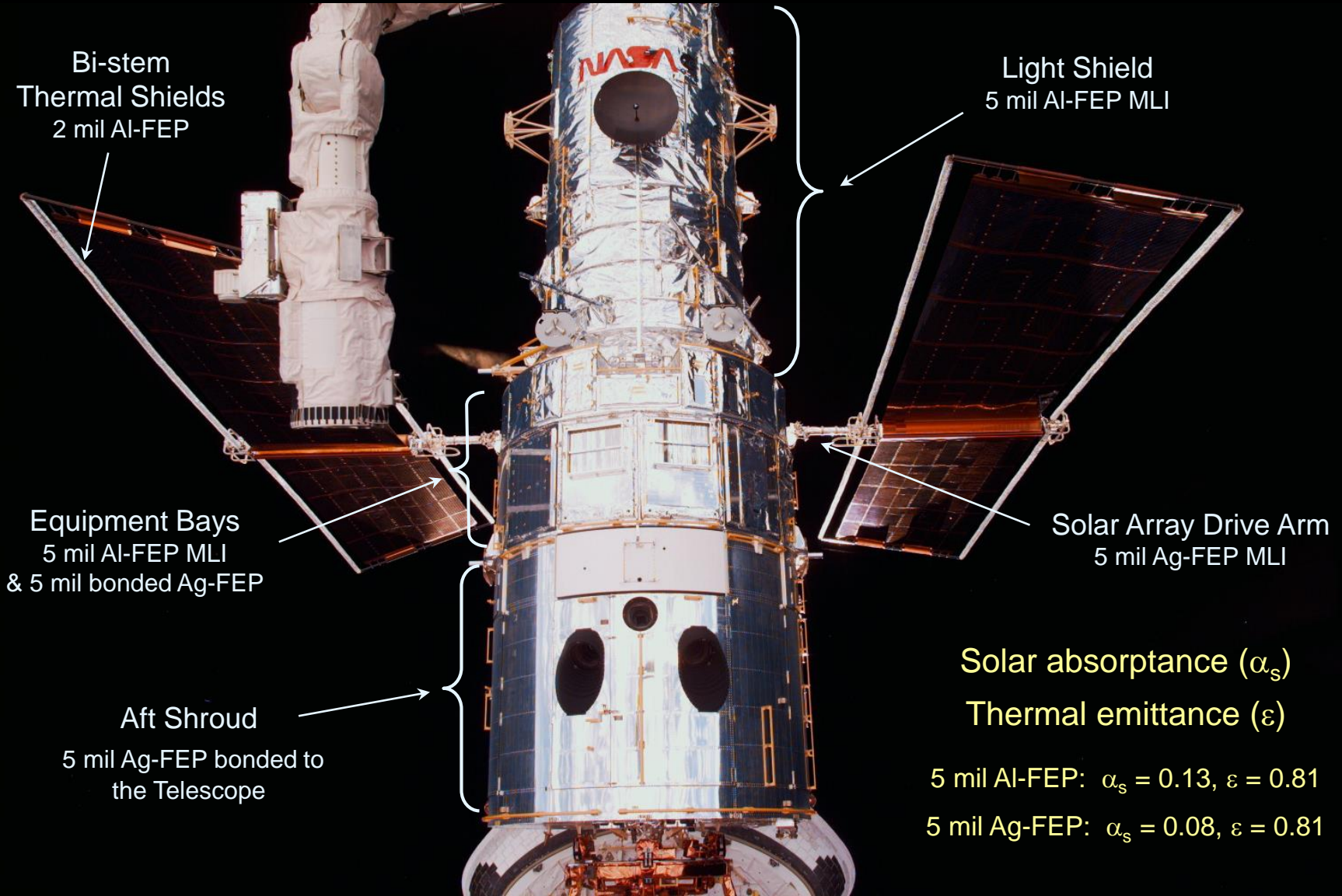
11th eroded layer (1 mil thick)



# Spacecraft Optical and Thermal Properties

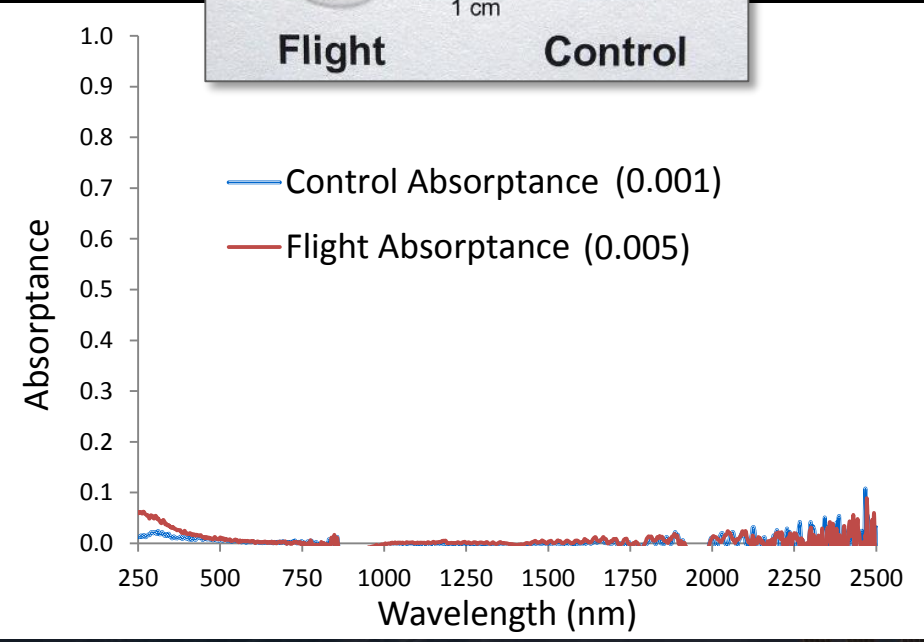
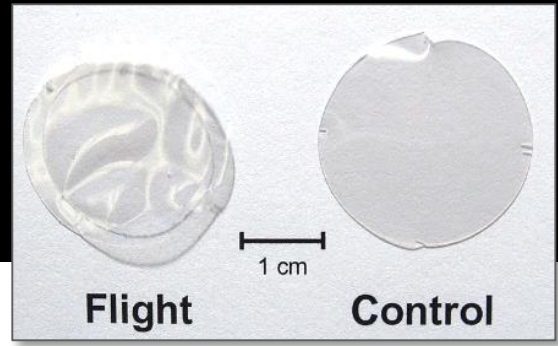
## Hubble Space Telescope

### Fluorinated Ethylene Propylene (FEP) Thermal Insulation



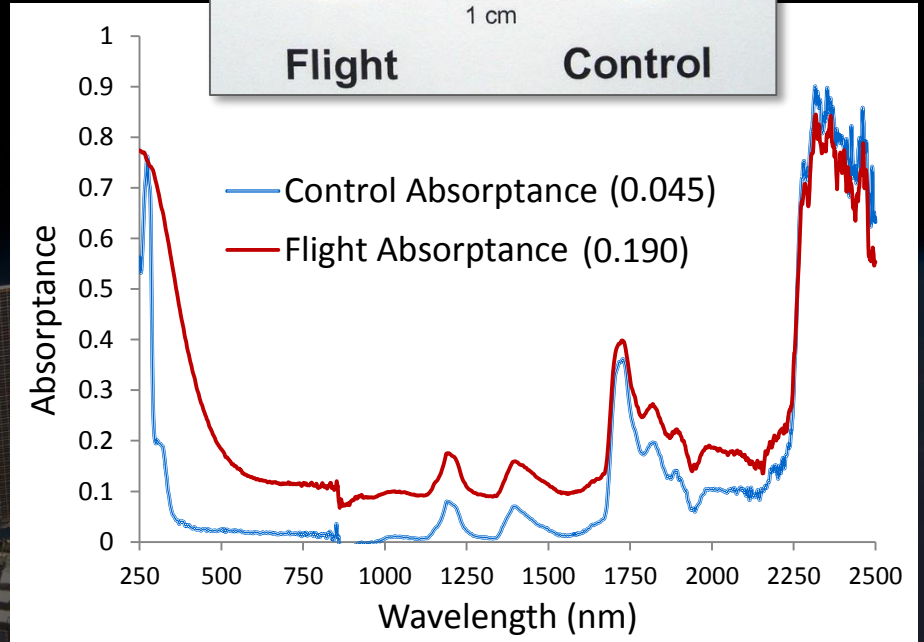
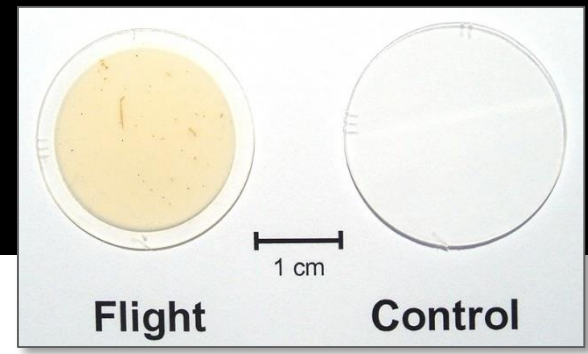
# Solar Absorptance of MISSE 2 Samples

Teflon FEP  
(2-E5-42)



AO did not significantly erode, or cause color changes in Teflon FEP, hence there was essentially **no change in  $\alpha_s$**

Polypropylene  
(2-E5-20)



AO eroded and textured the polypropylene, and caused it to darken, which resulted in an **increase in  $\alpha_s$**

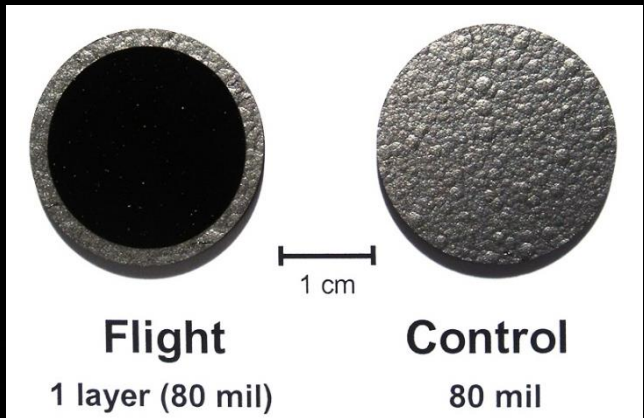


# Solar Absorptance & Thermal Emittance Changes

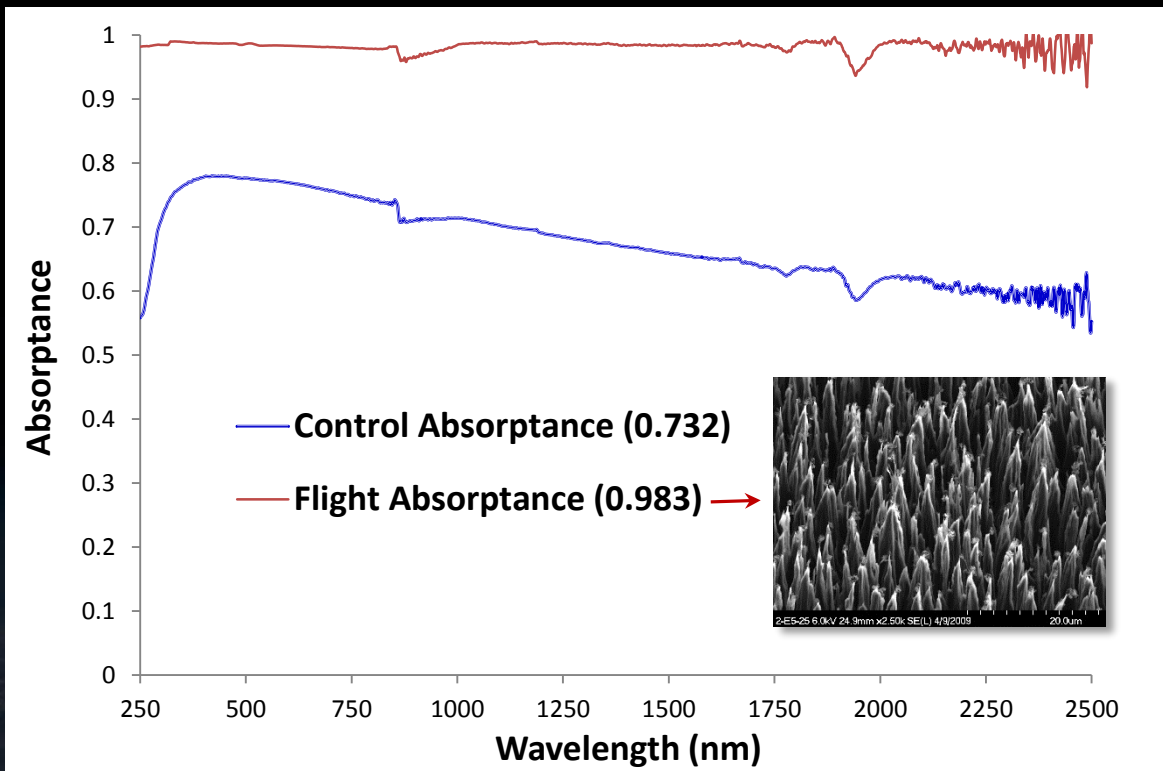
## MISSE 2 Ram Pyrolytic Graphite (PG)

2-E5-25

AO F =  $8.43 \times 10^{21}$  atoms/cm<sup>2</sup>



	Control	Flight	$\Delta$
TR	0.268	0.017	<b>-0.251</b>
DR	0.253	0.014	<b>-0.239</b>
SR	0.015	0.003	<b>-0.012</b>
$\alpha_s$	0.732	0.983	<b>0.251</b>
$\varepsilon$ (300k)	0.47	0.99	<b>0.52</b>



TR: Total Reflectance  
 DR: Diffuse reflectance  
 SR: Specular Reflectance  
 $\alpha_s$ : Solar absorptance  
 $\varepsilon$ : Thermal emittance

AO textured and darkened the pyrolytic graphite which resulted in an **increase in  $\alpha_s$  &  $\varepsilon$**

# MISSE 2 PEACE Polymers Experiment Results & Benefits

## 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



Post-flight photo of MISSE 2 PEACE

## 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

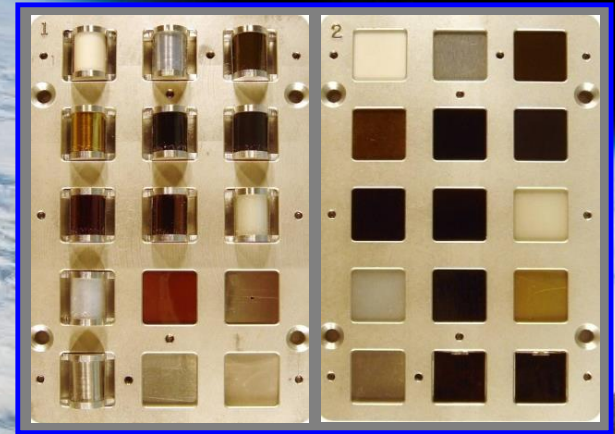


More accurate ground testing

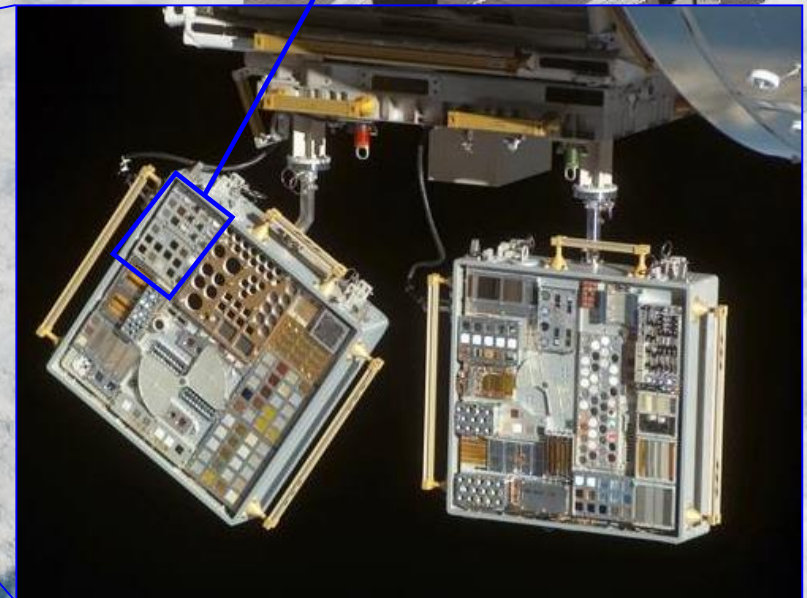


WorldView-3

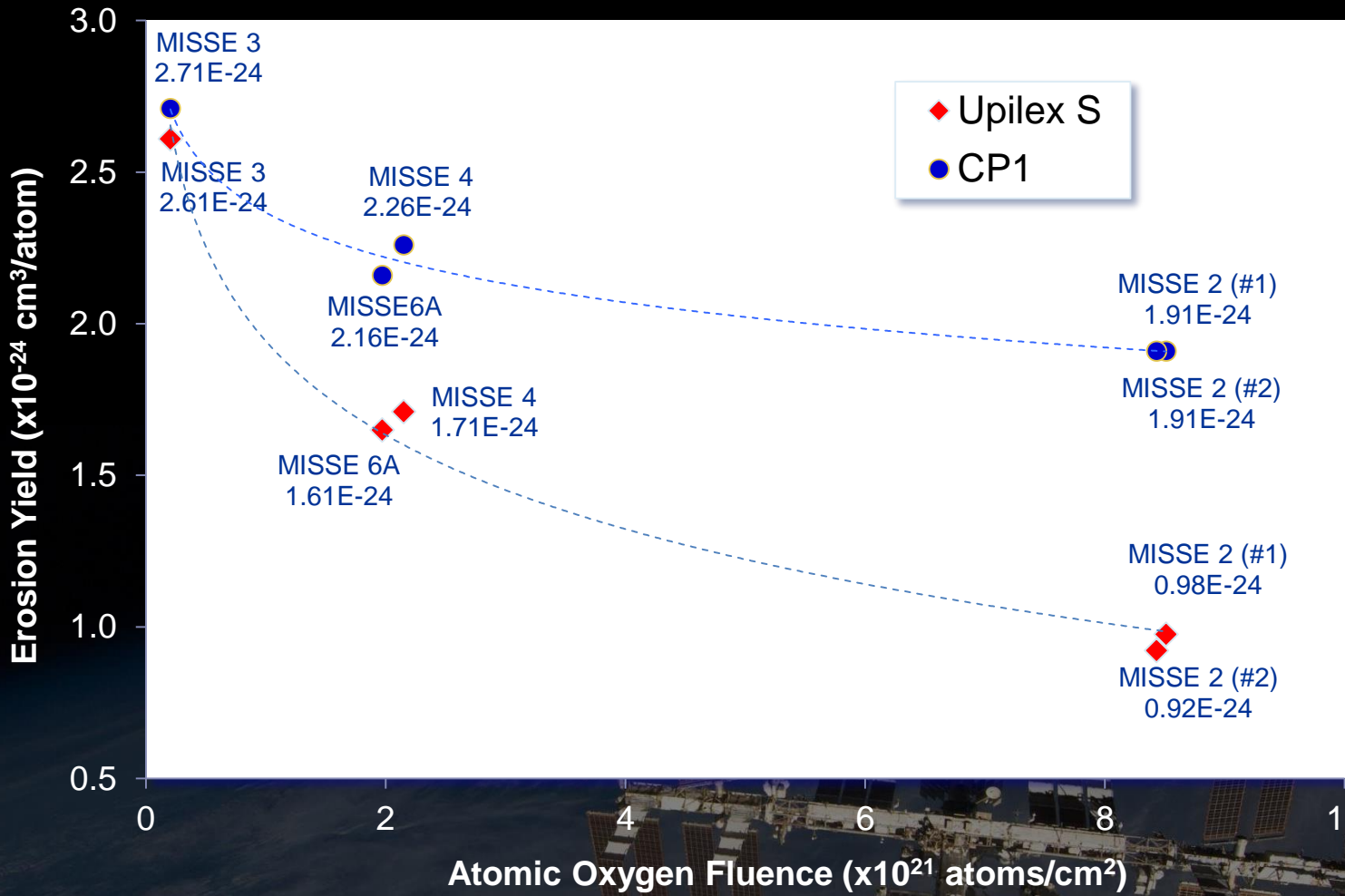
# Stressed Polymers Experiment



**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



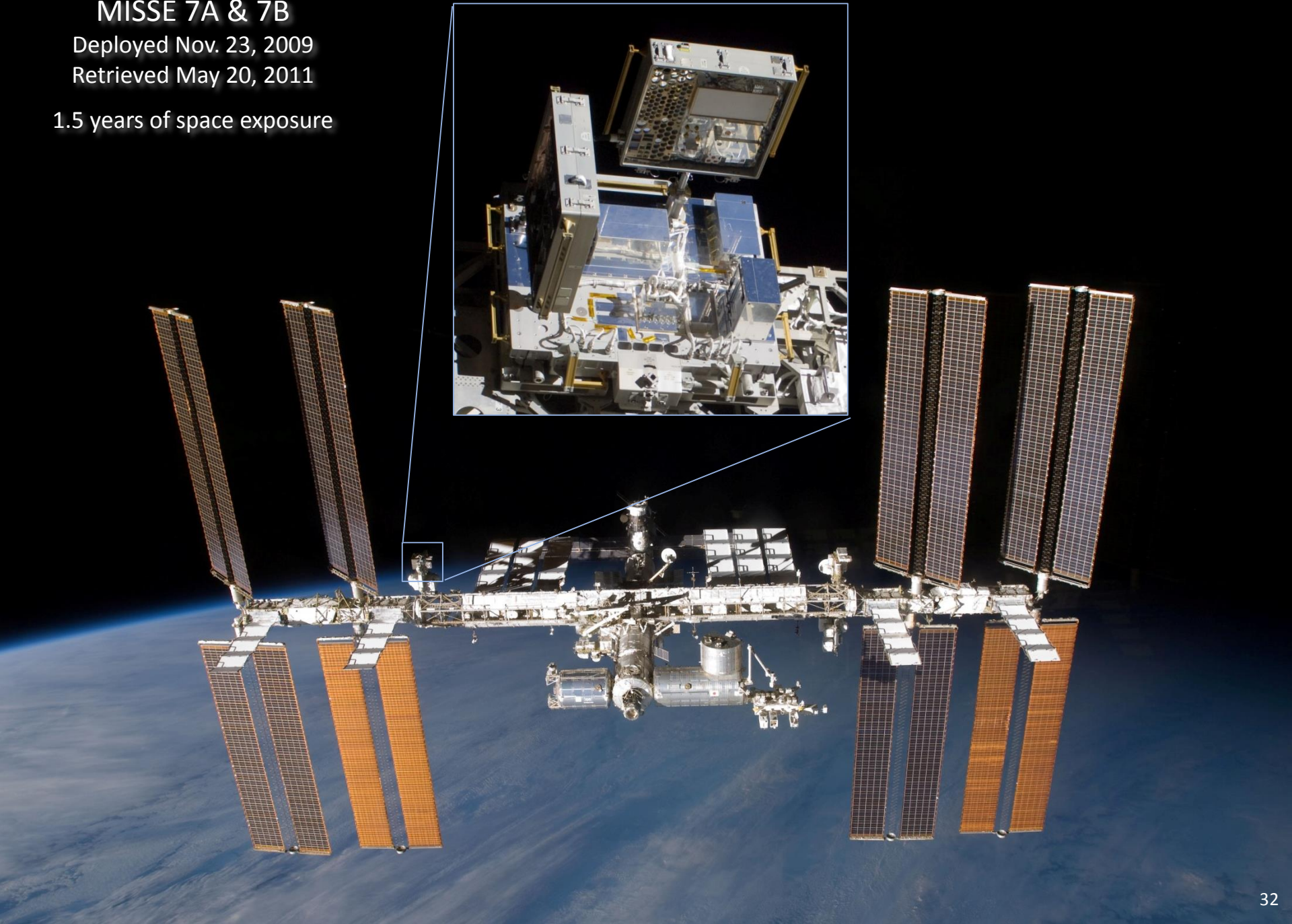
- ⇒ Flying the same polymer on various MISSE missions provides important information on erosion dependence on environmental exposure
- ⇒ One objective of MISSE-9 PCE is to obtain  $E_y$  vs. AO fluence data for additional spacecraft polymers

# MISSE 7A & 7B

Deployed Nov. 23, 2009

Retrieved May 20, 2011

1.5 years of space exposure



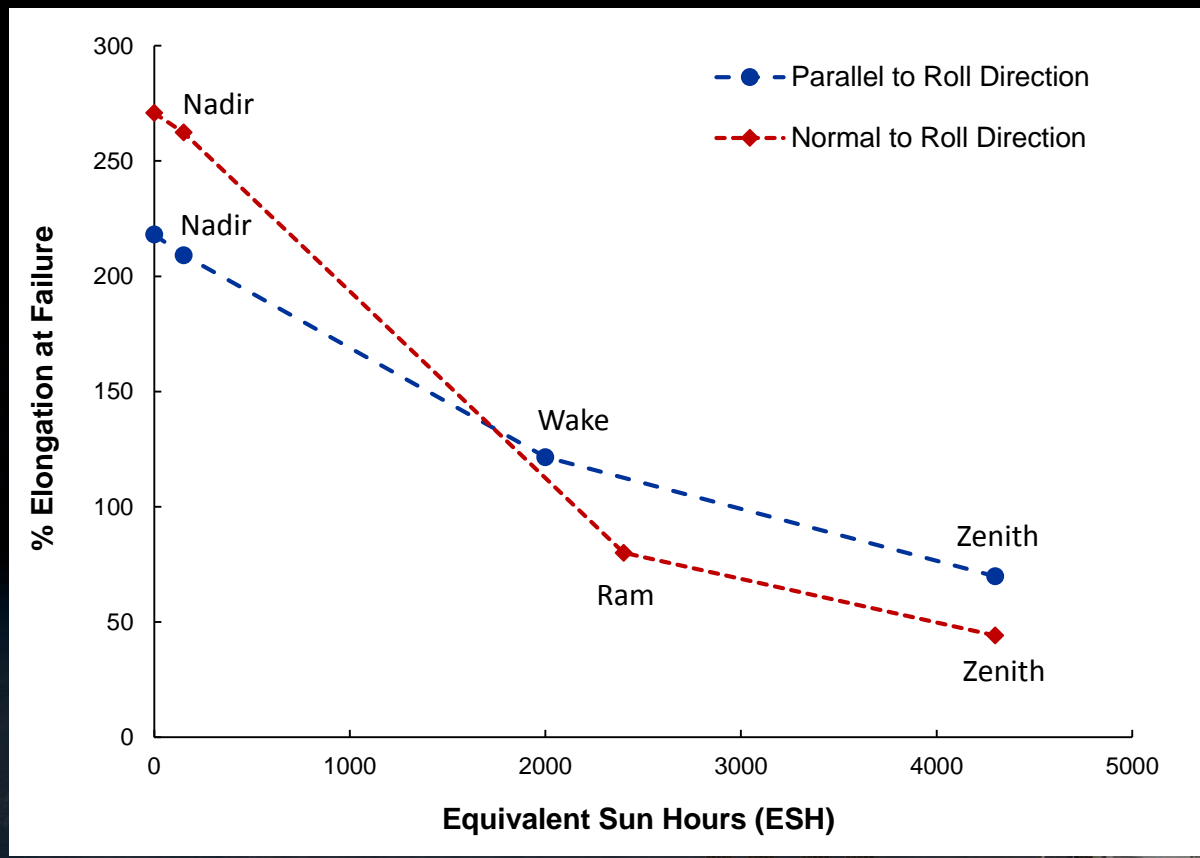
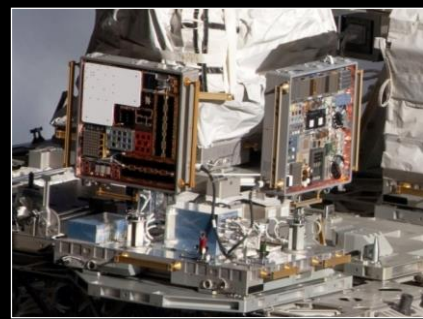




# MISSE 7

## AI-FEP

### % Elongation at Failure vs. Environmental Exposure



**Nadir**  
 150 ESH\*  
 AO F =  $\sim 1.6 \times 10^{20}$  atoms/cm<sup>2</sup>

**Wake**  
 2,000 ESH  
 AO F =  $2.9 \times 10^{20}$  atoms/cm<sup>2</sup>

**Ram**  
 2,400 ESH  
 AO F =  $4.2 \times 10^{21}$  atoms/cm<sup>2</sup>

**Zenith**  
 4,300 ESH  
 AO F =  $1.6 \times 10^{20}$  atoms/cm<sup>2</sup>

AI-FEP: Aluminized-Teflon fluorinated ethylene propylene

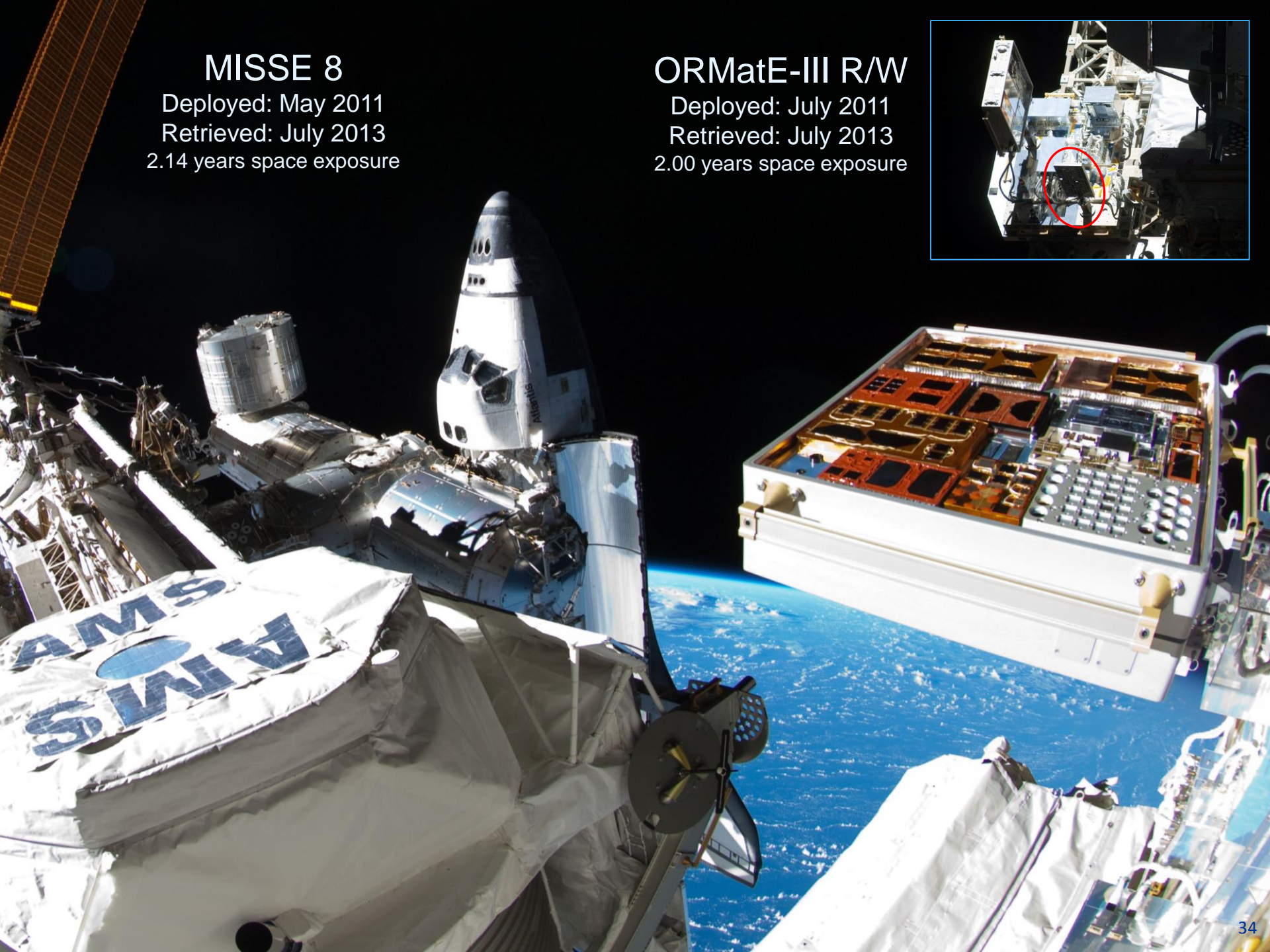
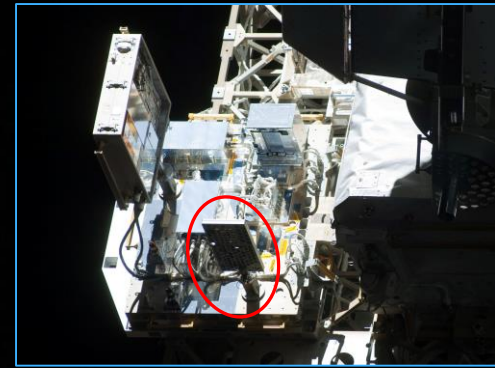
\*Nadir ESH was estimated at 150 ESH (no direct solar exposure, albedo reflected only)

## MISSE 8

Deployed: May 2011  
Retrieved: July 2013  
2.14 years space exposure

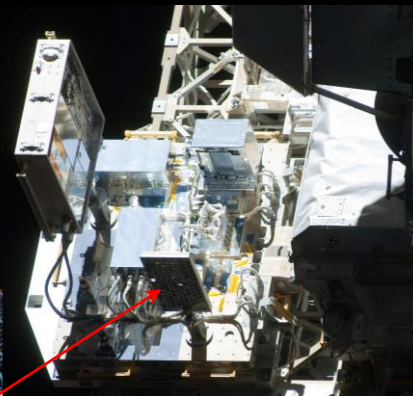
## ORMatE-III R/W

Deployed: July 2011  
Retrieved: July 2013  
2.00 years space exposure



# MISSE 8

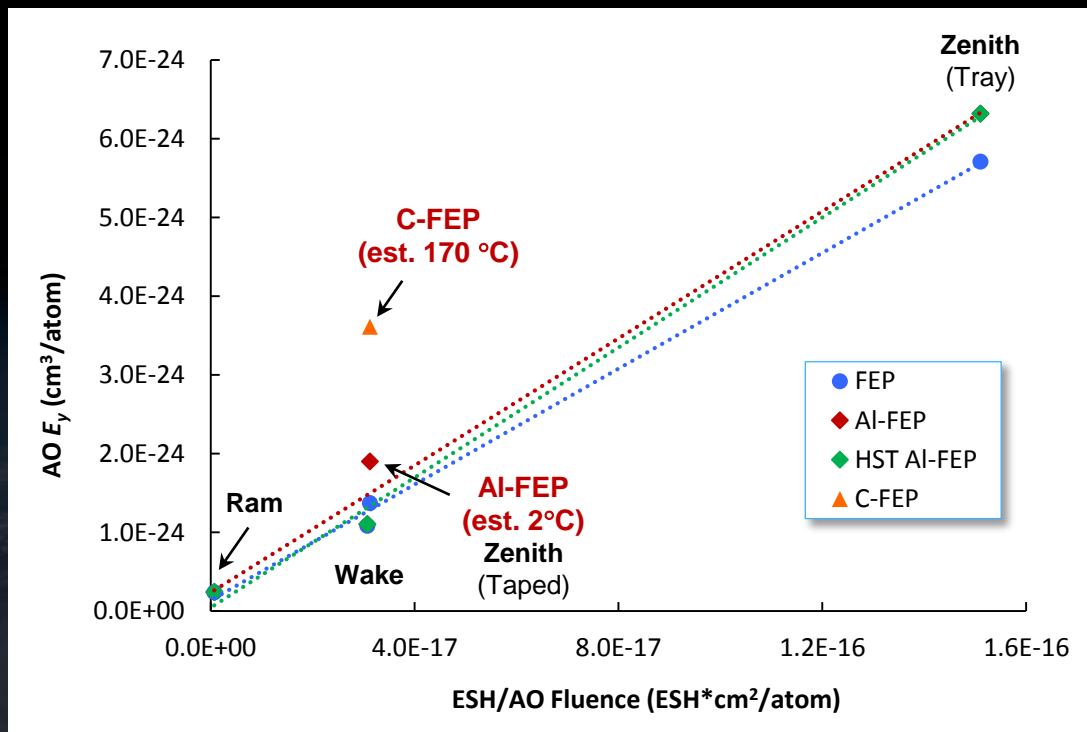
## Teflon FEP AO $E_y$ vs. Equivalent Sun Hours (ESH)/AO Fluence



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°C) has a significantly higher  $E_y$  than Al-FEP (2°C) for the same exposure:
  - Heating has a major impact on the  $E_y$  of FEP in the zenith orientation

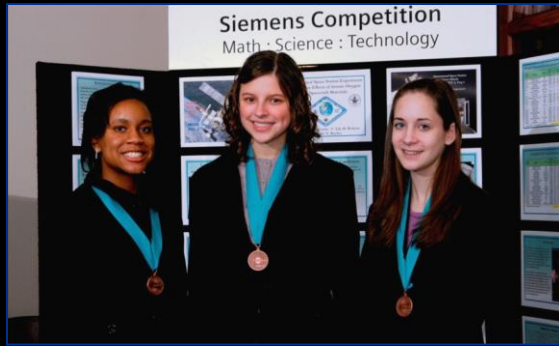


FEP: Fluorinated ethylene propylene  
C-FEP: Carbon back-surface painted FEP

Al-FEP: Aluminized-Teflon FEP  
HST Al-FEP: Hubble Space Telescope retrieved Al-FEP



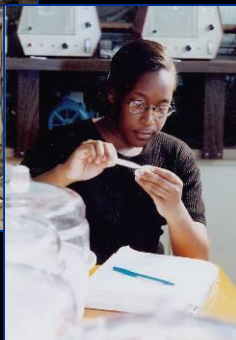
# NASA Glenn Research Center and Hathaway Brown School (HB) Collaborative MISSE Experiments



Siemen's Regional Winners & National Finalists



PEACE Team examining Glenn's MISSE 6 Stressed Polymers Experiment post-flight



## Student Involvement:

- 3 to 6 students worked on the MISSE "PEACE" team at a time (*31 students involved between 1998-2018*)
- Students worked at Glenn 7 wks full time each summer, plus 1 day per week after school in the school year
- Students research included:
  - MISSE pre-flight research
  - MISSE 2, 5-8 flight sample fab. & pre-flight characterization
  - MISSE 2, 5-8 post-flight characterization

## Benefits:

- Glenn gains technical collaboration
- Students gain technical knowledge & confidence
- Students graduate w/ publications & presentation experience
  - *Students have given presentations and won poster competition awards at international space conferences*
- Scholarships & fellowships (>\$80K from science fair awards)



# PEACE Team Presentations

## National & International Space Conferences



### Protection of Materials and Structures from Space Environment (ICPMSE-9), May 2008, Toronto, Canada

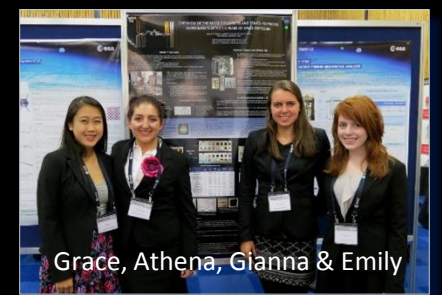
- Sophomores Arielle Stambler & Karen Inoshita presented "Ground-Laboratory to In-Space Atomic Oxygen Correlation for the Polymer Erosion and Contamination Experiment (PEACE) Polymers" as an oral presentation



Aobo & Claire

### 10th Int'l Space Conference, Protection of Materials and Systems from Space Environment (ICPMSE-10J), June 2011, Okinawa, Japan

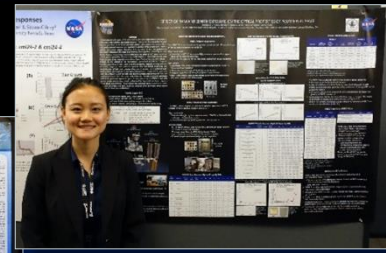
- Sophomores Grace Yi & Gianna Mitchell presented "Embrittlement of MISSE 5 Polymers After 13 Months of Space Exposure" as an oral & a poster presentation
- Jr. Claire Ashmead and Sr. Aobo Guo "Effect of Solar Exposure on the AO Erosion of Hubble Space Telescope Aluminized-Teflon Thermal Shields" as an oral presentation



Grace, Athena, Gianna & Emily

### 12th International Symposium on Materials in the Space Environment (ISMSE-12), Sept. 2012, Noordwijk, the Netherlands

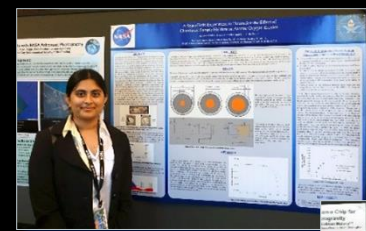
- Srs. Grace Yi & Gianna Mitchell, Jr. Athena Haloua and soph. Emily Imka presented "Overview of the MISSE 7 Polymers and Zenith Polymers Experiments after 1.5 Years of Space Exposure" as a poster presentation
- Poster awarded **2nd place** in Poster Competition for "Under 30" age group



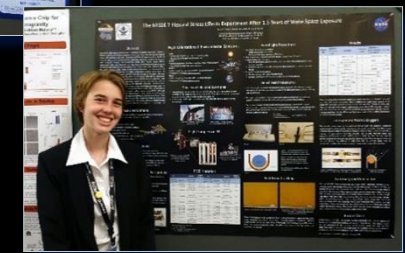
Joyce at 2017 ISSR&DC

### International Space Station Research & Development Conference (ISSR&DC), July 2017, Washington D.C.

- Sr. Yuanchun "Joyce" Li presented "Effect of Ram and Zenith Exposure on Optical Properties the of Polymers in Space" as a poster presentation
- Sr. Kate Snow presented "The MISSE 7 Flexural Stress Effects Experiment After 1.5 Years of Wake Space Exposure" as a poster presentation
- Sr. Kshama Girish presented "A Spaceflight Experiment to Determine the Effect of Chamfered Sample Holders on Atomic Oxygen Erosion" as a poster presentation



Kshama at 2017 ISSR&DC



Kate at 2017 ISSR&DC



# MISSE Students - Honors & Awards National & International Science Fair Competitions



## Intel International Science & Engineering Fair (ISEF):

- 54<sup>th</sup> ISEF, Cleveland (May 2003): **\$60,000 Scholarship Award**
  - *“Space Flight Experiments to Evaluate Atomic Oxygen Erosion and Ultraviolet Radiation Damage to Man-made Materials in Low Earth Orbit”*
- 56<sup>th</sup> ISEF, Phoenix (May 2005): **Finalists**
  - *“Analysis of Hubble Space Telescope Multilayer Insulation Following Long Term Exposure in Space Environment”*
- 61<sup>st</sup> ISEF\*, Phoenix (May 2010): **4<sup>th</sup> Place Grand Award (Earth and Planetary Science)**
  - *“Effect of Solar Exposure on the Atomic Oxygen Erosion of Hubble Space Telescope Bi-Stem Thermal Shield Aluminized-Teflon FEP”*



Maura, Chris & Allison  
at the 54th ISEF



Catherine, Allison & Sharon  
with astronaut Sally Ride  
at the 56th ISEF

## Siemens Math Science and Technology Competition

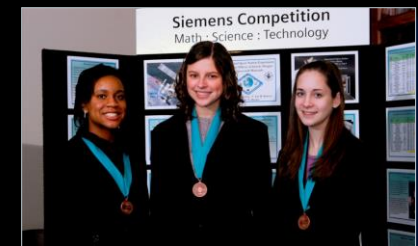
- 2002-2003, U. of Notre Dame, November 2002: **National Regional Finalists**
  - *“Space Flight Experiments to Measure Polymer Erosion and Silicone Contamination; Five-year Project”*
- 2005-2006: **Regional Semifinalists**
  - *“Analysis of Hubble Multilayer Insulation Following Long Term Exposure to LEO”*
- 2006-2007: **Midwest Regional Winners & \$10,000 National Winners**
  - *“International Space Station Experiment to Measure Effects of Atomic Oxygen on Spacecraft Materials”*
- 2008-2009: **Regional Semifinalists**
  - *“Ground Laboratory to In-Space Atomic Oxygen Correlation for the Polymer Erosion and Contamination Experiment (PEACE) Polymers”*
- 2009-2010: **Regional Semifinalists**
  - *“Effect of Solar Exposure on the Atomic Oxygen Erosion of Hubble Space Telescope Bi-Stem Thermal Shield Aluminized-Teflon FEP”*
- 2015: **Regional Semifinalists**
  - *“The Effect of 1.5 Years of Space Exposure on the Optical Properties of Spacecraft Polymers”*



Maura, Laura & Chris  
2002 National Regional Finalists



Claire & Aobo  
ISEF 4<sup>th</sup> Place Grand  
Award



Siemens' **Regional Winners  
& National Finalists**



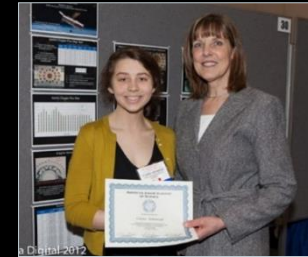
# MISSE Students - Honors & Awards Ohio Academy of Science (OAS) & American Junior Academy of Science (AJAS)



OAS Annual Meeting, Ada, OH, April 2010

AJAS Meeting/American Assoc. for the Advancement of Science (AAAS) Conference, Washington, D.C., Feb. 2011 & AJAS Meeting, Vancouver, Canada, Feb. 2012

- *"Effect of Solar Exposure on the Atomic Oxygen Erosion of Hubble Space Telescope Bi-Stem Thermal Shield Aluminized-Teflon FEP"*
- Aobo Guo & Claire Ashmead selected as *Melvin Scholars*, invited to present at 2011 & 2012 AJAS

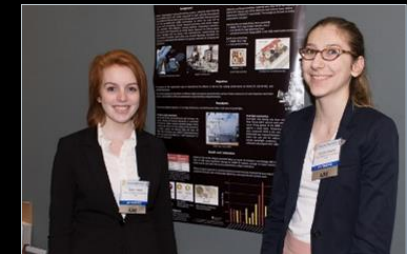


Claire Ashmead at the 2012 AJAS

OAS Annual Meeting, North Canton, OH, April 2014

AJAS Meeting/AAAS Conference, San Jose, CA, Feb. 2015

- *"Leak Rate Determination of Silicone Rubber Elastomer Materials After Space Exposure"*
- Emily Imka & Olivia Asmar selected as *Melvin Scholars*, invited to present at 2015 AJAS



Emily Imka & Olivia Asmar at the 2015 AJAS

OAS Annual Meeting, Columbus, Ohio, April 2015

AJAS Conference/AAAS Conference, Washington D.C., Feb. 2016

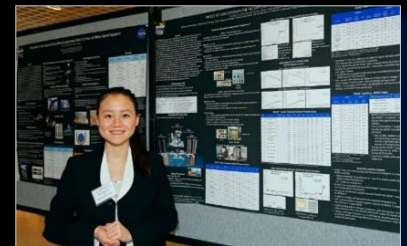
- *"The Effect of 1.5 Years of Space Exposure on Optical Properties of Spacecraft Polymers"*
- Halle Leneghan & Olivia Asmar selected as *Melvin Scholars*, invited to present at 2016 AJAS



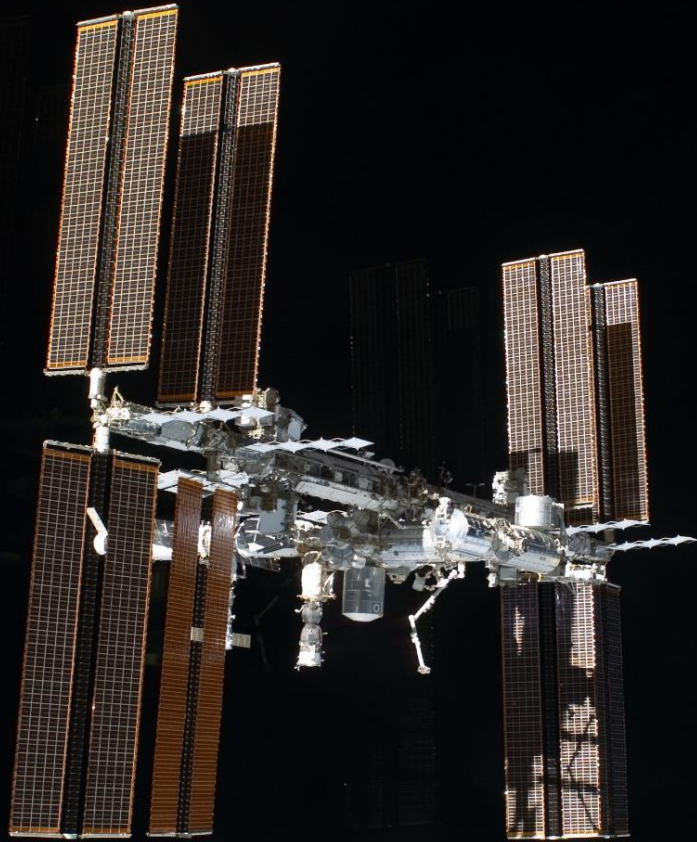
Halle, Olivia and astronaut George Nelson at the 2016 AJAS

OAS Annual Meeting, Cincinnati, Ohio, April 2017

- *"Overview of the Flexural Stress Effects Experiment after 1.5 Years of Wake Space Exposure"* (Kate Snow)
- *"Design of Low Earth Orbit Sample Holders for Determination of Chamfered Edge"* (Kshama Girish)
- *"The Effect of 1.5 Years of Space Exposure on Optical Properties of Spacecraft Polymers"* (Joyce Li)
- Joyce Li selected as a *Melvin Scholar*, invited to present at the 2018 AJAS/AAAS



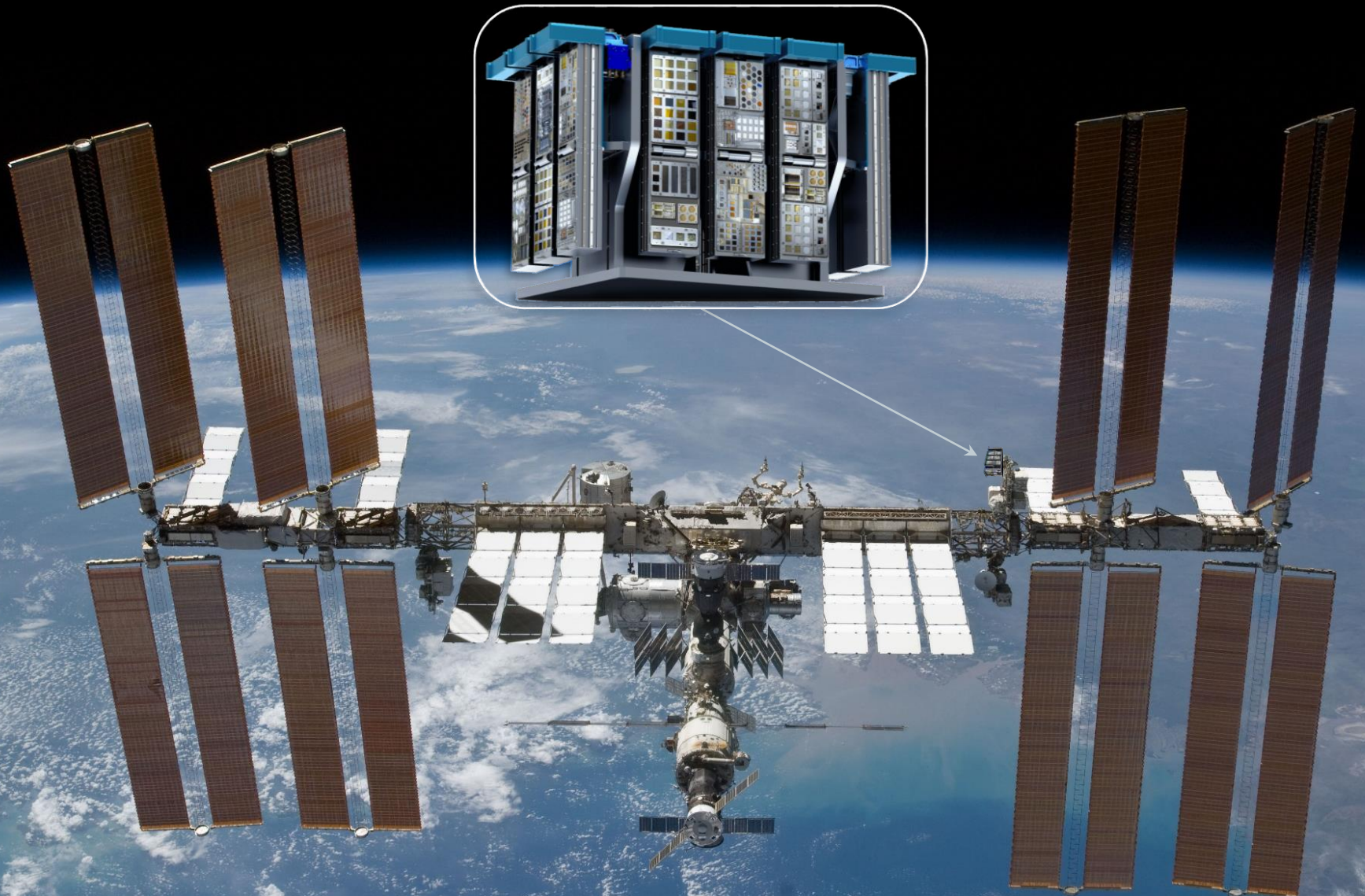
Joyce Li at the 2017 OAS



# ISS Experiments in the Post-Shuttle Era



# MISSE-Flight Facility (MISSE-FF)





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

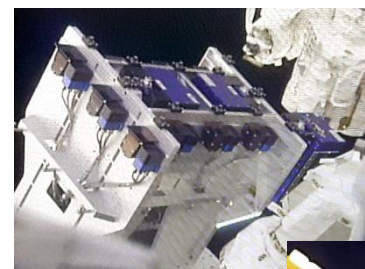


Alpha Space Test & Research Alliance, LLC

- 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 April 19, 2018
  - The **MISSE-10** & **-11** experiments were deployed April 26, 2019
- Modular design allows MISSE Sample Carriers (MSCs) with experiments to be added/replaced at different times
  - MSC duration: 6 months - 1 year
- 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)

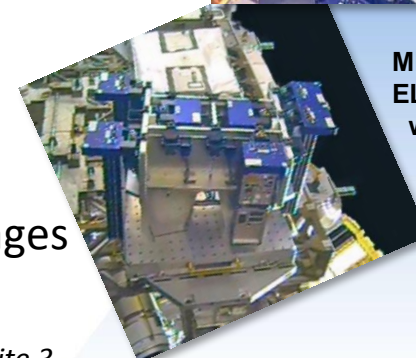


MISSE-FF being moved to ELC-2

Robotic insertion of a MSC



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





# MISSE-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



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 <sub>2</sub> O <sub>3</sub>	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 (Loctite Heavy Duty)	Epoxy	1	0.118	C	1
M9R-C12	2.9% ZnO powder filled epoxy (Loctite)	ZnO-Epoxy	1	0.125	C	1
M9R-C13	6.3% ZnO powder filled epoxy (Loctite)	ZnO-Epoxy	1	0.125	C	1
M9R-C14	9.78% ZnO powder filled epoxy (Loctite)	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 <sub>2</sub>	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 <sub>2</sub> Si <sub>3</sub> O <sub>7</sub> /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

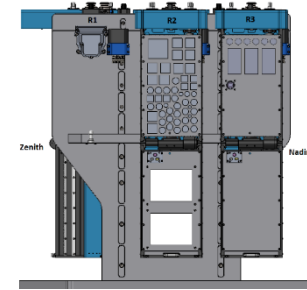
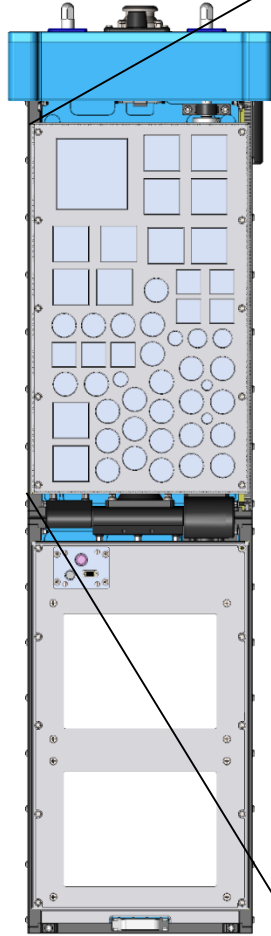
## 39 Samples

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

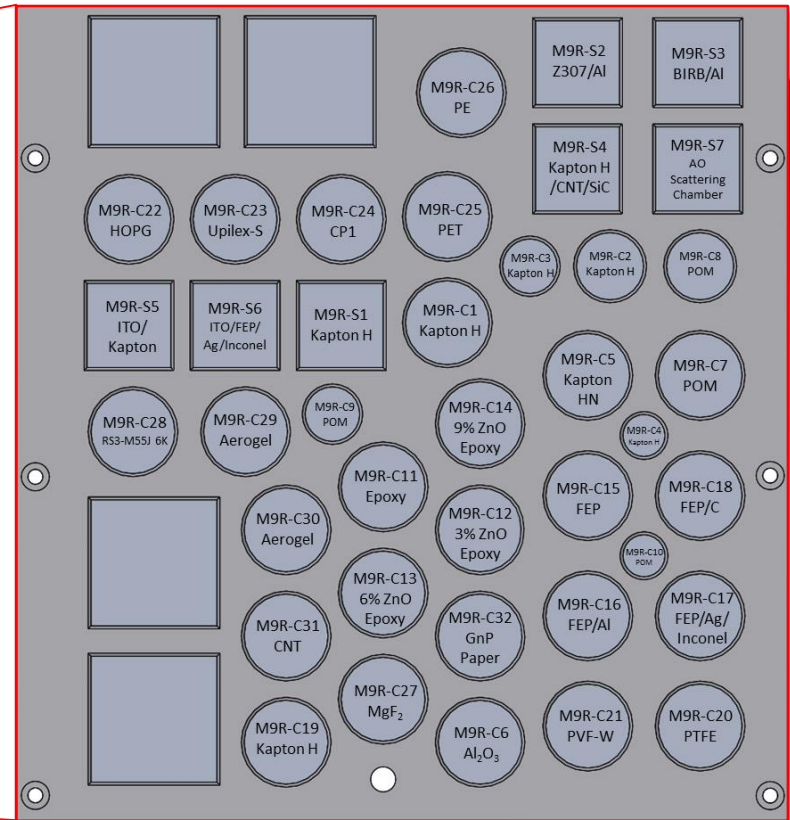


# MISSE-9 PCE Ram Samples

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



MSC R2



R2 mount side deck



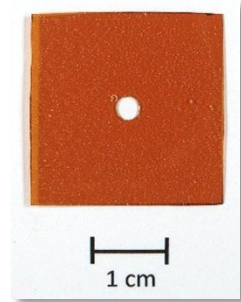
# Overview of PCE Ram Samples

(High AO & moderate solar exposure)



- **Ram Samples:**

- Kapton H for MISSE-9 ram AO fluence determination
- $\text{Al}_2\text{O}_3$  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*
  - *$\text{MgF}_2$*
  - *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 <sub>2</sub> O <sub>3</sub>	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)



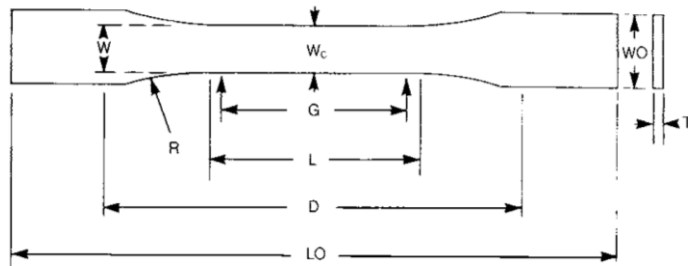
MISSE-9 ID	Material	Abbrev.	Thickness (inch)	Number of Samples
M9W-T1 to T5	Aluminized-Teflon (FEP/Al)* - Parallel	Al-FEP	0.002	5
M9W-T6 to T10	Aluminized-Teflon (FEP/Al)* - Normal	Al-FEP	0.002	5
M9W-T11 to T15	Aluminized-Teflon (FEP/Al)* - Parallel	Al-FEP	0.005	5
M9W-T16 to T20	Aluminized-Teflon (FEP/Al)* - 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

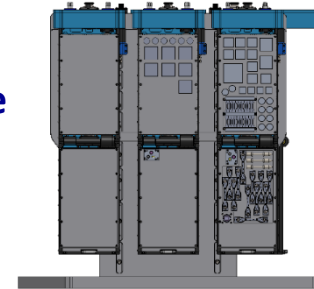
W—Width of narrow section	3.18 mm (0.125 in.)
L—Length of narrow section	9.53 mm (0.375 in.)
WO—Width overall, min	9.53 mm (0.375 in.)
LO—Length overall, min	63.5 mm (2.5 in.)
G—Gage length	7.62 mm (0.300 in.)
D—Distance between grips	25.4 mm (1.00 in.)
R—Radius of fillet	12.7 mm (0.500 in.)



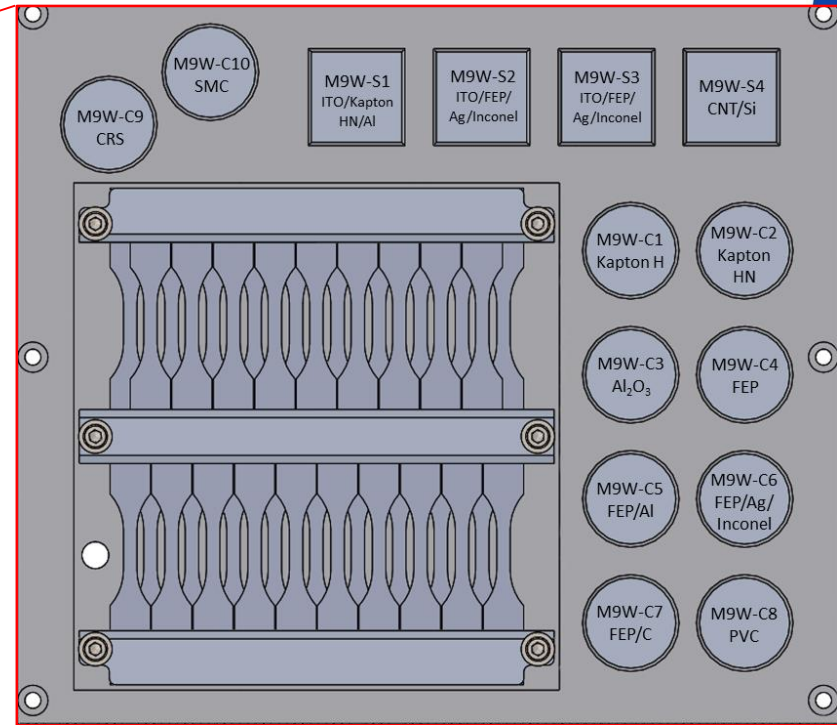
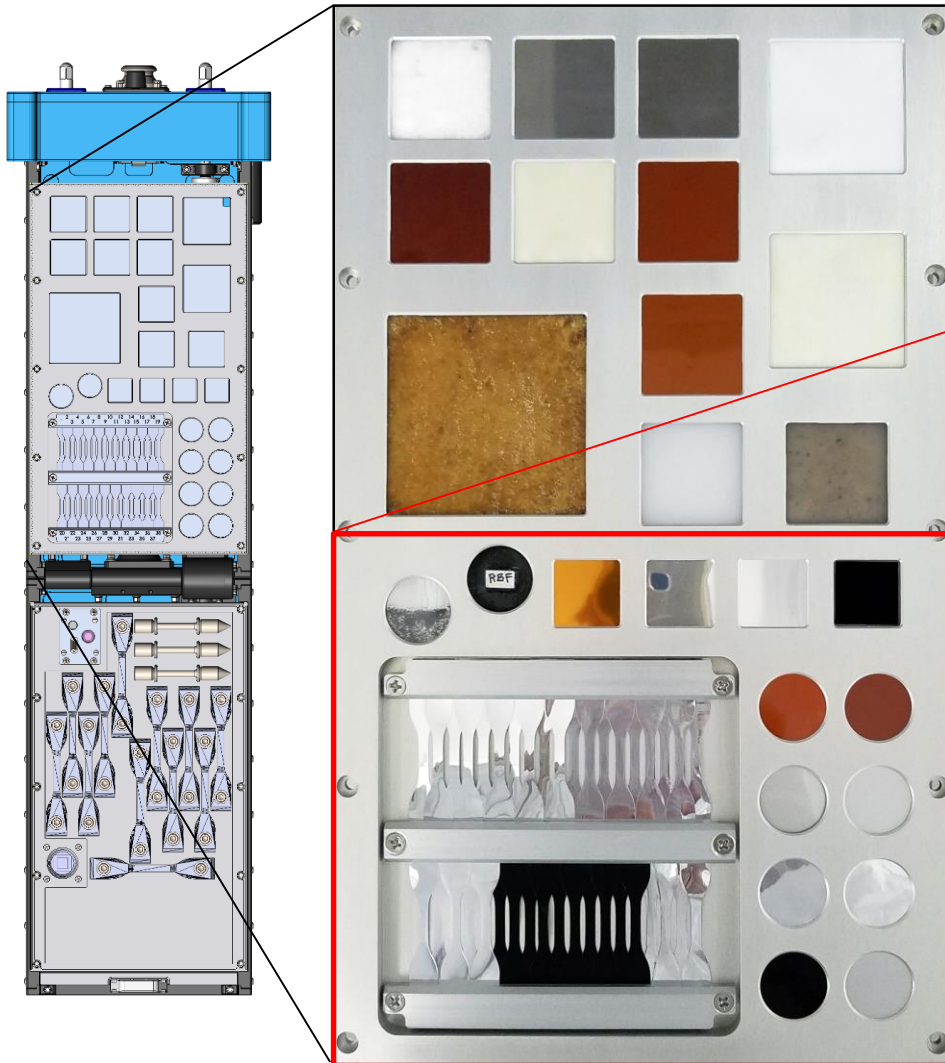


# MISSE-9 PCE Wake Samples

52 samples: 38 tensile & 14 1-inch



**MISSE Sample Carrier (MSC) W3**



**W3 mount side deck**



# 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 <sub>2</sub> O <sub>3</sub>	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 <sub>2</sub>	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)

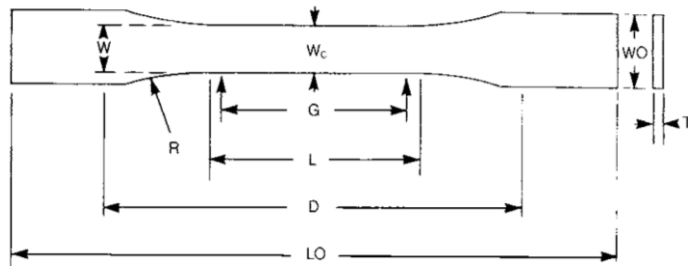


MISSE-9 ID	Material	Abbrev.	Thickness (inch)	Number of Samples
M9Z-T1 to T4	Aluminized-Teflon (FEP/Al)* - Parallel	Al-FEP	0.002	4
M9Z-T5 to T8	Aluminized-Teflon (FEP/Al)* - Normal	Al-FEP	0.002	4
M9Z-T9 to T12	Aluminized-Teflon (FEP/Al)* - Parallel	Al-FEP	0.005	4
M9Z-T13 to T16	Aluminized-Teflon (FEP/Al)* - 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

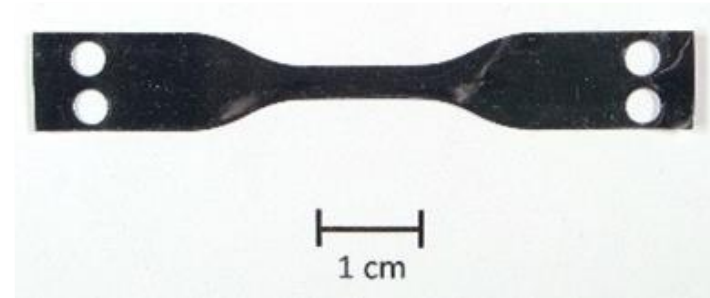
\*FEP is space facing

# Tensile Samples

24



TYPES I, II, III & V



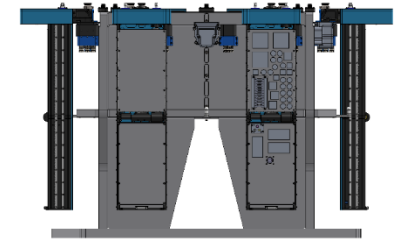
### ASTM D638-08 Type V Specimen Dimensions

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.)

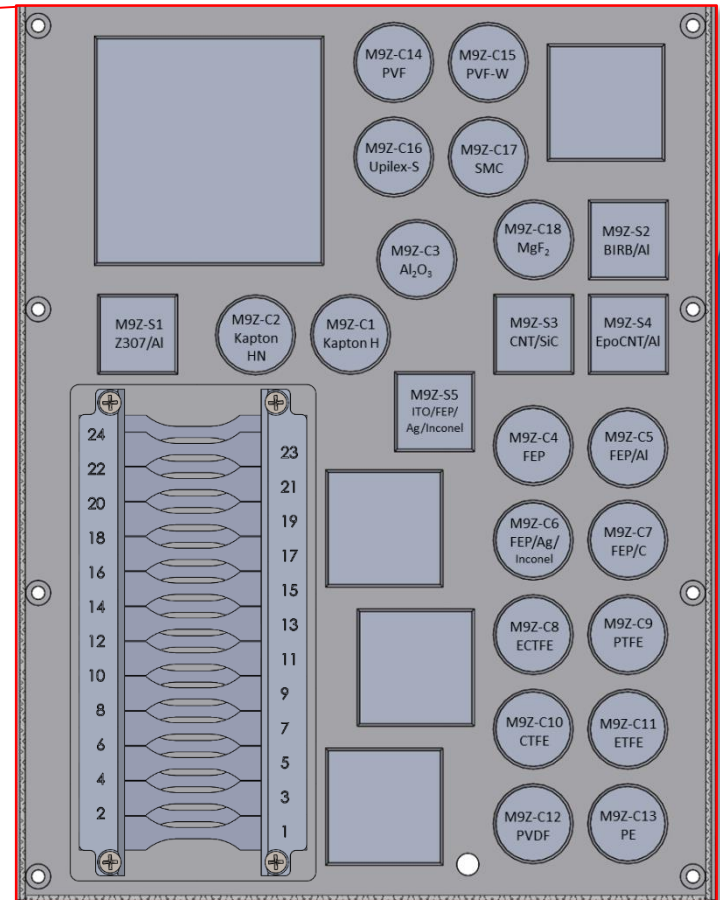
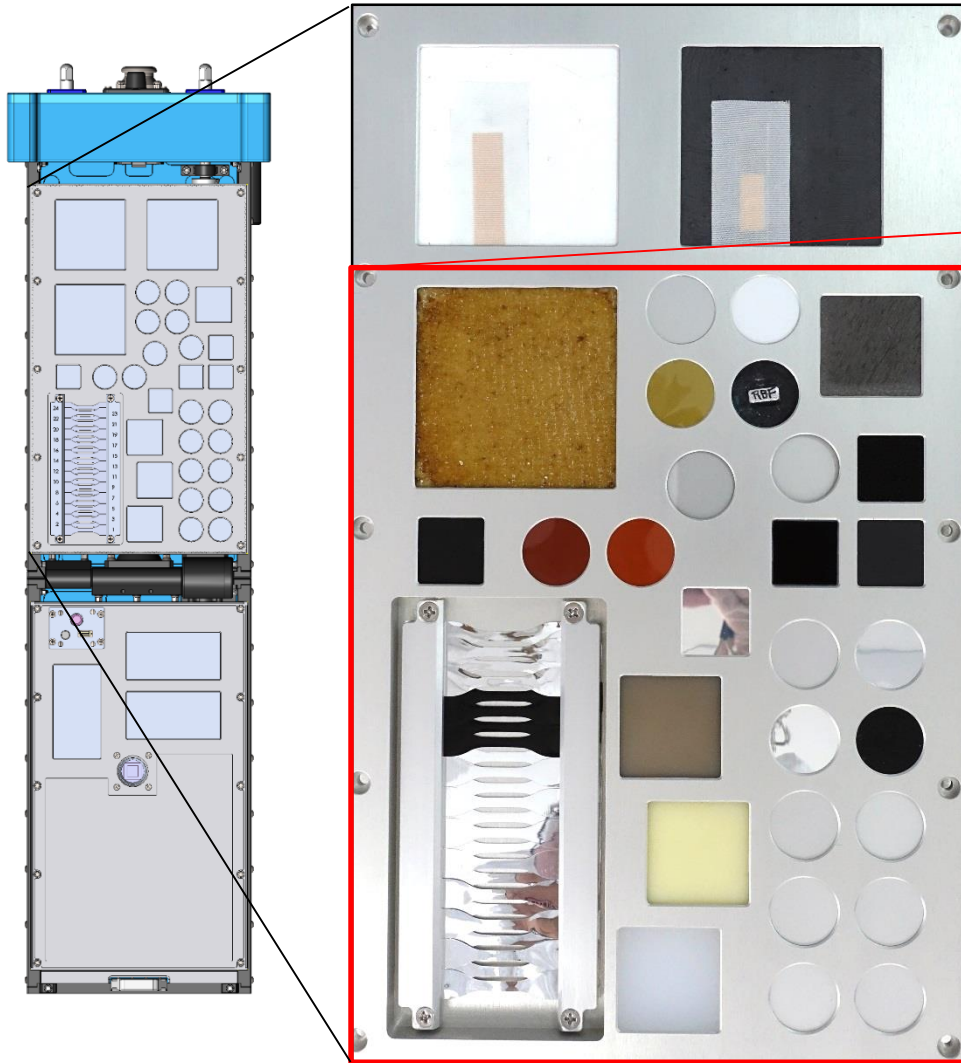


# MISSE-9 PCE Zenith Samples

47 samples: 24 tensile & 23 1-inch



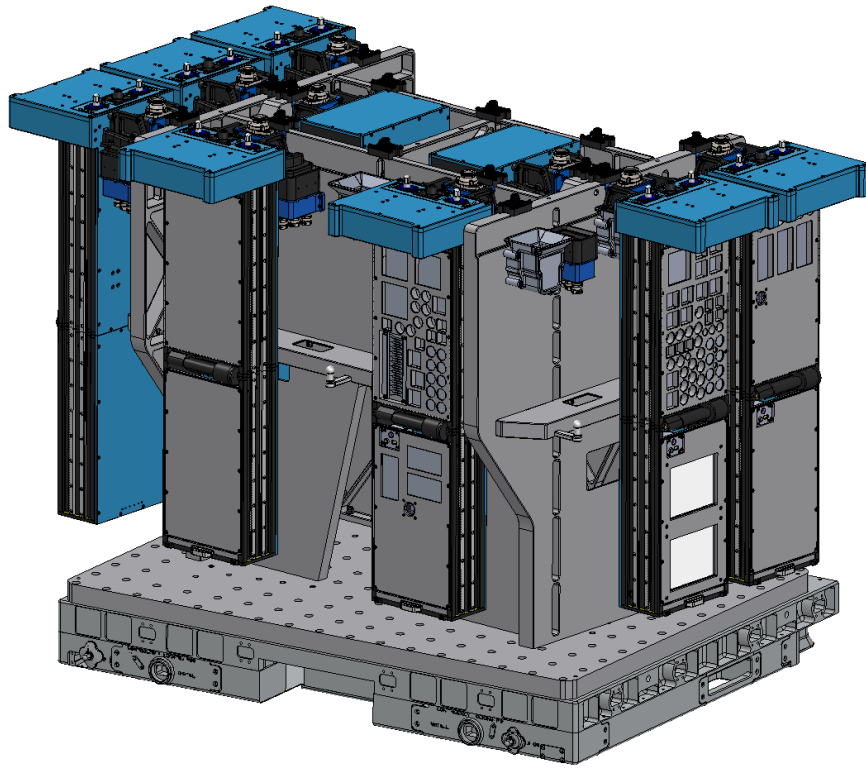
MSC Z3



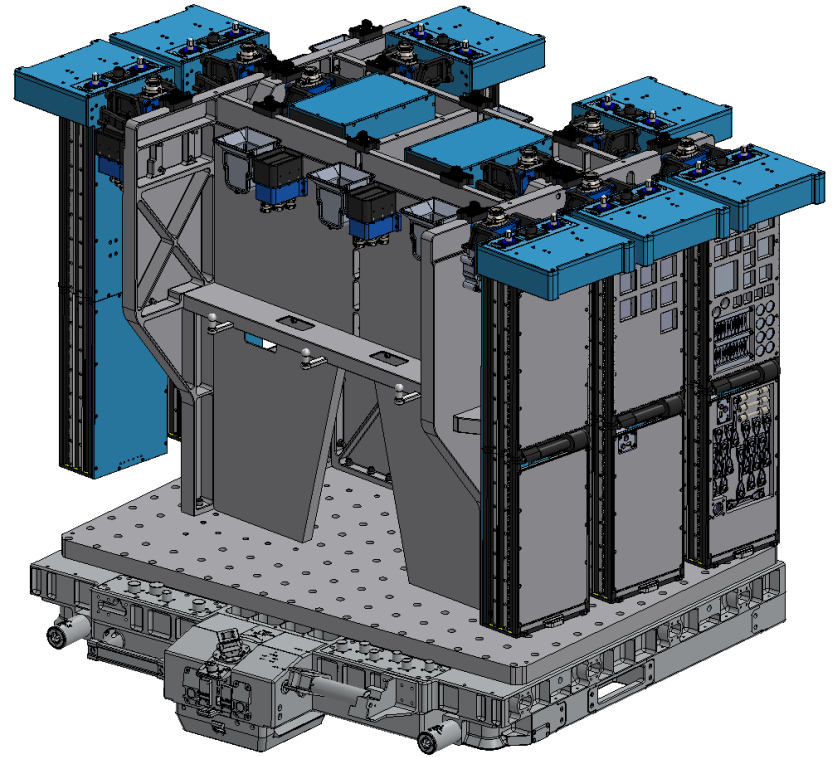
Z3 mount side deck



# MISSE-FF with MISSE Sample Carriers (MSCs)



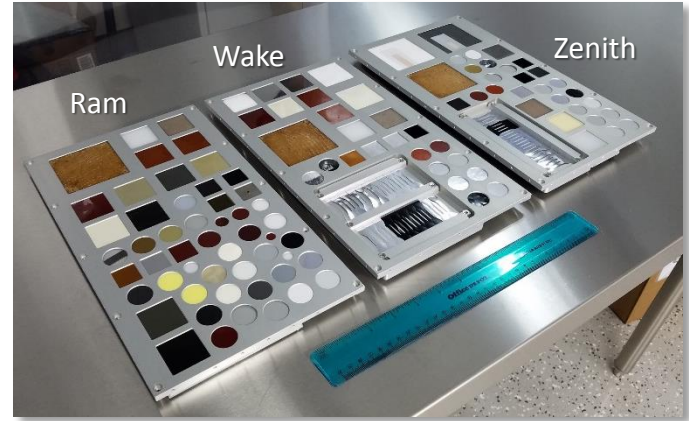
**Ram and Zenith MSCs**



**Wake MSCs**



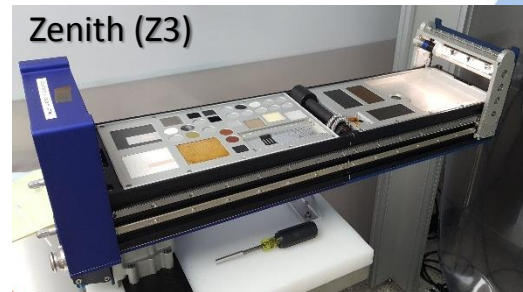
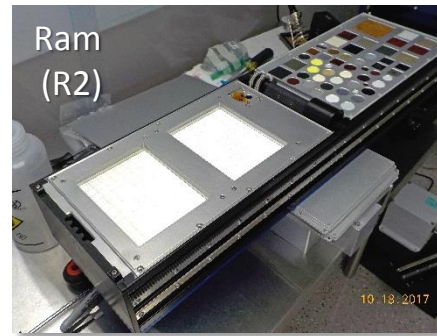
# Polymer and Composites Experiment (PCE) Integration of the PCE samples into the MISSE-9 Decks



R2

W3

Z3



Alpha Space, Houston  
August 4, 2017

Pre-flight full MSC photos courtesy of Alpha Space



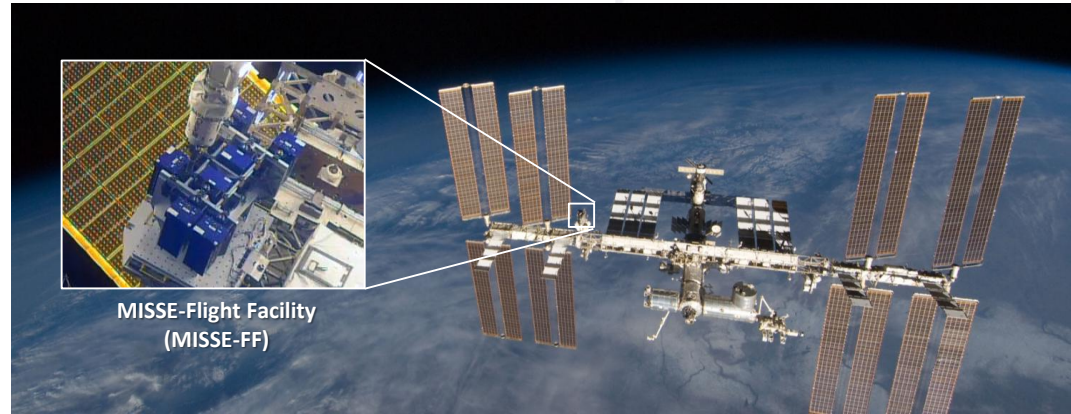
# MISSE-Flight Facility

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

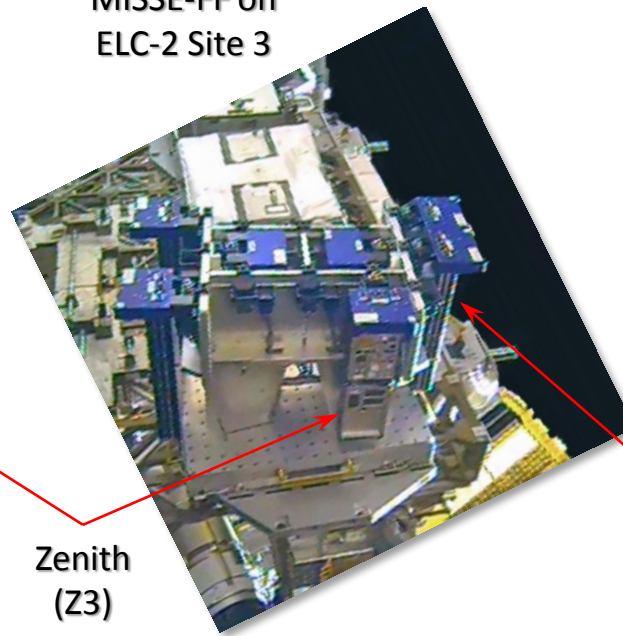


MISSE-FF launched  
aboard SpaceX CRS-14  
on April 2, 2018

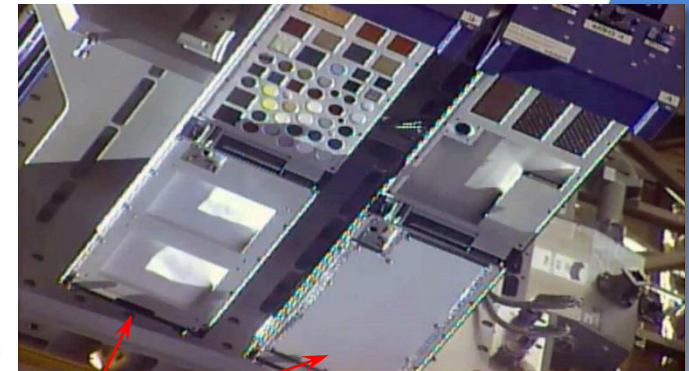
Robotically installed  
on ELC-2 Site 3  
on April 8, 2018



Zenith  
(Z3)



MISSE-FF on  
ELC-2 Site 3



Ram  
(R2 & R3)



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



Pre-flight Image



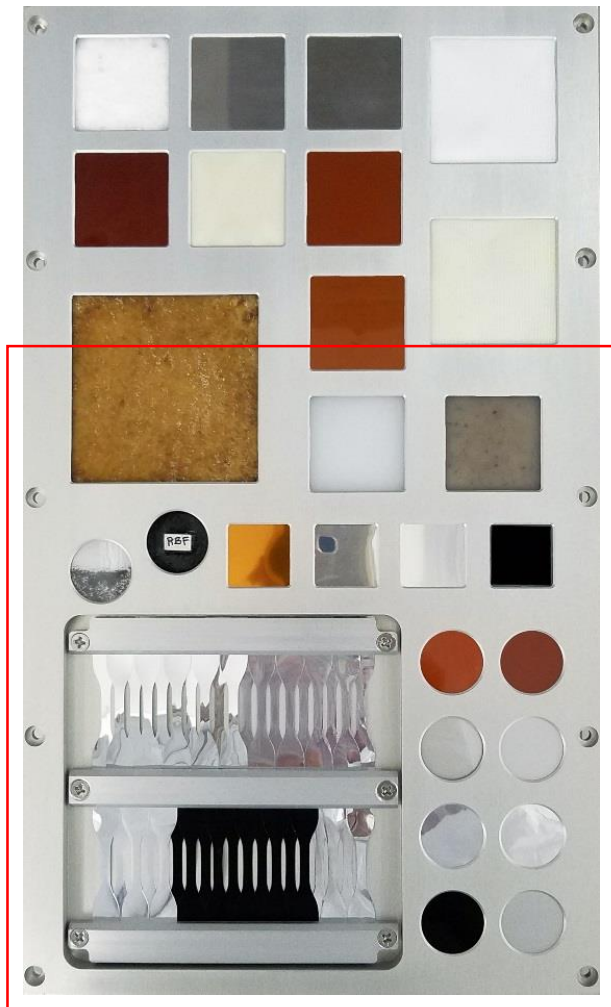
On-Orbit Image Composite



On-orbit images taken April 23, 2018



# MISSE-9 PCE Wake Samples On-orbit Images 9-24-18

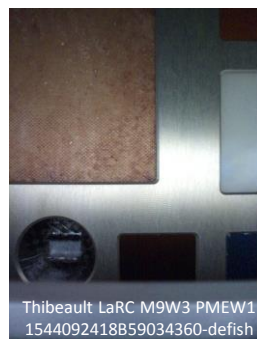


Pre-flight Photograph of the M9 W3 Deck

On-orbit sample photos courtesy of NASA and Alpha Space



Thibeault LaRC M9W3 PMEW1  
1544092418A59034360-defish



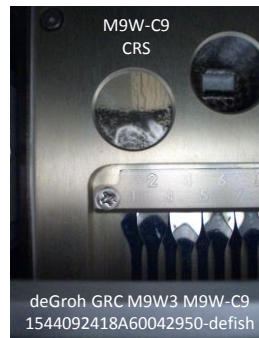
Thibeault LaRC M9W3 PMEW1  
1544092418B59034360-defish



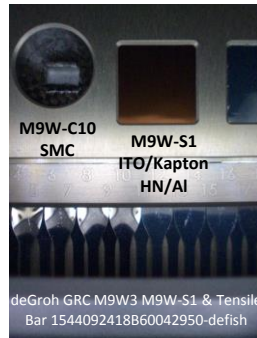
Thibeault LaRC M9W3 PMEW2  
1544092418C59034360-defish



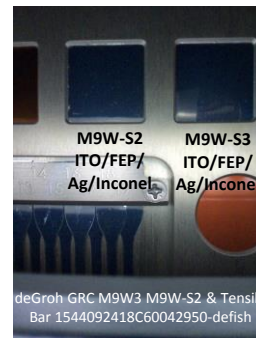
Thibeault LaRC M9W3 PMEW3  
1544092418D59034360-defish



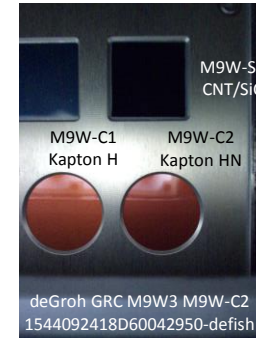
deGroh GRC M9W3 M9W-C9  
1544092418A60042950-defish



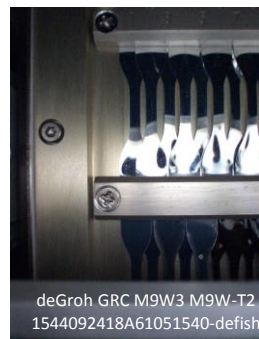
deGroh GRC M9W3 M9W-S1 & Tensile  
Bar 1544092418B60042950-defish



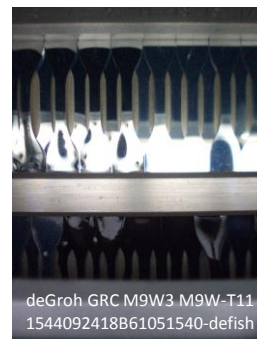
deGroh GRC M9W3 M9W-S2 & Tensile  
Bar 1544092418C60042950-defish



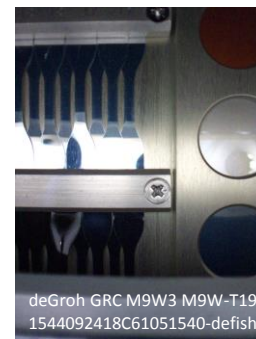
deGroh GRC M9W3 M9W-C2  
1544092418D60042950-defish



deGroh GRC M9W3 M9W-T2  
1544092418A61051540-defish



deGroh GRC M9W3 M9W-T11  
1544092418B61051540-defish



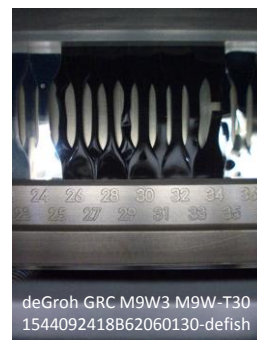
deGroh GRC M9W3 M9W-T19  
1544092418C61051540-defish



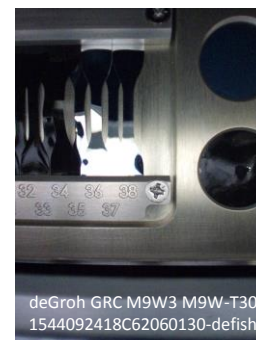
deGroh GRC M9W3 M9W-C4  
1544092418D61051540-defish



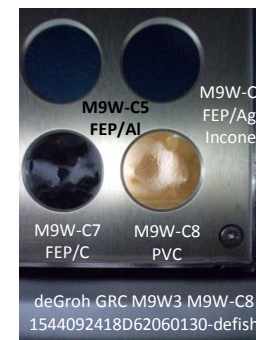
deGroh GRC M9W3 M9W-T20  
1544092418A62060130-defish



deGroh GRC M9W3 M9W-T30  
1544092418B62060130-defish



deGroh GRC M9W3 M9W-T30  
1544092418C62060130-defish



deGroh GRC M9W3 M9W-C8  
1544092418D62060130-defish



# Polymer and Composites Experiment (PCE) Wake (W3) On-Orbit Images

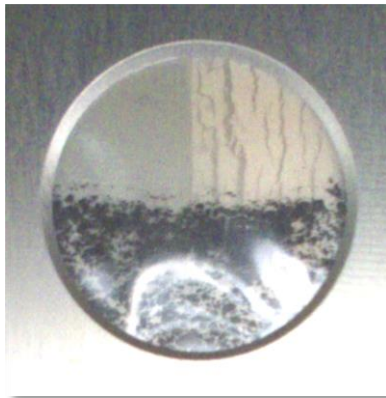


## On-Orbit Sample Darkening

**M9W-C9**  
Cosmic Ray  
Shielding (CRS)  
On-orbit



4-23-18

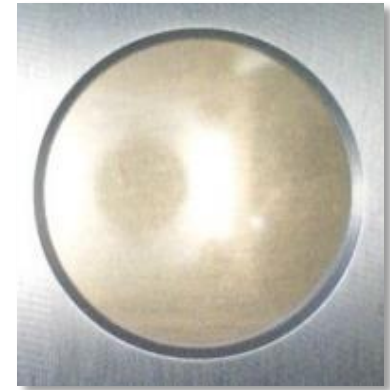


12-26-18

Pre-flight W3 Deck Image



**M9W-C8**  
Polyvinyl chloride  
(PVC)  
On-Orbit



4-23-18



12-26-18

M9W-C9

M9W-C8



# Polymer and Composites Experiment (PCE)

## Wake (W3) On-Orbit Images



Pre-flight  
W3 Deck Image

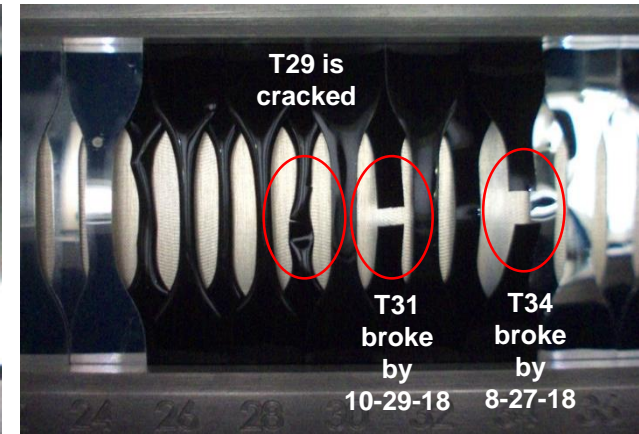


On-orbit  
image area

7-25-18 On-orbit Image  
Wake samples are  
**NOT broken**



12-26-18 On-orbit Image  
M9W-T31 and M9W-T34  
**are BROKEN!**



- Wake tensile sample M9W-T34 (carbon back-surface painted 5 mil Teflon FEP (FEP/C)) broke on-orbit after  $\leq 5$  months of space exposure
- M9W-T31 (5 mil FEP/C) broke after  $\leq 7$  months of space exposure & M9W-T29 (2 mil FEP/C) is cracked
- The black coating causes the sample to passively heat to a higher temperature than corresponding aluminized-Teflon (FEP/Al) samples
  - *The higher on-orbit temperature causes a synergistic effect that increases the radiation-induced embrittlement of Teflon FEP in LEO*



# MISSE-10

## Polymers and Composites Experiment-2 (PCE-2)

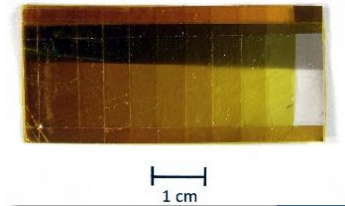


**Principal Investigator (PI):** Kim de Groh (GRC)

**Collaborators:** Bruce Banks (SAIC/GRC), Loredana Santo (U. of Rome “Tor Vergata”), Fabrizio Quadrini (U. of Rome “Tor Vergata”) & Jin Ho Kang (NIA/LaRC)

### Primary Objectives:

1. Determine the low Earth orbit (LEO) atomic oxygen (AO) erosion yield ( $E_y$ ) of spacecraft polymers, composites and coated samples as a function of solar irradiation and AO fluence
2. Determine optical and thermal property degradation of spacecraft polymers in LEO
3. Determine AO fluence and contamination for MISSE-10 ram, zenith & nadir orientations
4. Use the flight data to improve AO predictive models (erosion and scattering)
5. Document the flight data, and provide for archiving in the MISSE MARTIS database



M10R-R1AO Photo Monitor

### Experiment Description:

- Passive experiment with 43 samples flown in ram, zenith & nadir orientations
  - 21 Ram, 10 Zenith & 12 Nadir
- Pre-flight & post-flight data will be measured in ground-facilities



M10N-C4 90° Kapton (Au & NaCl)

### Expected Results:

- AO fluence and contamination data in ram, zenith & nadir directions (also AO fluence vs. time in ram direction)
- LEO  $E_y$  values as a function of AO fluence, solar irradiation & sample holder design
- AO scattering characteristics (relevant to AO undercutting and “reflected” erosion degradation)
- Changes in optical & thermal properties, and functionality



# MISSE-10 Ram Samples

## 21 Samples: 20 – 1" Circular (C) & 1 Rectangular (R)



MISSE-10 ID	Material	Abbreviation	Thickness (mils)	# Layers	Total Thickness (inch)	C or R	Size (Inch)
M10R-C1	Polyimide (PMDA) (Kapton H) - 45° chamfer (Std)	Kapton H	5	2	0.010	C	1
M10R-C2	Polyimide (PMDA) (Kapton H) - 30° chamfer edge	Kapton H	5	2	0.010	C	1
M10R-C3	Polyimide (PMDA) (Kapton H) - 60° chamfer edge	Kapton H	5	2	0.010	C	1
M10R-C4	Alumina slide	Al <sub>2</sub> O <sub>3</sub>	63	1	0.063	C	1
M10R-C5	Au/Polyoxymethylene (Delrin acetal) - Scratched	Au/POM	10	1	0.010	C	1
M10R-C6	Al/Kapton H - Scratched vertically & horizontally	Al/Kapton H	5	1	0.005	C	1
M10R-C7	Polyimide (PMDA) (Kapton HN)	Kapton HN	5	2	0.010	C	1
M10R-C8	Fluorinated ethylene propylene (Teflon FEP)	FEP	5	1	0.005	C	1
M10R-C9	Aluminized-Teflon (FEP/Al)*	FEP/Al	5	1	0.005	C	1
M10R-C10	Teflon FEP clad carbon paint (India Ink) (FEP/C/FEP)*	FEP/C/FEP	14	1	0.014	C	1
M10R-C11	Polyethylene naphthalate (PEN)	PEN	2.95	2	0.006	C	1
M10R-C12	Metallized Polyethylene naphthalate (PEN) film (Al (100 nm)/PEN (2 micron)/black Cr (15 nm)) with Kapton ring	Al/PEN/Bk Cr (M-PEN)	0.083	2	0.000	C	1
M10R-C13	Crystalline polyvinyl fluoride w/white pigment (white Tedlar)	PVF-W	2	1	0.002	C	1
M10R-C14	Polyimide (BPDA) (Upilex-S)	Upilex-S	1	2	0.002	C	1
M10R-C15	Scattering chamber with salt-sprayed POM lid	S.C.	275	1	0.275	C	1
M10R-C16	Scattering chamber with salt-sprayed POM lid (30° angle)	S.C. (30°)	275	1	0.275	C	1
M10R-C17	Shape memory composite sample (SMC)**	SMC	275	1	0.275	C	1
M10R-C18	Shape memory composite sample (SMC)**	SMC	275	1	0.275	C	1
M10R-C19	Cyanate ester graphite fiber composite	CEGFC	72.5	1	0.073	C	1
M10R-C20	LaRC SI (soluble imide) based polyimide/inorganic nanoparticle composite	LaRC RPI-2	1	3	0.003	C	1
M10R-R1	Photographic AO Fluence Monitor	Kapton H/C/PVF-W	5.7	1	0.006	R	2.2 x 1.0

\* Teflon FEP is space facing

\*\* SMC is made with 2 carbon fiber epoxy composite layers and epoxy resin (3M Scotchkote 206 N)



# MISSE-10 Zenith Samples

## 10 – 1” Circular (C)



MISSE-10 ID	Material	Abbreviation	Thickness (mils)	# Layers	Total thickness (inch)	C or S	Size (inch)
M10Z-C1	Polyimide (PMDA) (Kapton H)	Kapton H	5	1	0.005	C	1
M10Z-C2	Carbon ( $\approx 700\text{\AA}$ ) coated Crystalline polyvinyl fluoride w/white pigment (white Tedlar)	C/PVF-W	2	1	0.002	C	1
M10Z-C3	Polyimide (PMDA) (Kapton HN)	Kapton HN	5	1	0.005	C	1
M10Z-C4	Au-Kapton H - mounted $90^\circ$ to nadir (1/2 Au coated, 1/2 NaCl sprayed), Ni base	Au-Kapton H/Ni	275	1	0.275	C	1
M10Z-C5	Alumina slide	$\text{Al}_2\text{O}_3$	63	1	0.063	C	1
M10Z-C6	Fluorinated ethylene propylene (Teflon FEP)	FEP	5	1	0.005	C	1
M10Z-C7	Aluminized-Teflon (FEP/Al)*	FEP/Al	5	1	0.005	C	1
M10Z-C8	Teflon FEP clad carbon paint (India Ink) (FEP/C/FEP)*	FEP/C/FEP	14	1	0.014	C	1
M10Z-C9	Metallized Polyethylene naphthalate (PEN) film (aluminum (100 nm)/PEN (2 micron)/black chromium (15 nm)) with Kapton ring	Al/PEN/Bk Cr	0.083	2	0.000	C	1
M10Z-C10	LaRC SI (soluble imide) based polyimide/inorganic nanoparticle composite (radiation resistant polyimide (RPI))	LaRC RPI-2	0.9	3	0.003	C	1

\* Teflon FEP is space facing



# MISSE-10 Nadir Samples

## 12 Samples: 11 – 1” Circular (C) & 1 – 1” Square (S)

MISSE-10 ID	Material	Abbreviation	Thickness (mils)	# Layers	Total thickness (inch)	C or S	Size (inch)
M10N-C1	Polyimide (PMDA) (Kapton H) - 45° chamfer (Standard)	Kapton H	5	1	0.005	C	1
M10N-C2	Polyimide (PMDA) (Kapton H) - 30° chamfer edge	Kapton H	5	1	0.005	C	1
M10N-C3	Polyimide (PMDA) (Kapton H) - 60° chamfer edge	Kapton H	5	1	0.005	C	1
M10N-C4	Au-Kapton H - mounted 90° to nadir (1/2 Au coated, 1/2 NaCl sprayed), Ni base	Au-Kapton H/Ni	275	1	0.275	C	1
M10N-C5	Alumina slide	Al <sub>2</sub> O <sub>3</sub>	63	1	0.063	C	1
M10N-C6	Fluorinated ethylene propylene (Teflon FEP)	FEP	5	1	0.005	C	1
M10N-C7	Aluminized-Teflon (FEP/Al)*	FEP/Al	5	1	0.005	C	1
M10N-C8	Teflon FEP clad carbon paint (India Ink) (FEP/C/FEP)*	FEP/C/FEP	14	1	0.014	C	1
M10N-C9	Shape memory composite sample (SMC)**	SMC	275	1	0.275	C	1
M10N-C10	Low density polyethylene for cosmic ray shielding (CRS)***	CRS	22	1	0.022	C	1
M10N-C11	Polyimide (PMDA) (Kapton HN)	Kapton HN	5	1	0.005	C	1
M10N-S1	Photographic AO Fluence Monitor#	Kapton H/C/PVF-W	7.9	1	0.008	S	1x1

\* Teflon FEP is space facing

\*\* SMC is made with 2 carbon fiber epoxy composite layers and epoxy resin (3M Scotchkote 206 N)

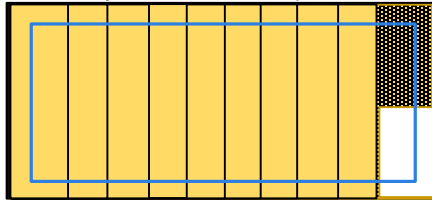


# PCE-2 Ram Photographic AO Fluence Monitor (M10R-R1)



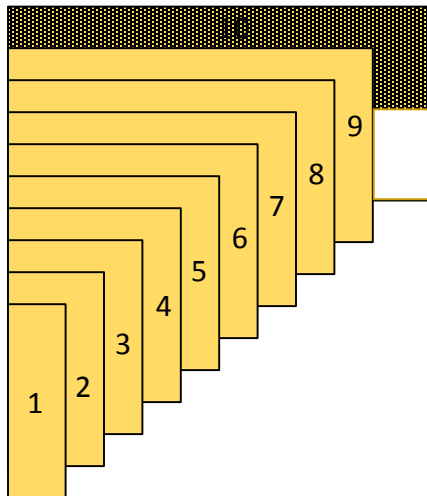
9 MSC deck marks ever 0.2"

Layers  
stacked in  
MSC deck  
Interface  
opening



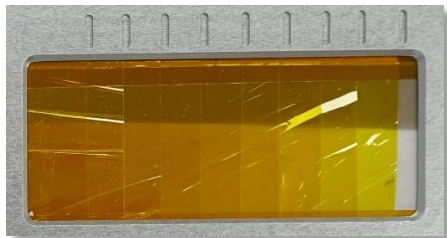
MSC holder (black):  $2.250'' \pm 0.005'' \times 1.020'' +0.005''/-0.000''$   
M10R-R1 sample (yellow) :  $2.200'' \pm 0.005'' \times 1.005'' \pm 0.005''$   
MSC exposure area (blue):  $2.000'' \pm 0.005'' \times 0.822'' \pm 0.005''$

Individual  
sample  
layers



## M10R-R1 Photographic AO Fluence Monitor (10 layer sample):

Layer 10 (base) - Carbon/2 mil white Tedlar:  $2.200'' \pm 0.005'' \times 1.005'' \pm 0.005''$   
Layer 9 - 0.3 mil Kapton H:  $1.900'' \pm 0.005'' \times 1.005'' \pm 0.005''$  (1.8" exposed)  
Layer 8 - 0.3 mil Kapton H:  $1.700'' \pm 0.005'' \times 1.005'' \pm 0.005''$  (1.6" exposed)  
Layer 7 - 0.3 mil Kapton H:  $1.500'' \pm 0.005'' \times 1.005'' \pm 0.005''$  (1.4" exposed)  
Layer 6 - 0.3 mil Kapton H:  $1.300'' \pm 0.005'' \times 1.005'' \pm 0.005''$  (1.2" exposed)  
Layer 5 - 0.3 mil Kapton H:  $1.100'' \pm 0.005'' \times 1.005'' \pm 0.005''$  (1.0" exposed)  
Layer 4 - 0.3 mil Kapton H:  $0.900'' \pm 0.005'' \times 1.005'' \pm 0.005''$  (0.8" exposed)  
Layer 3 - 0.3 mil Kapton H:  $0.700'' \pm 0.005'' \times 1.005'' \pm 0.005''$  (0.6" exposed)  
Layer 2 - 0.3 mil Kapton H:  $0.500'' \pm 0.005'' \times 1.005'' \pm 0.005''$  (0.4" exposed)  
Layer 1 (top) - 0.3 mil Kapton H:  $0.300'' \pm 0.005'' \times 1.005'' \pm 0.005''$  (0.2" exposed)



In the MISSE-10 R1 deck

Total sample thickness = 2 mil + 0.3 mil x 10 (3 mils) = 5 mils





# Polymer and Composites Experiment-2 (PCE-2)

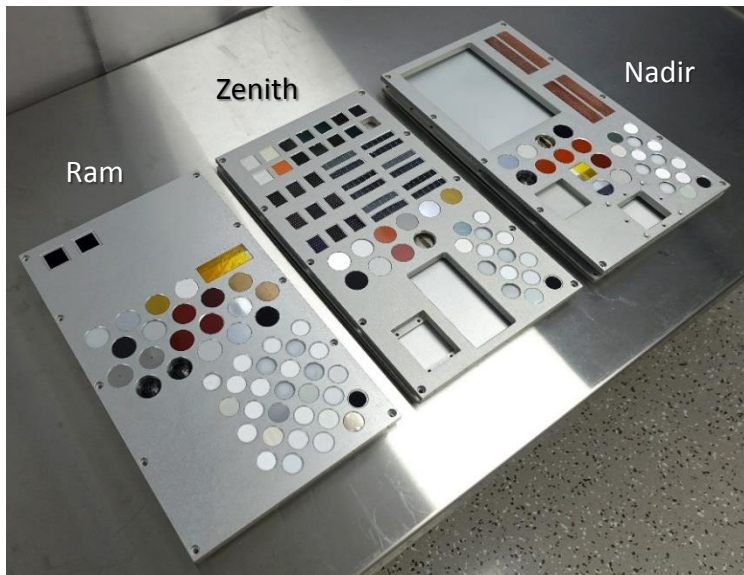
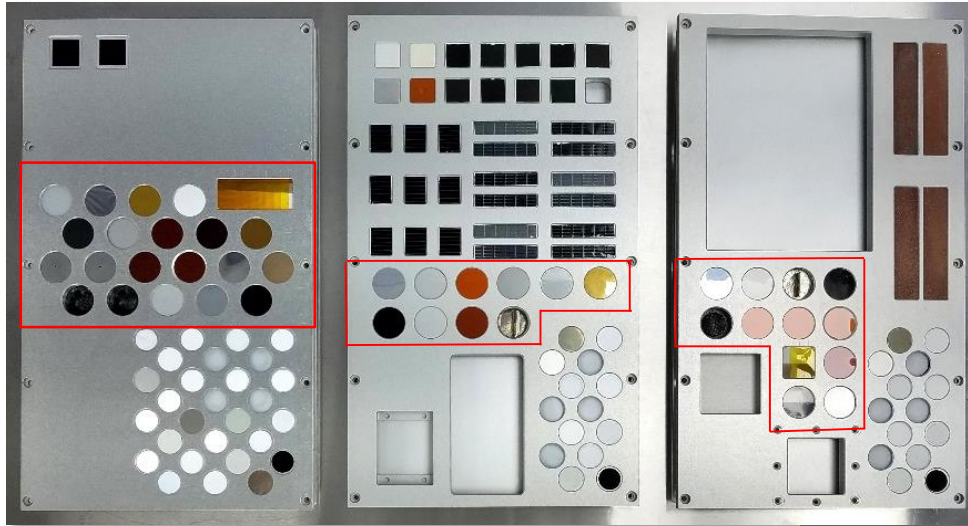
## Integration of the PCE-2 samples into the MISSE-10 Decks



R1

Z2

N3



MISSE-10 sample integration  
at Alpha Space in Houston, TX  
August 29-30, 2018



# MISSE-Flight Facility

## MISSE-9 and MISSE-10 On-Orbit



### November 17, 2018:

The MISSE-10 MISSE Sample Carriers (MSCs) were launched aboard Cygnus NG-10 and transferred to inside ISS

### December 26, 2018:

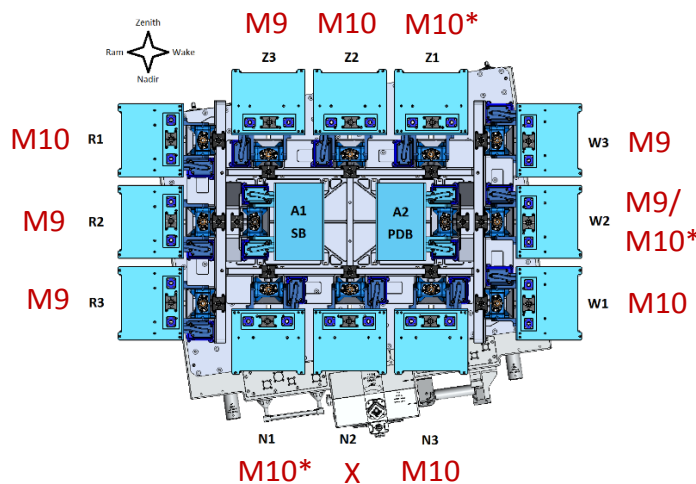
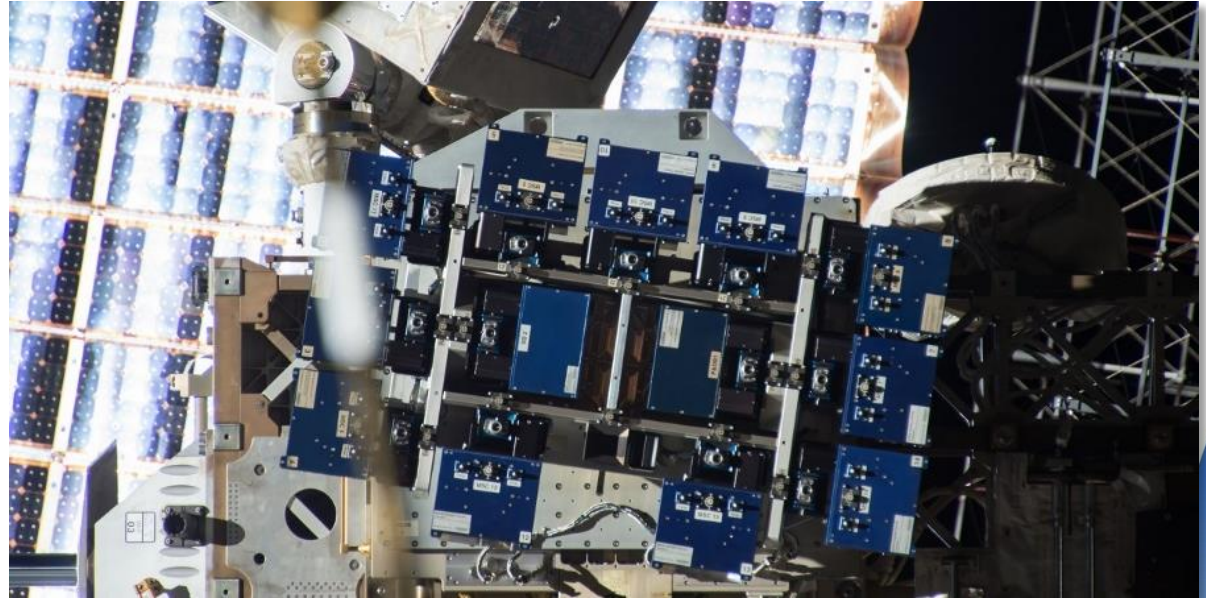
MISSE-9 MSCs were closed in preparation for MISSE-10 installation and the MISSE-10 MSCs were moved through the JEM Airlock to outside ISS

### January 2, 2019:

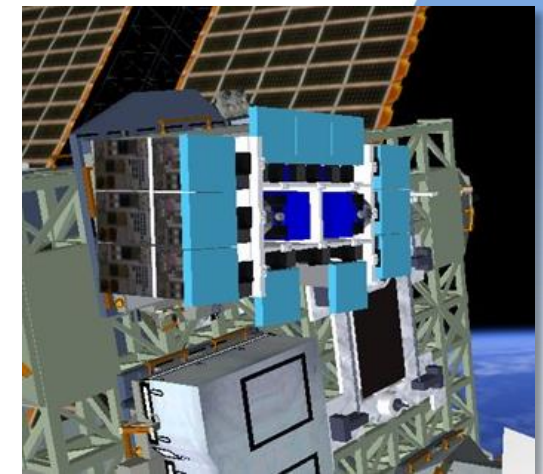
The MISSE-10 MSCs were robotically installed on the MISSE-FF starting on January 2

### January – April 2019:

The MISSE-9 & MISSE-10 MSCs remained *closed* due to an anomaly that occurred in the communication system during MISSE-10 installation



\*6 month MSC





# MISSE-Flight Facility

## MISSE-9, MISSE-10 & MISSE-11 On-Orbit



### April 17, 2019:

A new Power and Data Box (PDB) was launched April 17, 2019 on Cygnus NG-11

The MISSE-11 MCSs were also launched on NG-11

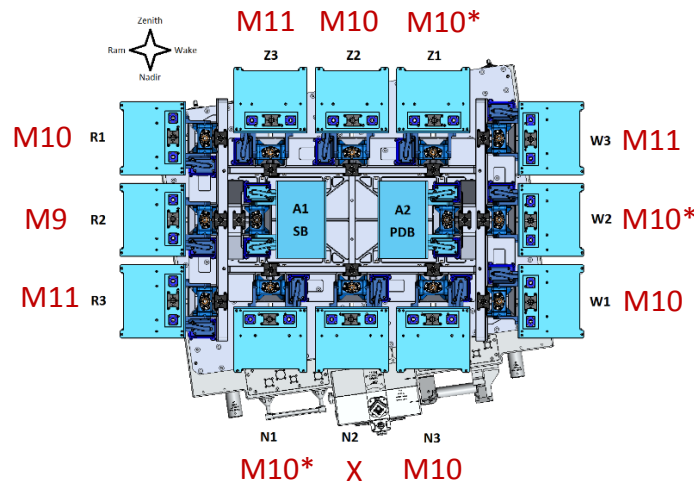
### April 26, 2019 Up-date:

The PDB has successfully solved the communication issue

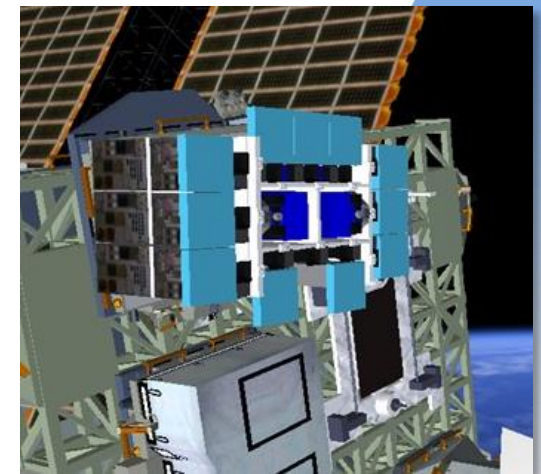


MISSE-9 (except M9 R2) was retrieved, and the MISSE-11 MSCs were installed

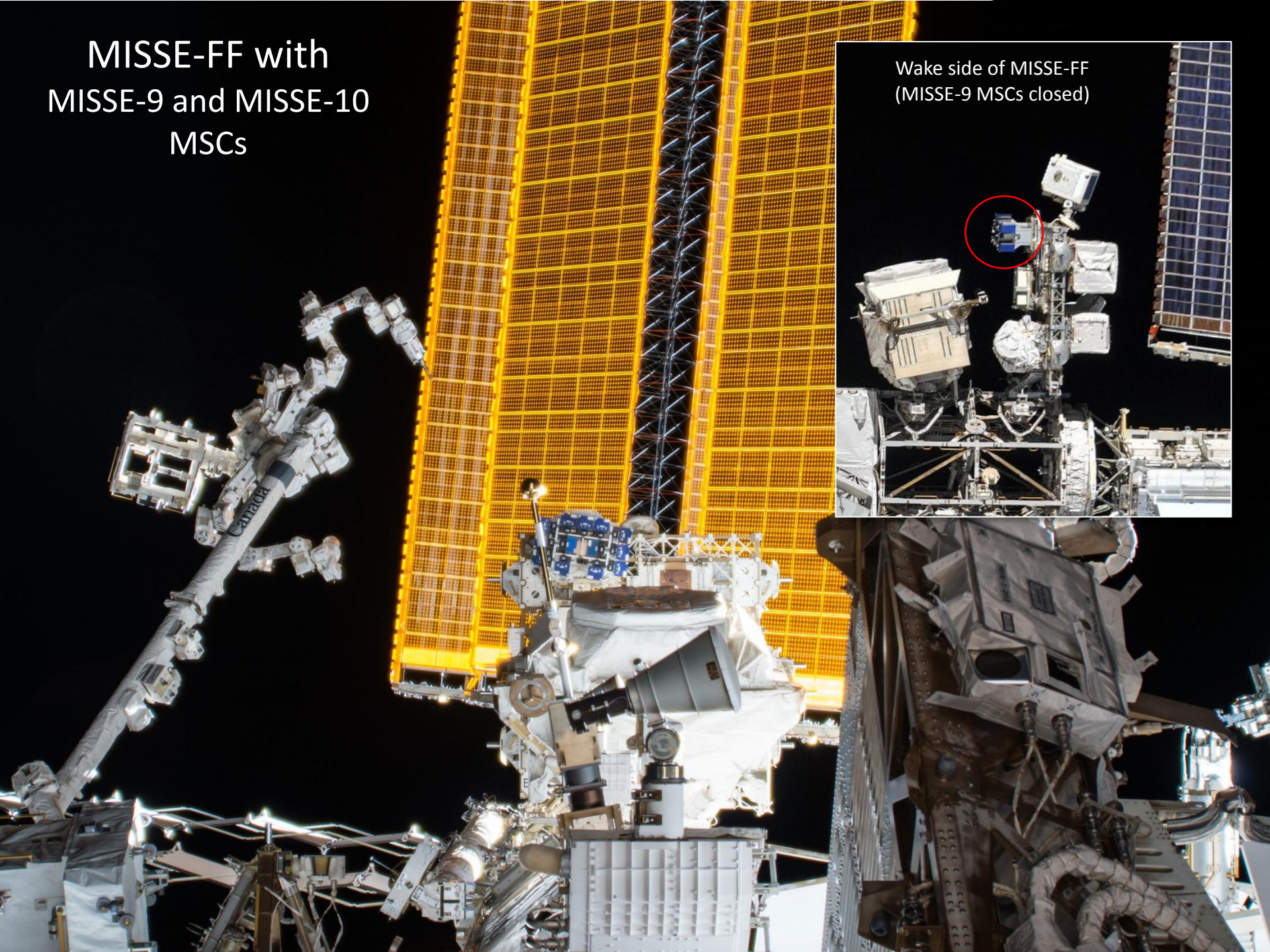
On April 26, 2019 the MISSE-9 R2 MSC, MISSE-10 and MISSE-11 MSCs were successfully deployed



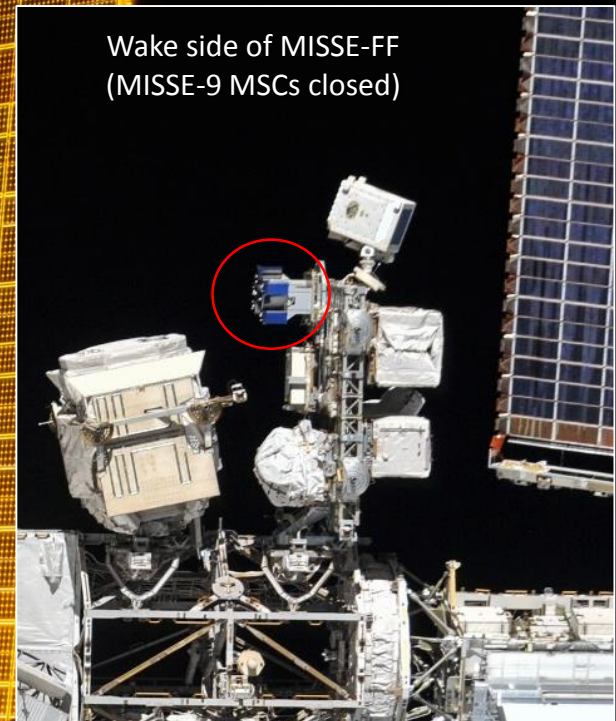
\*6 month MSC



# MISSE-FF with MISSE-9 and MISSE-10 MSCs



Wake side of MISSE-FF  
(MISSE-9 MSCs closed)



# MISSE-12

## Polymers and Composites Experiment-3 (PCE-3)



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

**Collaborators:** Bruce Banks (GRC/SAIC), Santo Padula (GRC), Sharon Miller (GRC), Andrew Trunek\* (GRC), Theresa Benyo\* (GRC), Maryann Meador (GRC), Loredana Santo & Fabrizio Quadrini (Univ. of Rome), John Fleming (Ball Aerospace) & Dave Wilt (AFRL)

### 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 property degradation of spacecraft materials in LEO
3. Determine the functionality of shape memory alloys (SMAs), shape memory polymer composites (SMPCs), melanin based composites and new solar cell cover slides after space radiation exposure
4. Determine AO fluence and contamination for MISSE-12 flight orientations
5. Use data to improve AO predictive models & archive data in MISSE MAPTIS database

### Experiment Description:

- Passive experiment with 85 samples flown in ram, wake & zenith orientations
  - 30 Ram, 41 Wake & 14 Zenith
- Pre-flight & post-flight data will be measured in ground-facilities

### Expected Results:

- AO fluence and contamination data in each flight direction
- LEO  $E_y$  values as a function of AO fluence & solar irradiation
- Changes in optical, thermal & tensile properties
- Functionality of SMAs, SMPCs, melanin based materials and solar cell cover slides after space radiator exposure
- Quantification of AO erosion of bonded metals



Shape memory alloy (SMA) tires for rovers

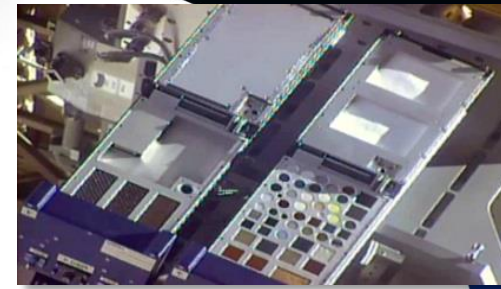


ISS replacement solar array materials

\* In collaboration with University of Akron, Johns Hopkins University, redhouse studio



# MISSE-FF Experiment Summary



PCE ram samples on-orbit

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

- The PCE is part of MISSE-9, the inaugural mission of MISSE-FF
- Passive experiment with *138 samples: 39 Ram, 52 Wake & 47 Zenith*
- MISSE-9 & MISSE-FF launched in April 2019 (SpaceX-14) & deployed April 19, 2018
  - MISSE-9 wake & zenith MSCs were retrieved **April 26, 2019**, after 8 months of exposure\*
  - MISSE-9 ram (R2) MSC will be retrieved in **October 2019**, after 14 months exposure\*

## MISSE-10 Polymers and Composites Experiment-2 (PCE-2)

- Passive experiment with *43 samples: 21 Ram, 10 Zenith & 12 Nadir*
- MISSE-10 launched in Nov. 2018 (NG-10) & was deployed April 26, 2019

## MISSE-12 Polymers and Composites Experiment-3 (PCE-3)

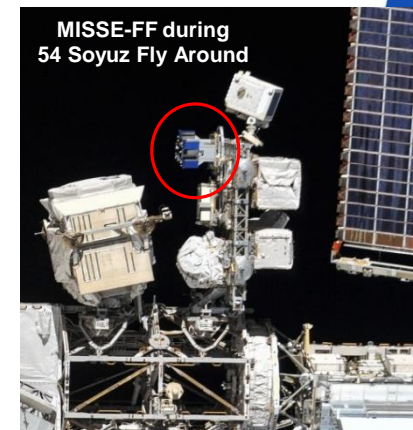
- Passive experiment with *85 samples: 30 Ram, 41 Wake & 14 Zenith*
- MISSE-12 integration is planned for July & launch is planned for Dec. 2019

## MISSE-13 Polymers and Composites Experiment-4 (PCE-4)

- A PCE-4 experiment proposal has been submitted to the MISSE-13 Experiment Call

## NASA Technical Standards Handbook Revision

- Data from Glenn's MISSE-FF experiments will be used to write a revision to NASA Technical Standards **Spacecraft Polymers Atomic Oxygen Durability Handbook** to include  $E_y$  vs. AO fluence and/or solar exposure data and new MISSE-FF flight data



MISSE-FF during  
54 Soyuz Fly Around

\* Minus 10-20% for contamination avoidance (closed from December 26, 2018 to April 26, 2019)



# Acknowledgements

Glenn's MISSE research has been supported by numerous projects over the past 19 years (ISS Research Program, MISSE-X Project, MISSE Informatics Project)

This work is currently supported by the Glenn Research Center and the Space Life and Physical Sciences Research and Applications (SLPSRA) Division