Erosion Data from the MISSE 8 Polymers Experiment after 2 Years of Space Exposure on the International Space Station

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Abstract

The Polymers Experiment was exposed to the low Earth orbit (LEO) space environment for 2.14 and 2.0 years as part of the Materials International Space Station Experiment 8 (MISSE 8) and the Optical Reflector Materials Experiment-III (ORMatE-III), respectively. The experiment contained 42 samples, which were flown in either ram, wake, or zenith orientations. The primary objective was to determine the effect of solar exposure on the atomic oxygen erosion yield (Ey) of fluoropolymers. This paper provides an overview of the experiment with details on the polymers flown, the characterization techniques used, the atomic oxygen fluence for each exposure orientation, and the LEO Ey results. The Ey values for the fluoropolymers range from 1.45 x 10^{-25} cm^3/atom for white Tedlar® (polyvinyl fluoride with white titanium dioxide pigment) flown in the ram orientation to 6.32 x 10^{-24} cm^3/atom for aluminized-Teflon® fluorinated ethylene propylene (Al-FEP) flown in the zenith orientation. Erosion yield data for FEP flown in ram, wake and zenith orientations are compared, and the Ey was found to be highly dependent on orientation, hence environmental exposure. Teflon FEP had an order of magnitude higher Ey when flown in the zenith direction (6.32 x10^{-24} cm^3/atom) as compared to the ram direction (2.37 x 10^{-25} cm^3/atom). The Ey of FEP was found to increase with a direct correlation to the solar exposure/AO fluence ratio showing the effect of solar radiation and/or heating due to solar exposure on FEP erosion. In addition, back-surface carbon painted FEP (C-FEP) flown in the zenith orientation had a significantly higher Ey than clear FEP or Al-FEP further indicating that heating has a significant impact on the erosion of FEP, particularly in the zenith orientation.

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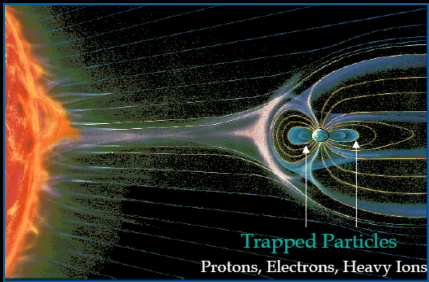
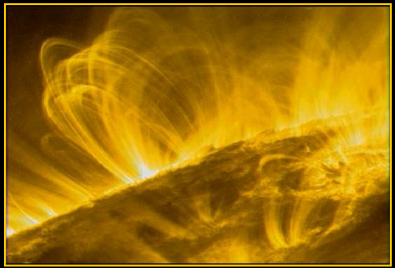


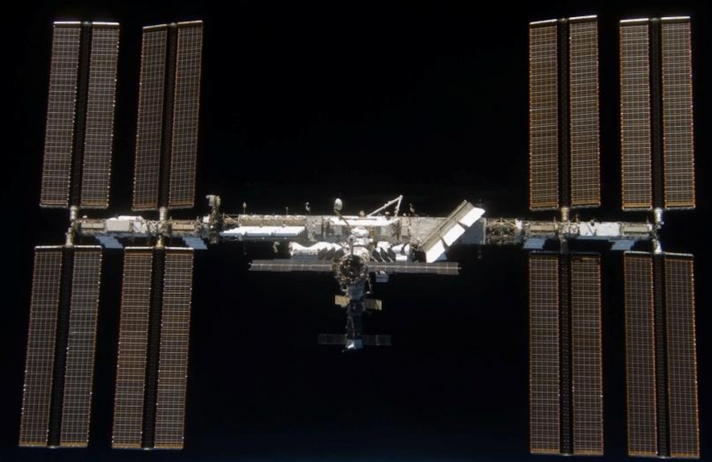
The Space Environment



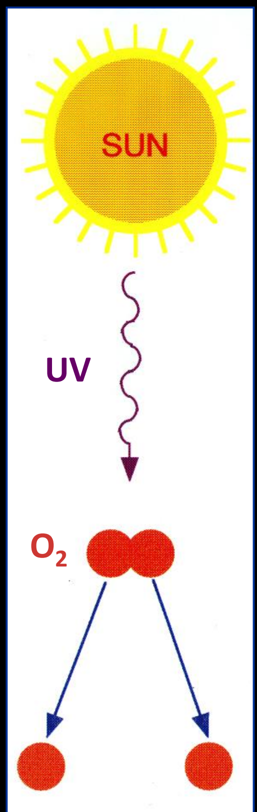
Materials on the exterior of spacecraft are exposed to many harmful environmental threats

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 (reactive oxygen atoms)



Atomic Oxygen (AO)

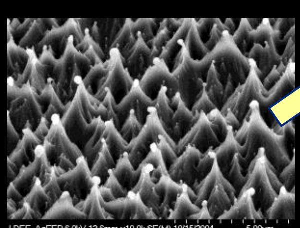


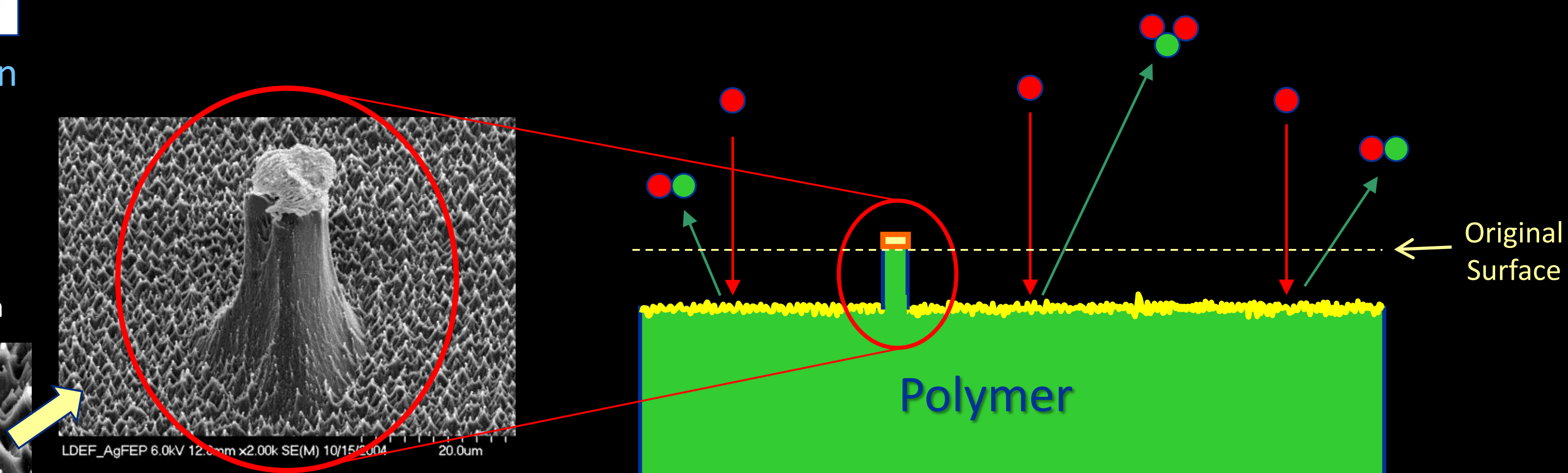
Atomic Oxygen

- 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*

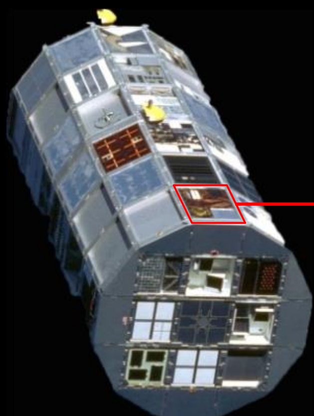
Ram AO erosion causes "cone" formation





2000X

Atomic Oxygen Erosion of a Kapton Insulation Blanket on the Long Duration Exposure Facility (LDEF)



Tray F-9

Pre-flight

Post-flight

After 5.8 years in space

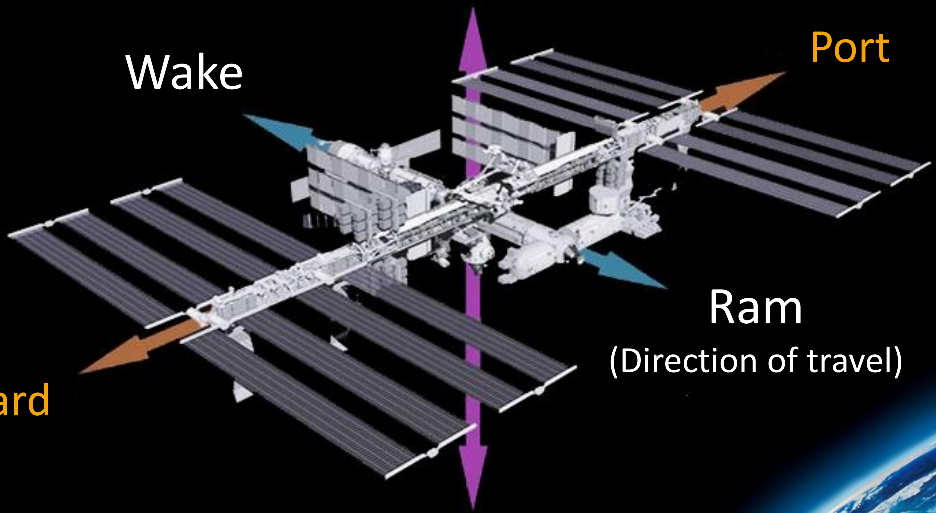
Materials International Space Station Experiment (MISSE)

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

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

Objective:

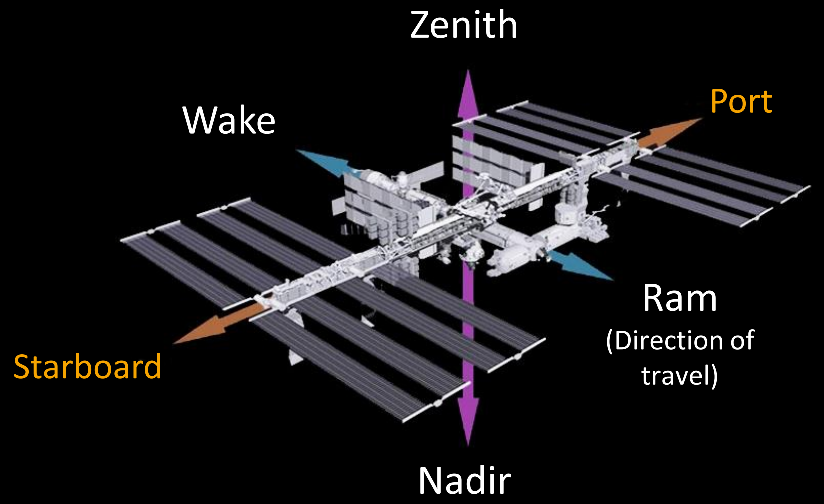
To test the stability and durability of materials and devices in the space environment



Flight Orientations & Environmental Exposures

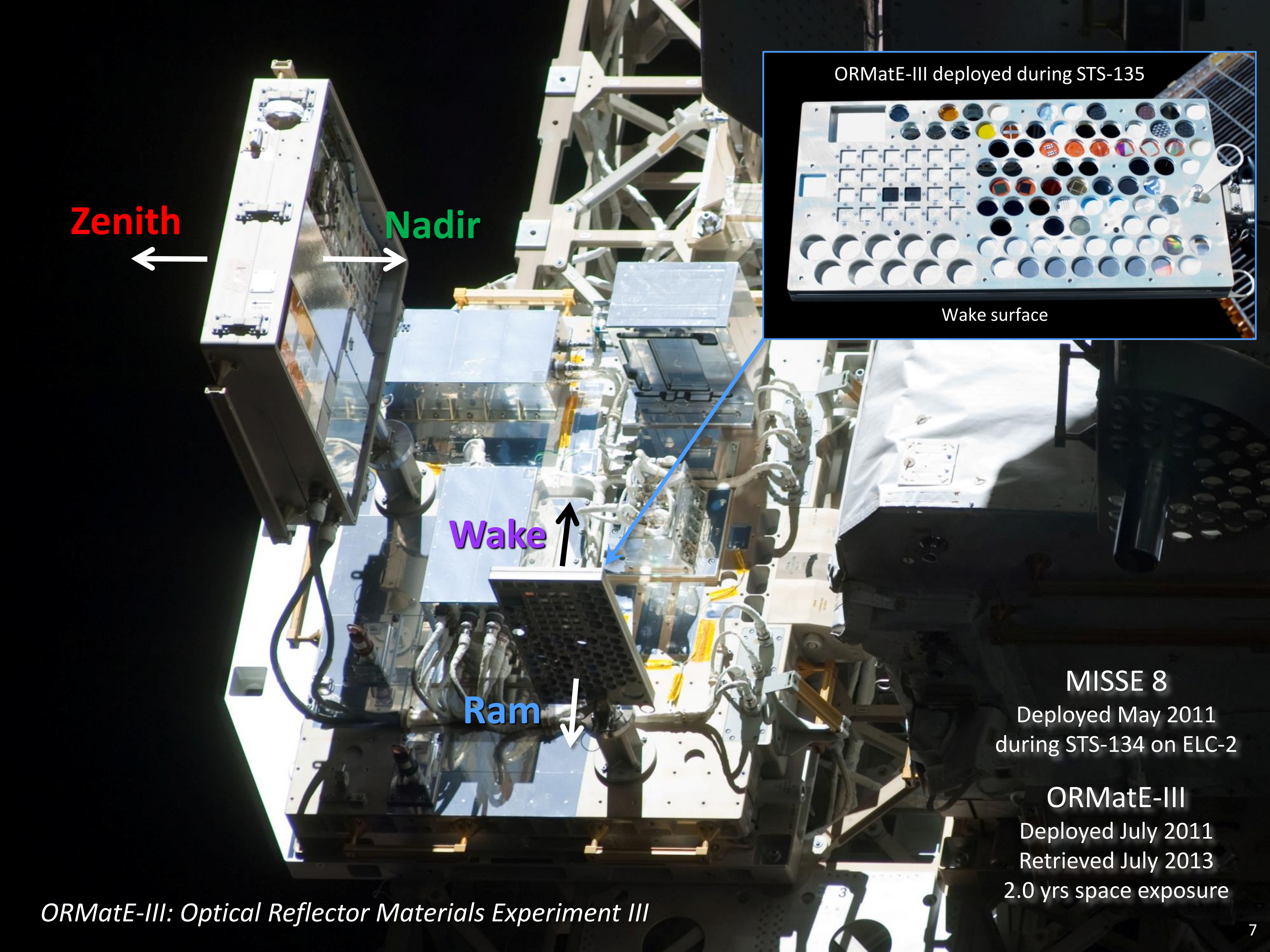
Ram:
- *Facing the direction of travel (i.e. forward pointing or leading edge)*
- *<u>Highest AO</u> & moderate solar exposure*

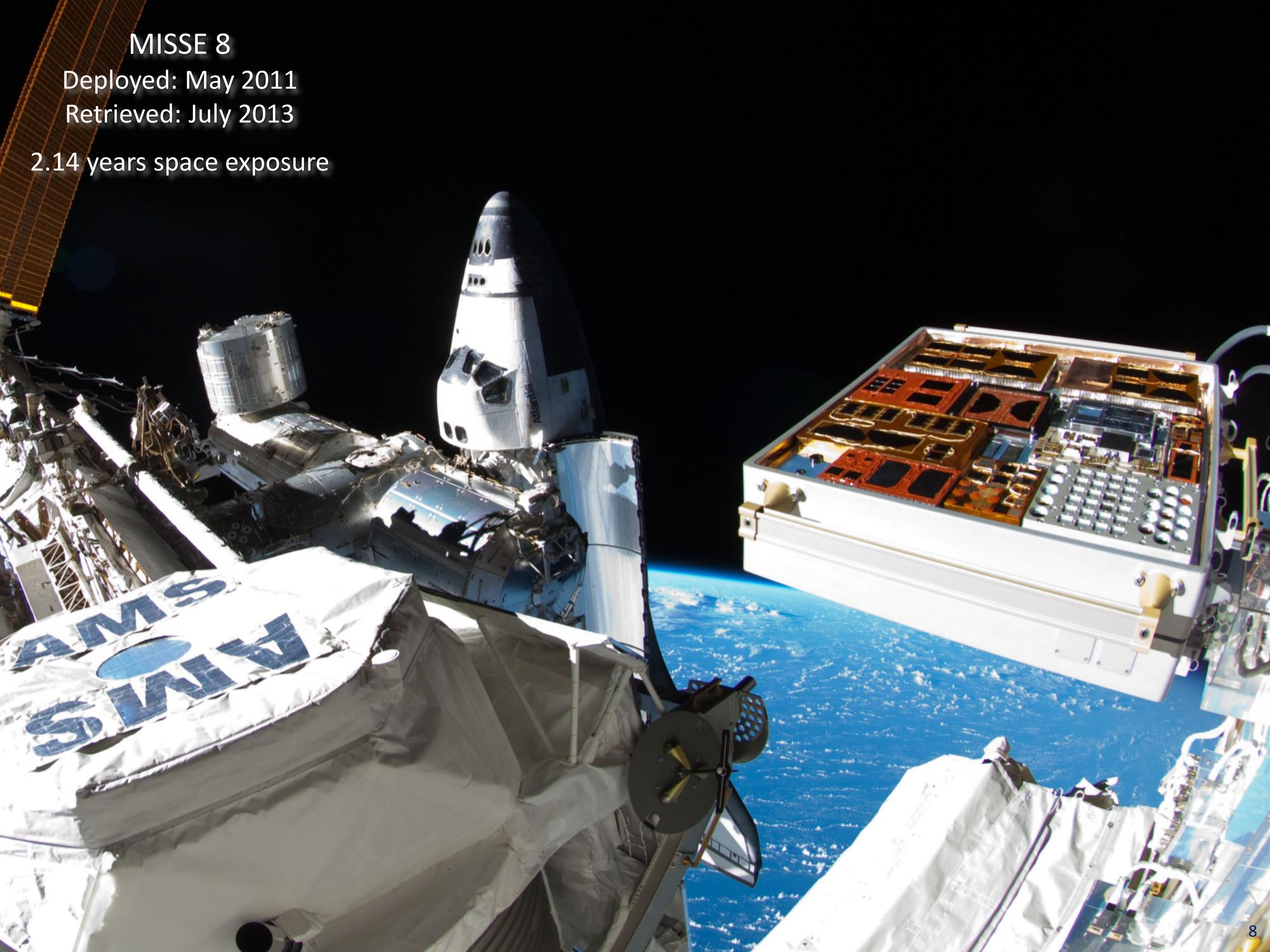
Wake:
- *Facing away from the direction of travel (i.e. aft pointing or trailing edge)*
- *<u>Very little AO</u> & moderate solar exposure*



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

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

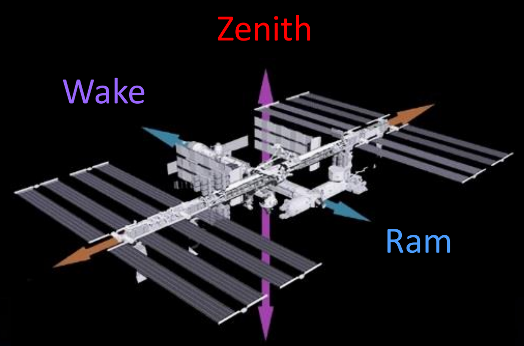

ORMatE-III deployed during STS-135
Wake surface
Zenith
Nadir
Wake
Ram
MISSE 8
Deployed May 2011
during STS-134 on ELC-2
ORMatE-III
Deployed July 2011
Retrieved July 2013
2.0 yrs space exposure
ORMatE-III: Optical Reflector Materials Experiment III


MISSE 8
Deployed: May 2011
Retrieved: July 2013
2.14 years space exposure
AMS
Atlantis

MISSE 8 Polymers Experiment

- Passive experiment w/ 42 samples exposed to space for 2 or 2.14 years
  - Primary objective:
    - *Determine the effect of solar exposure on the atomic oxygen erosion yield (Ey, cm^3/atom) of fluoropolymers*
  - Additional samples were included for environmental durability assessment, and will be reported elsewhere
    - *Tensile samples, composites, spacesuit fabrics, pinhole camera, docking seal sample, etc.**

- Sample exposures
  - *ORMatE-III **ram** orientation (2 yrs) – 8 samples*
    - *1 AO fluence sample*
    - *6 Ey samples*
    - *1 AO pinhole camera**
  - *ORMatE-III **wake** orientation (2 Yrs) – 11 samples*
    - *1 AO fluence sample*
    - *3 Ey samples*
    - *1 silicone rubber sample, 4 composite samples & 2 spacesuit fabric samples**
  - *MISSE 8 **zenith** orientation (2.14 yrs) – 23 samples*
    - *2 AO fluence samples (1 tray & 1 taped)*
    - *8 Ey samples (3 tray & 5 taped)*
    - *12 tensile samples + 1 – 6 layered Teflon FEP sample (for tensile samples)**



** Results to be reported elsewhere*

MISSE 8 Zenith Samples

Zenith Electronics and Polymer Exposure Experiment (ZEPEE)

Polymer Experiment Samples: 4 tray & 11 taped samples

MISSE 8 Zenith Tray (pre-flight)

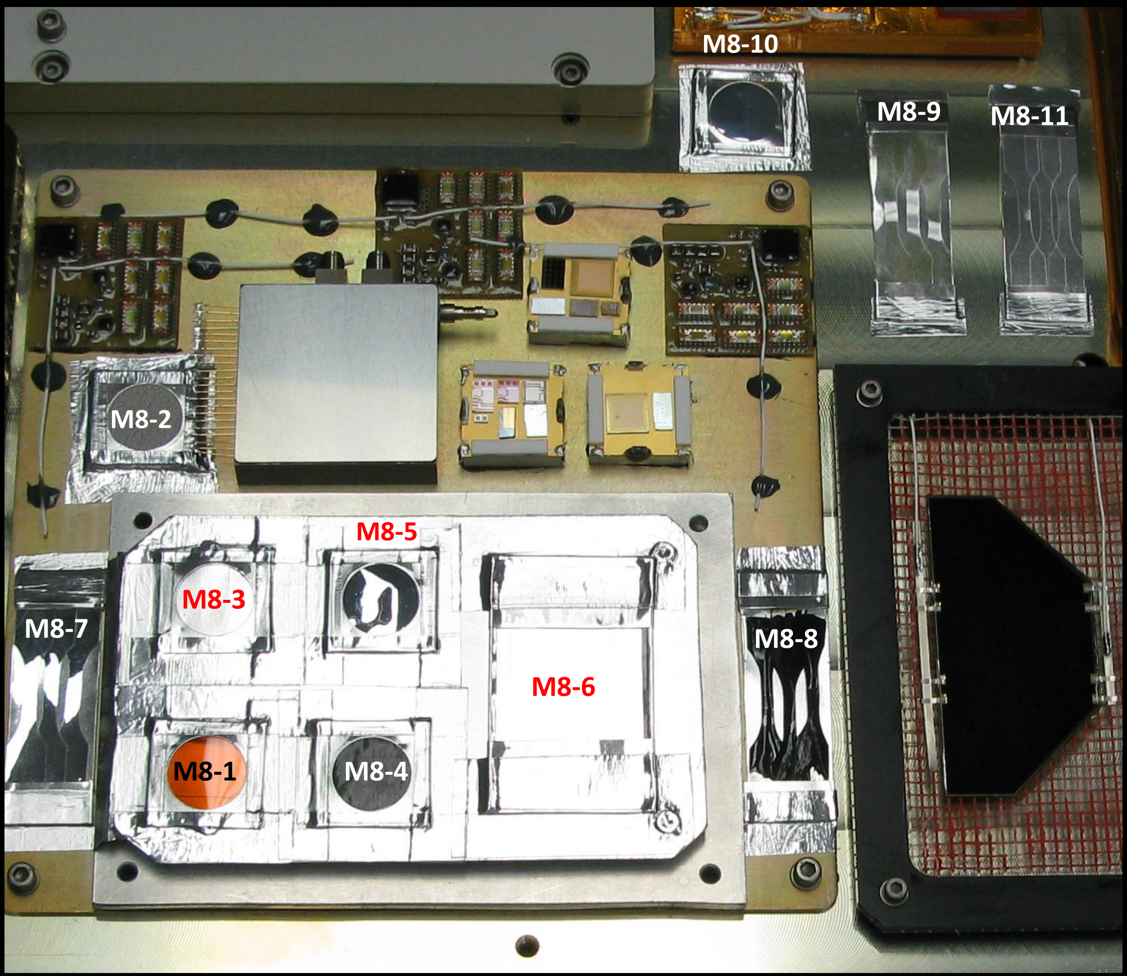


Photo credit: Naval Research Laboratory

MISSE 8 Zenith Tray (pre-flight)

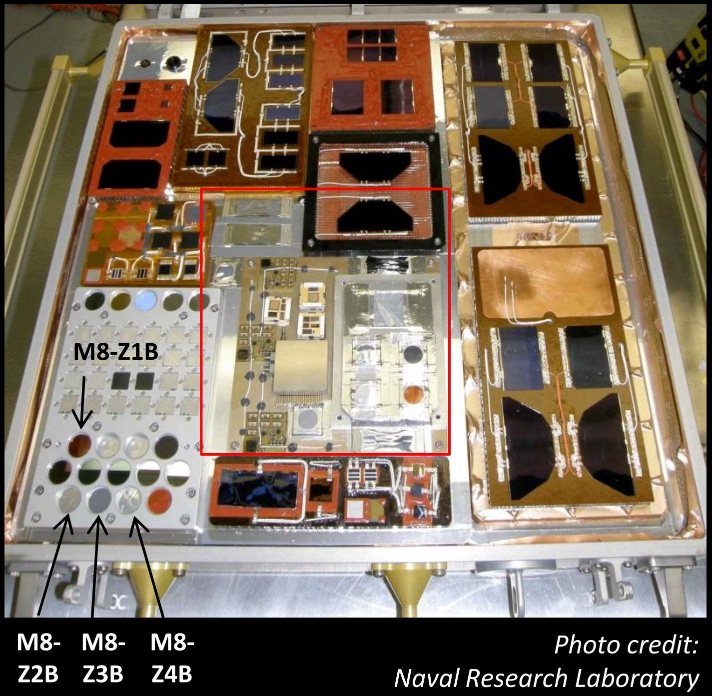


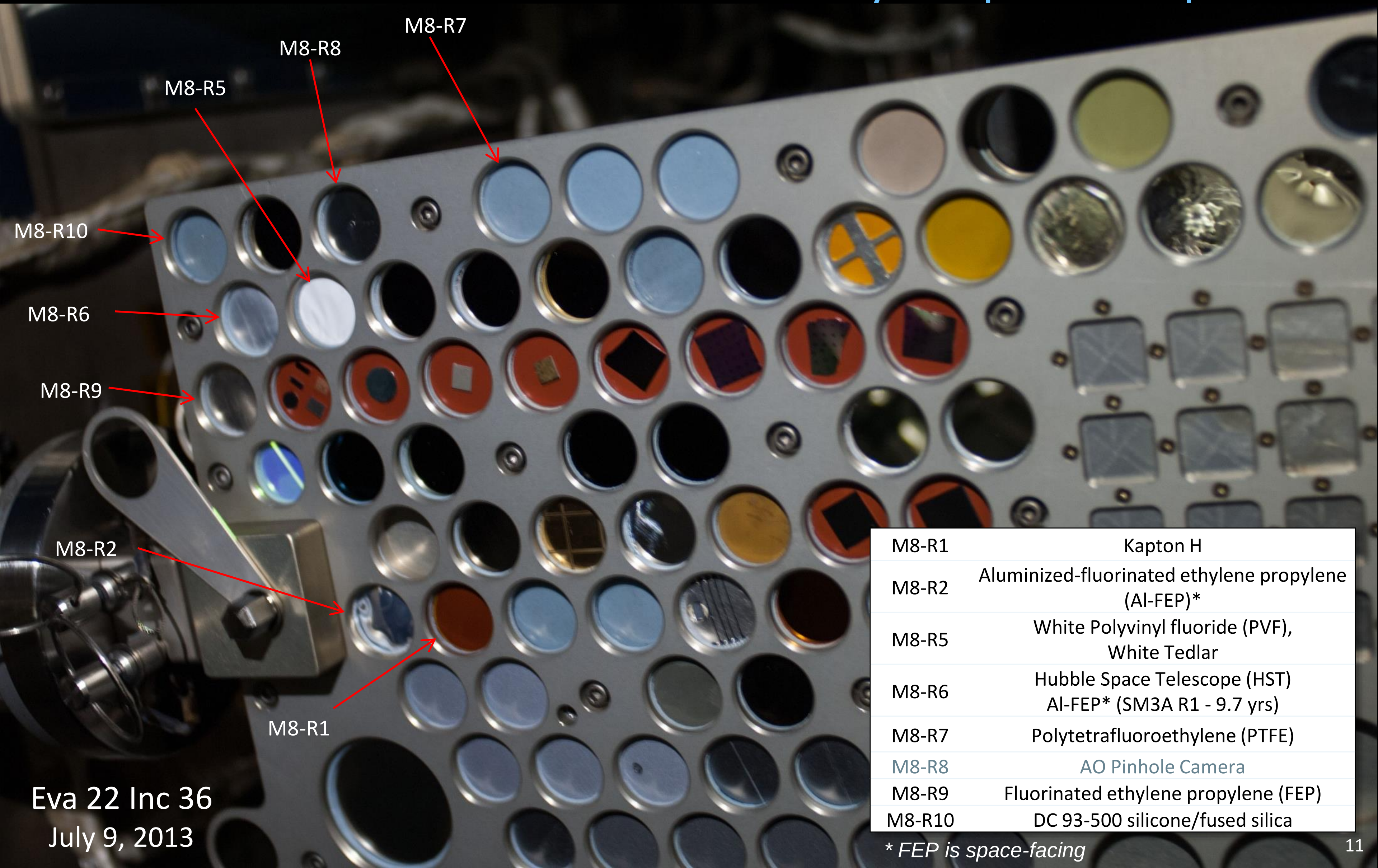
Photo credit: Naval Research Laboratory

GRC ID	MISSE 8 Sample
M8-Z1B	Kapton H
M8-Z2B	FEP
M8-Z3B	Al-FEP*
M8-Z4B	HST Al-FEP* (SM3A R1 - 9.7 yrs)
	11 Taped Samples
M8-1	Kapton H
M8-2	Pyrolytic Graphite (PG)
M8-3	FEP
M8-4	Carbon back-surface painted FEP (C-FEP)*
M8-5	Al-FEP*
M8-6	6 layers FEP (3 tensile samples x 6)
M8-7	Al-FEP tensile samples* (3)
M8-8	C-FEP tensile samples* (3)
M8-9	CP1 tensile samples (3)
M8-10	Ag-FEP*
M8-11	FEP tensile samples (3)

** FEP is space-facing*

ORMatE-III Ram Samples

8 Polymer Experiment Samples



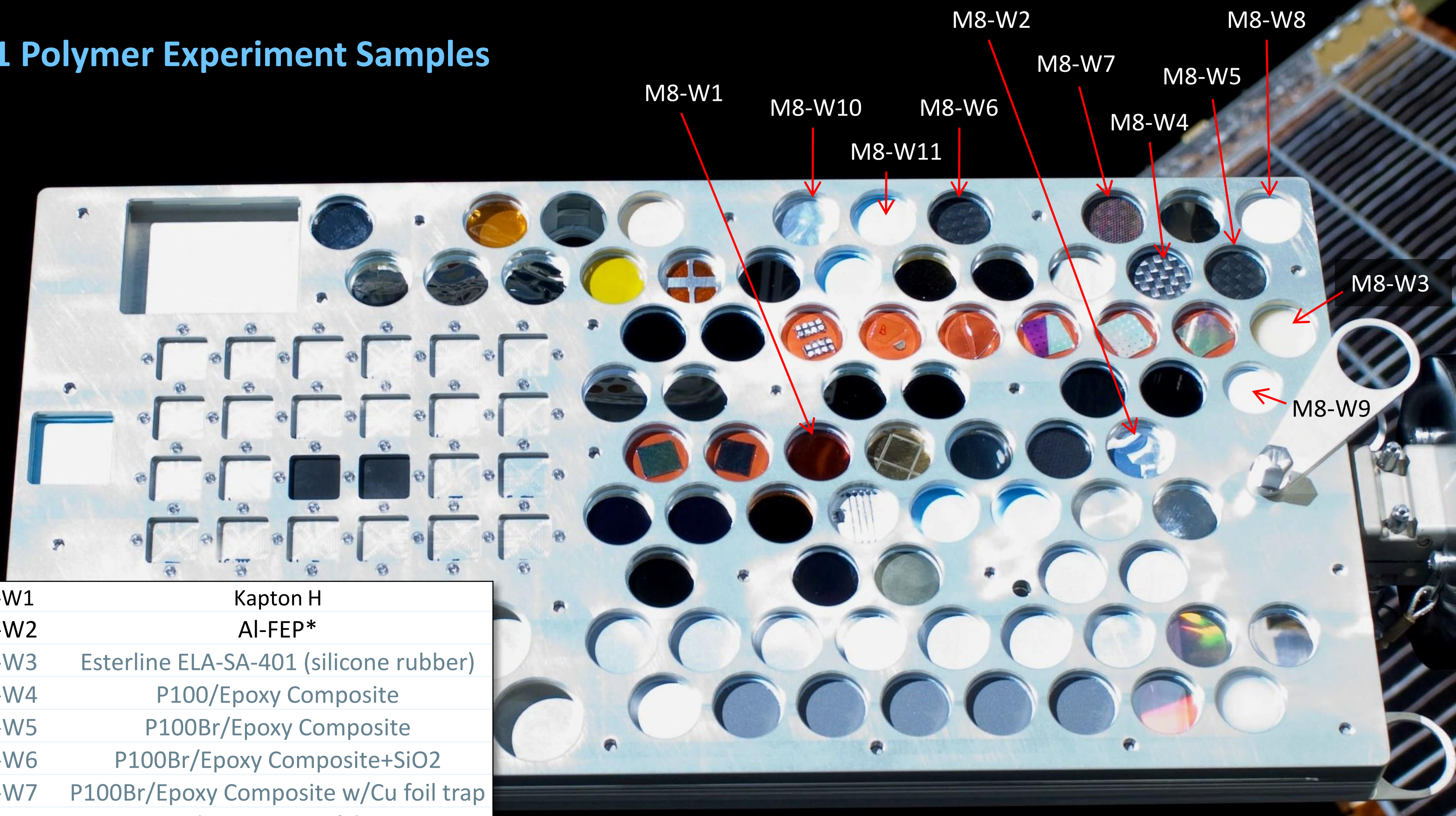
Eva 22 Inc 36
July 9, 2013

M8-R1	Kapton H
M8-R2	Aluminized-fluorinated ethylene propylene (Al-FEP)*
M8-R5	White Polyvinyl fluoride (PVF), White Tedlar
M8-R6	Hubble Space Telescope (HST) Al-FEP* (SM3A R1 - 9.7 yrs)
M8-R7	Polytetrafluoroethylene (PTFE)
M8-R8	AO Pinhole Camera
M8-R9	Fluorinated ethylene propylene (FEP)
M8-R10	DC 93-500 silicone/fused silica

** FEP is space-facing*

ORMatE-III Wake Samples

11 Polymer Experiment Samples



M8-W1	Kapton H
M8-W2	Al-FEP*
M8-W3	Esterline ELA-SA-401 (silicone rubber)
M8-W4	P100/Epoxy Composite
M8-W5	P100Br/Epoxy Composite
M8-W6	P100Br/Epoxy Composite+SiO2
M8-W7	P100Br/Epoxy Composite w/Cu foil trap
M8-W8	Ortho spacesuit fabric
M8-W9	Apollo spacesuit fabric
M8-W10	HST Al-FEP* (SM3A R1 - 9.7 yrs)
M8-W11	FEP

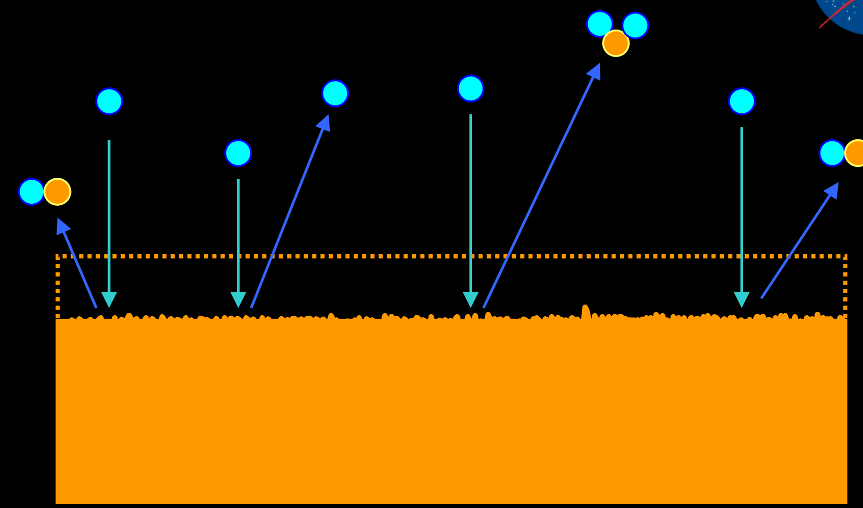
** FEP is space-facing*

ORMatE-III Deploy
STS-135
July 12, 2011

Atomic Oxygen Erosion Yield (E_y)

(Also called Reaction Efficiency or Recession Rate)

Ey 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:
- ΔM_s = Mass loss of polymer sample (g)
- A_s = Area of polymer sample (cm^2)
- ρ_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:
- ΔM_k = Mass loss of Kapton H witness (g)
- A_k = Area of Kapton H witness (cm^2)
- ρ_k = Density of Kapton H sample (1.427 g/cm^3)
- E_k = Erosion yield of Kapton H (3.0×10^{-24} cm^3/atom)

Experimental Procedures

Mass Measurements:

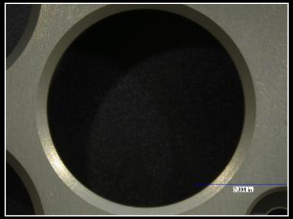
Hygroscopic materials can have large weight variations due to moisture absorption (i.e. Kapton can absorb up to 2% of its weight in moisture)

Samples were vacuum dehydrated (≈60-100 mtorr) for a min. of 72 hours prior to measuring mass before, & after, flight using a Sartorius ME 5 Microbalance (0.000001 g sensitivity)

Exposed Surface Area (SA) Measurements:

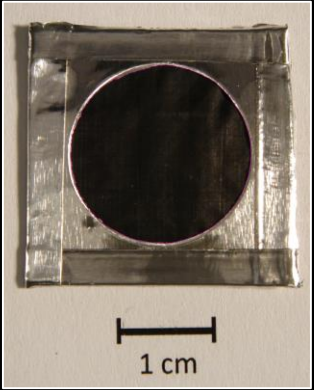
Tray Samples:

4 diameter measurements were taken of each tray opening with a Bore Gauge (±0.001 mm) and averaged



Taped & irregularly shaped samples:

AutoCAD computer design software was used to trace the border of the sample on a photograph & the SA was computed with the AutoCAD software



AutoCAD photo-trace

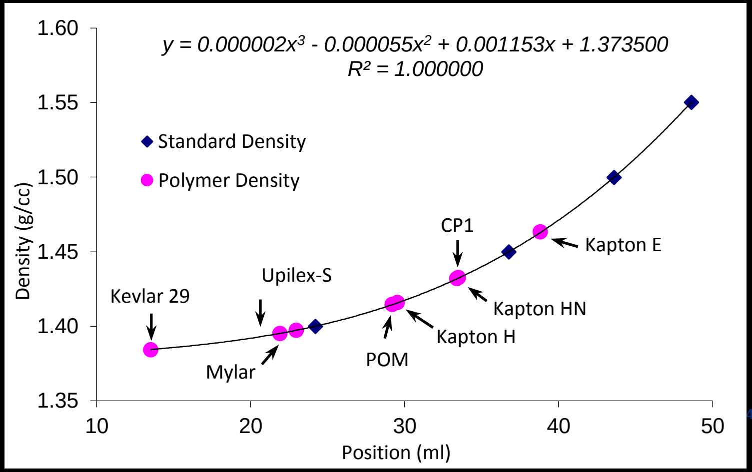
Density Measurements: Density Gradient Columns*

Solvents for low density

- Cesium Chloride (CsCl, $\rho = 2$ g/cm^3) & Water (H_2O, $\rho = 1$ g/cm^3)

Solvents for high density

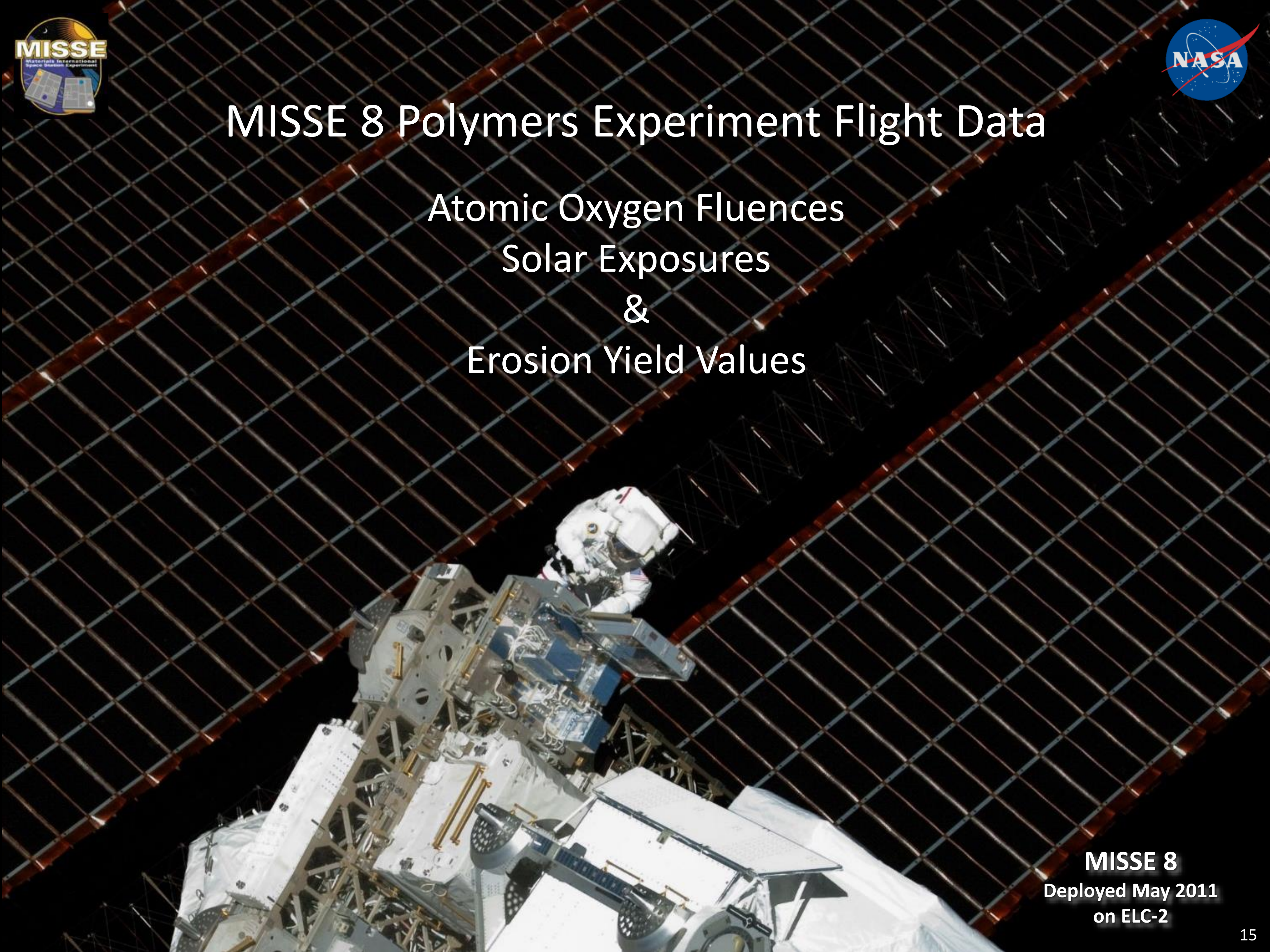
- Carbon Tetrachloride (CCl_4, $\rho = 1.594$ g/cm^3) & Bromoform ($CHBr_3$, $\rho = 2.899$ g/cm^3



*Ref: de Groh et al. HPP 20: 388-409, 2008

MISSE 8 Polymers Experiment Flight Data

Atomic Oxygen Fluences
Solar Exposures
&
Erosion Yield Values



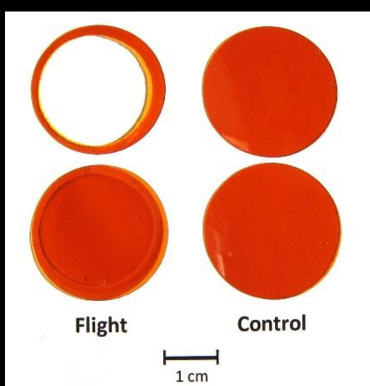
MISSE 8
Deployed May 2011
on ELC-2

MISSE 8 AO Fluence

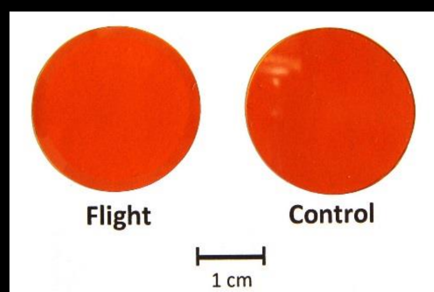
GRC AO Fluence Data

Orientation	Experiment	Sample ID	Material	Thickness	Holder	Technique	AO Fluence (atoms/cm^2)
Ram	Polymers Experiment	M8-R1	Kapton H*	5 mil	Beveled Tray	Mass loss	4.62 E21
Wake	Polymers Experiment	M8-W1	Kapton H*	5 mil	Beveled Tray	Mass loss	8.80 E19
Zenith	Polymers Experiment	M8-Z1B	Kapton H*	5 mil	Beveled Tray	Mass loss	4.04 E19
Zenith	Polymers Experiment	M8-1	Kapton H*	5 mil	Thin Al foil (taped)	Mass loss	1.96 E20

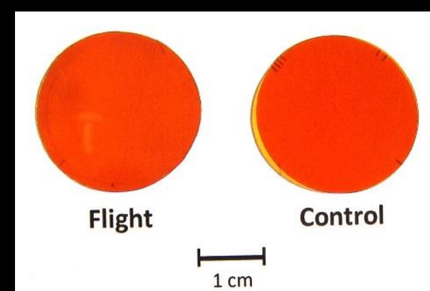
** Kapton H E_y based on prior LEO flight experiments*



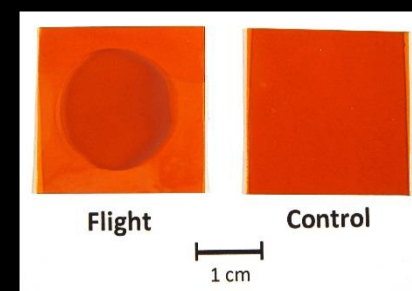
Kapton H (M8-R1)
Tray (sample recessed)
Ram
AO F= 4.62 x 10^{21} atoms/cm^2



Kapton H (M8-W1)
Tray (sample recessed)
Wake
AO F= 8.80 x 10^{19} atoms/cm^2



Kapton H (M8-Z1B)
Tray (sample recessed)
Zenith Tray
AO F= 4.04 x 10^{19} atoms/cm^2



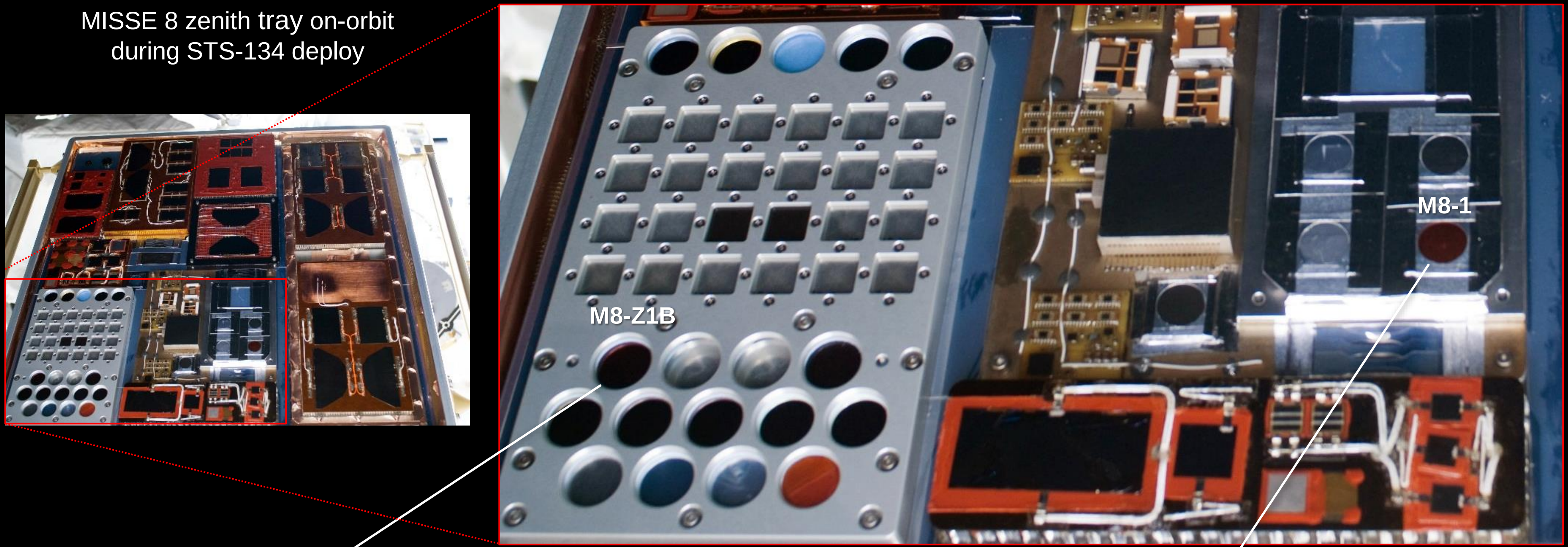
Kapton H (M8-1)
Taped (sample not recessed)
Zenith Taped
AO F= 1.96 x 10^{20} atoms/cm^2

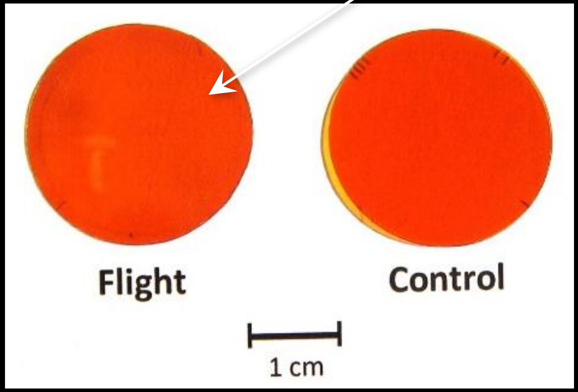
4.9X higher than tray

MISSE 8 Zenith Samples

Kapton H AO Fluence Witness Samples

MISSE 8 zenith tray on-orbit during STS-134 deploy

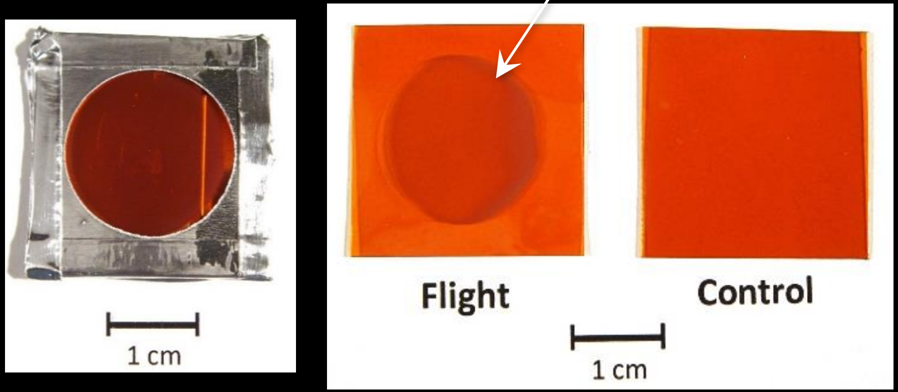




Kapton H (M8-Z1B) – top layer Tray (sample recessed)

Very little texture visible

The AO fluence for surfaces receiving grazing AO is dependent on the sample holder geometry



Kapton H (M8-1) Taped Al Holder (sample not recessed)

Erosion texture visible

MISSE 8

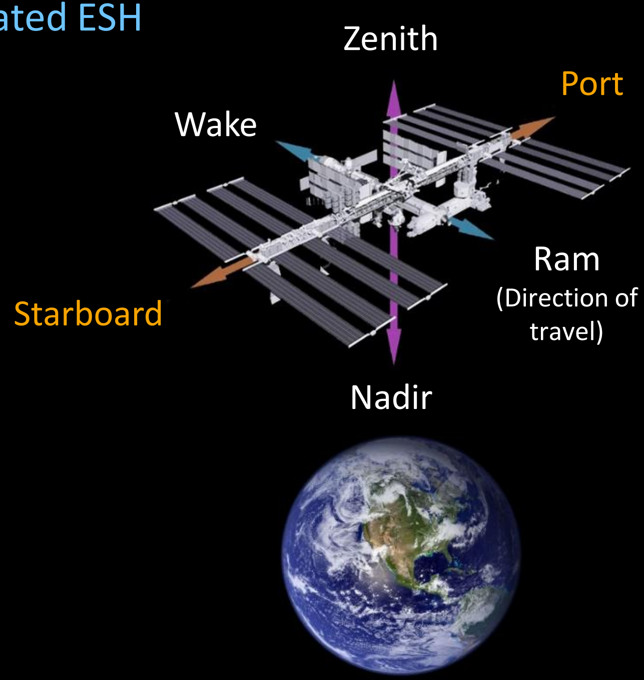
Ram & Wake Solar Exposure Approximations

Flight Orientation	MISSE 7 Exposure (Yrs)	MISSE 7 Equivalent Sun Hours (ESH)	MISSE 7 ESH Relative to Zenith	MISSE 8 ESH Relative to MISSE 7 ESH	MISSE 8 (ESH)
Zenith	2.14	4,300	1	6,100*	6,100 ± 1,000*
Ram	2.00	2,400	0.56	3,182**	3,200⁺
Wake	2.00	2,000	0.47	2,652**	2,700⁺
Nadir	2.14	<<2,000	-	-	800 ± 300⁺

* Reference: Phil Jenkins, Naval Research Laboratory, Calculated ESH

** Ram & wake also multiplied by 2.00/2.14 (0.93)

⁺ Approximations
(Nadir approximation provided by M. Finckenor, NASA MSFC)



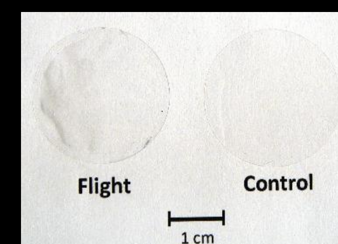
MISSE 8 Ram Samples

GRC ID	Material	Thickness (mil)	Number of layers	Mass Loss (g)	Bore Gauge Area (cm^2)	Density (g/cm^3)	AO Fluence ($atoms/cm^2$)	MISSE 8 Ey ($cm^3/atom$)
M8-R1	Kapton H	5	2	0.079104	3.9953	1.4273	**4.62E+21**	3.00E-24*
M8-R2	Al-FEP**	5	1	0.009489	3.9969	2.1443	4.62E+21	2.39E-25
M8-R5	White Tedlar	1	7	0.004358	3.9945	1.6241	4.62E+21	1.45E-25
M8-R6	Hubble Space Telescope (HST) 9.7 yrs, Al-FEP**	5	1	0.009870	3.9925	2.137	4.62E+21	2.50E-25
M8-R7	PTFE	2	1	0.007712	3.9956	2.1503	4.62E+21	1.94E-25
M8-R9	FEP	2	1	0.009399	3.9924	2.1443	4.62E+21	2.37E-25
M8-R10	DC 93-500 silicone on fused silica	10	1	0.000076	3.9940	1.08	4.62E+21	3.81E-27

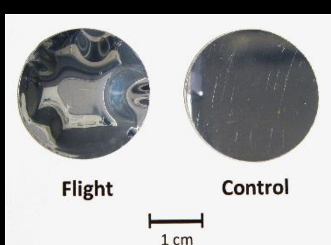
** Kapton H Ey based on prior LEO flight experiments*

*** FEP is space facing*

PTFE (M8-R7)



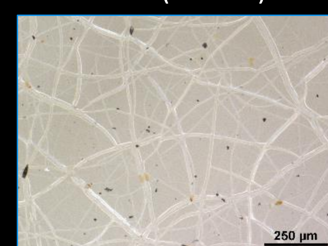
FEP (M8-R9)



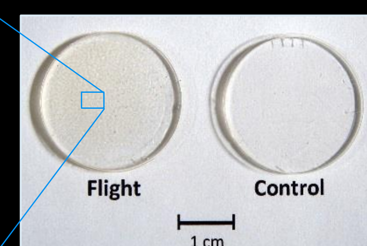
Al-FEP (M8-R2)

White Tedlar (M8-R5)

HST Al-FEP (M8-R6)



AO induced surface cracks



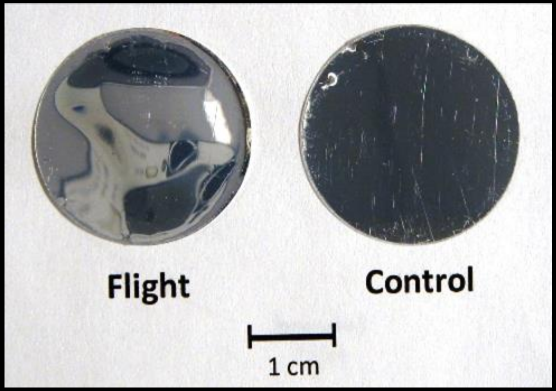
DC 93-500 (M8-R10)

MISSE 8 Wake Samples

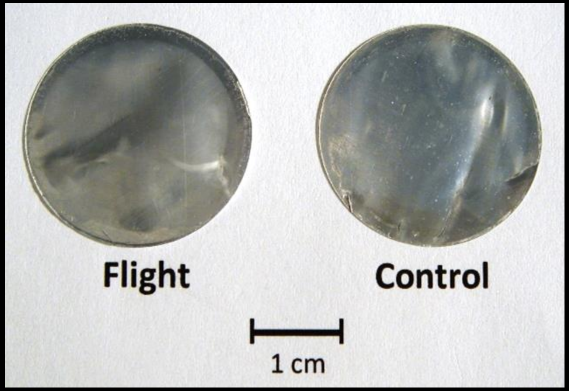
GRC ID	Material	Thickness (mil)	Number of layers	Mass Loss (g)	Bore Gauge Area (cm^2)	Density (g/cm^3)	AO Fluence ($atoms/cm^2$)	MISSE 8 Ey ($cm^3/atom$)
M8-W1	Kapton H	5	1	0.001523	4.0415	1.4273	**8.80E+19**	3.00E-24*
M8-W2	Al-FEP**	5	1	0.000839	4.0440	2.1443	8.80E+19	1.10E-24
M8-W10	HST Al-FEP** (9.7 yrs)	5	1	0.000790	4.0437	2.137	8.80E+19	1.04E-24
M8-W11	FEP	2	1	0.000827	4.0410	2.1443	8.80E+19	1.08E-24

** Kapton H Ey based on prior LEO flight experiments*

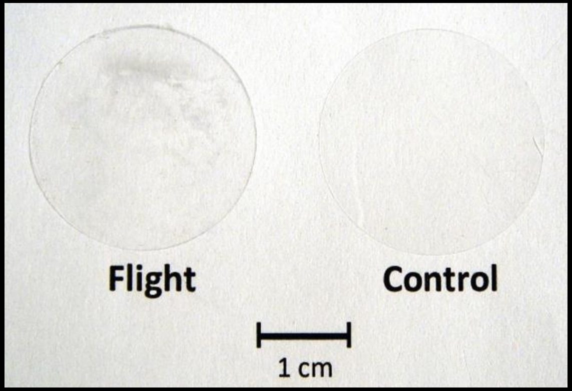
*** FEP is space facing*



Al-FEP (M8-W2)



HST Al-FEP (M8-W10)



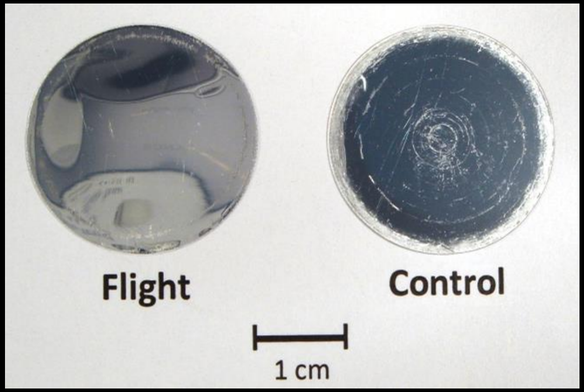
FEP (M8-W11)

MISSE 8 Zenith Tray Samples

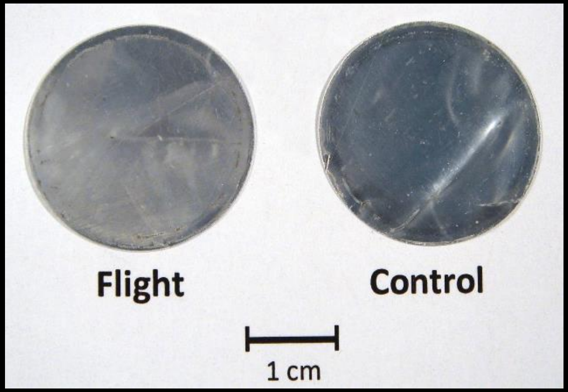
GRC ID	Material	Thickness (mil)	Number of layers	Mass Loss (g)	Bore Gauge Area (cm^2)	Density (g/cm^3)	AO Fluence ($atoms/cm^2$)	MISSE 8 Ey ($cm^3/atom$)
M8-Z1B	Kapton H	5	1	0.000670	3.8771	1.4273	**4.04E+19**	3.00E-24*
M8-Z2B	FEP	2	1	0.001916	3.8772	2.1443	4.04E+19	5.71E-24
M8-Z3B	Al-FEP**	5	1	0.002120	3.8742	2.1443	4.04E+19	6.32E-24
M8-Z4B	HST Al-FEP** (9.7 yrs)	5	1	0.002113	3.8774	2.137	4.04E+19	6.32E-24

** Kapton H Ey based on prior LEO flight experiments*

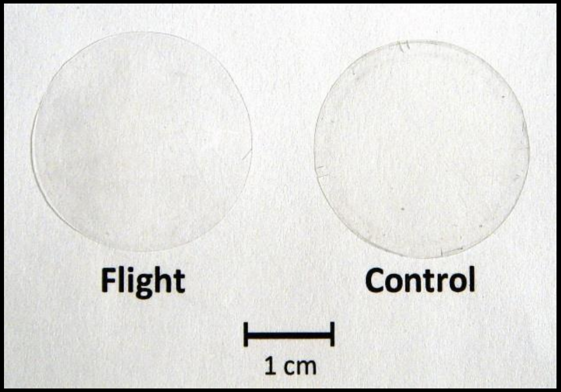
*** FEP is space facing*



Al-FEP (M8-Z3B)



HST Al-FEP (M8-Z4B)



FEP (M8-Z2B)

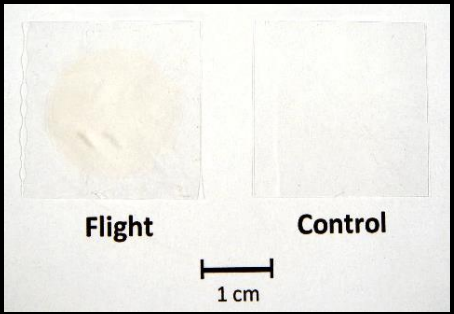
Note: Control samples were loaded into, and stored in, trays

MISSE 8 Zenith Taped Samples

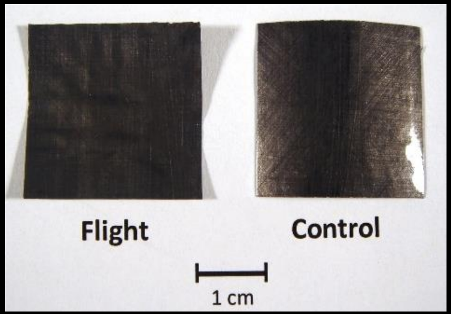
GRC ID	Material	Thickness (mil)	Number of layers	Mass Loss (g)	Bore Gauge Area (cm^2)	Density (g/cm^3)	AO Fluence ($atoms/cm^2$)	MISSE 8 Ey ($cm^3/atom$)
M8-1	Kapton H	5	1	0.002330	2.7819	1.4273	**1.96E+20**	3.00E-24*
M8-2	Pyrolytic Graphite	80	1	0.000513	2.9277	2.22	1.96E+20	4.04E-25
M8-3	FEP	2	1	0.001573	2.7310	2.1443	1.96E+20	1.37E-24
M8-4	C-FEP**	2	1	0.004134	2.7264	2.1443	1.96E+20	3.61E-24
M8-5	Al-FEP**	2	1	0.002172	2.7213	2.1443	1.96E+20	1.90E-24
M8-10	Ag-FEP**	5	1	0.001565	2.7606	2.1443	1.96E+20	1.35E-24

** Kapton H Ey based on prior LEO flight experiments*

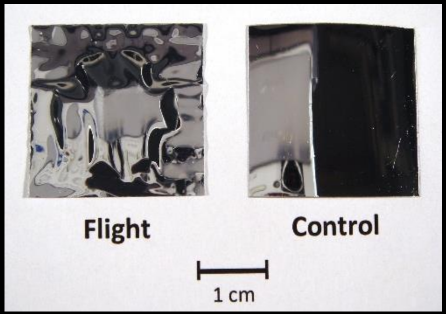
*** FEP is space facing*



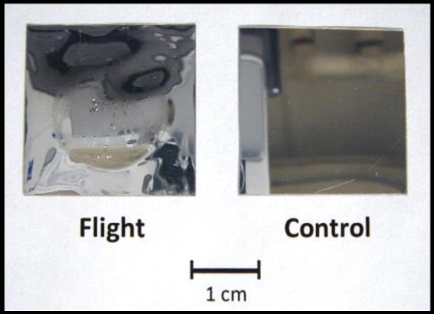
FEP (M8-3)



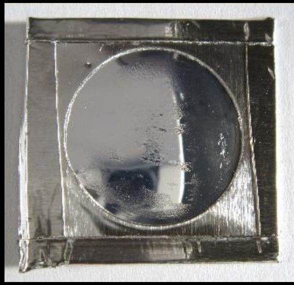
C-FEP (M8-4)



Al-FEP (M8-5)



Ag-FEP (M8-10)



The Ey of C-FEP was 1.9X greater than Al-FEP:

⇒ Heating has a significant impact on the erosion of FEP

MISSE 8 Teflon FEP
Ram vs Wake vs Zenith Ey

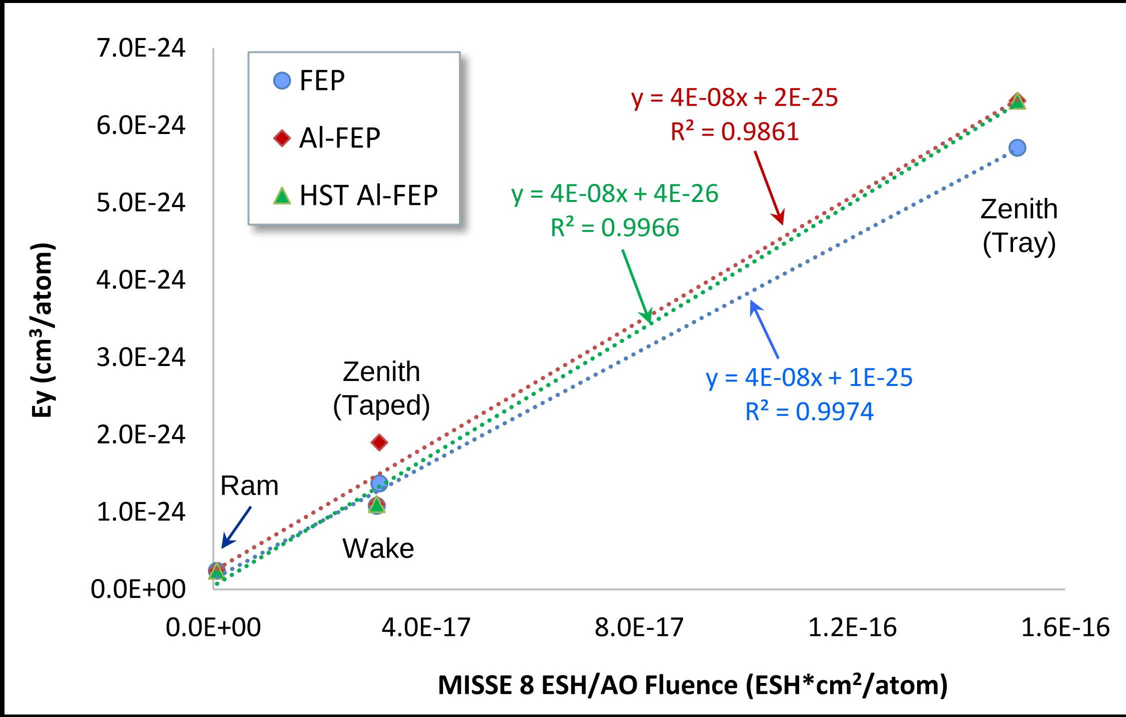
Orientation	MISSE 8 ESH	MISSE 8 AO Fluence (atoms/cm^2)	ESH/AO Fluence (ESH*cm^2/atom)	FEP Ey (cm^3/atom)	Al-FEP Ey (cm^3/atom)	HST Al-FEP Ey (cm^3/atom)
Ram	3,200	4.62E+21	6.92E-19	2.37E-25	2.39E-25	2.39E-25
Wake	2,700	8.80E+19	3.07E-17	1.08E-24	1.10E-24	1.10E-24
Zenith (Taped)	6,100	1.96E+20	3.12E-17	1.37E-24	1.90E-24	-
Zenith (Tray)	6,100	4.04E+19	1.51E-16	5.71E-24	6.32E-24	6.32E-24

Al-FEP consistently slightly higher than FEP

MISSE 8 FEP
Ey vs. ESH/AO Fluence

Excellent correlation of Ey to ESH/AO F ratio:

⇒ *Shows the effect of solar radiation and/or heating due to solar exposure on erosion of FEP*



MISSE 8 Teflon FEP

Ram vs Wake vs Zenith Ey

Orientation	MISSE 8 ESH	MISSE 8 AO Fluence (atoms/cm^2)	ESH/AO Fluence (ESH*cm^2/atom)	FEP Ey (cm3/atom)	Al-FEP Ey (cm^3/atom)	HST Al-FEP Ey (cm^3/atom)	C-FEP Ey (cm^3/atom)
Ram	3,200	4.62E+21	6.92E-19	2.37E-25	2.39E-25	2.39E-25	-
Wake	2,700	8.80E+19	3.07E-17	1.08E-24	1.10E-24	1.10E-24	-
Zenith (Taped)	6,100	1.96E+20	3.12E-17	1.37E-24	1.90E-24	-	3.61E-24
Zenith (Tray)	6,100	4.04E+19	1.51E-16	5.71E-24	6.32E-24	6.32E-24	-

Al-FEP consistently slightly higher than FEP

Temperature Estimates:

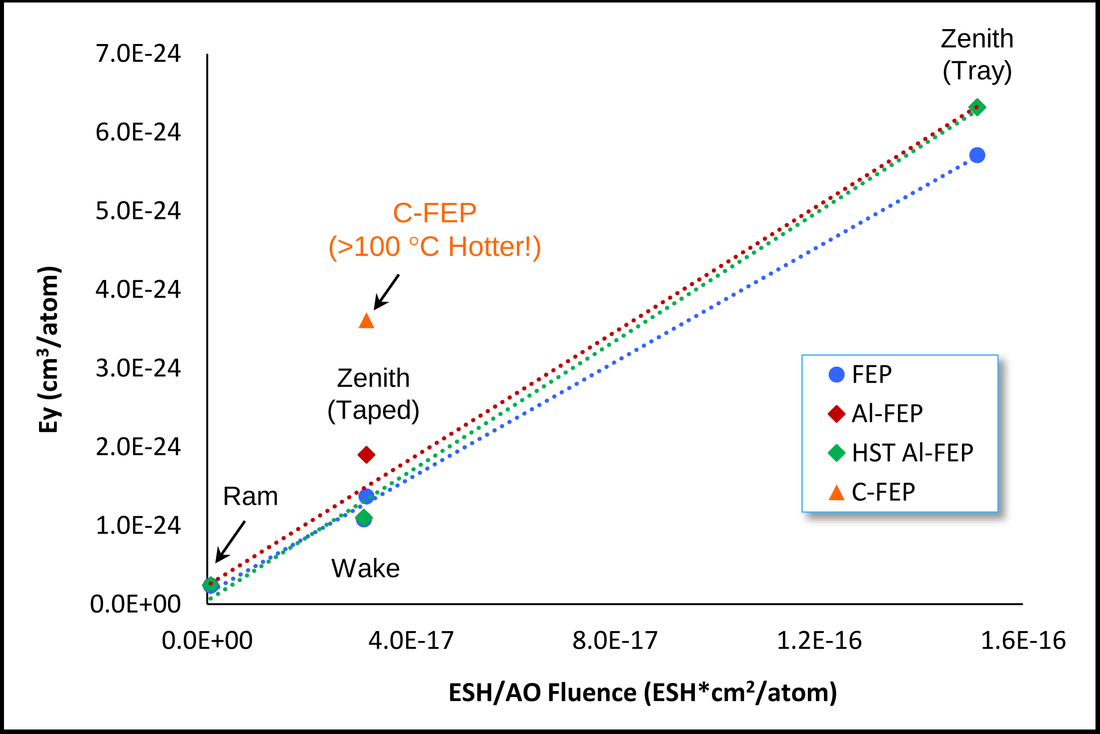
Assumptions:

- *Same sample configuration and orientation*
- *Solar absorptance:*
  - *0.179 for 2 mil Al- FEP*
  - *0.96 for 2 mil C-FEP*
- *Thermal emittance:*
  - *0.66 for both*
- *Constraint:*
  - *Radiated heat is ejected only in the space direction (due to Al on the back or Al in the sample holder)*

Maximum temperature:

- *Al-FEP: 2°C*
- *C-FEP: 170 °C*

Ey vs. ESH/AO F



Heating has a major impact on the Ey of FEP in the zenith orientation

Summary & Conclusions

- The MISSE 8 Polymers Experiment was successfully flown & exposed to the LEO space environment for 2-2.14 years
  - *Samples flown in ram, wake & zenith orientations ⇒ received different exposures*
  - *Kapton H samples were used to determine the AO fluence in each orientation*
    - *The AO fluence on grazing surfaces is dependent on the sample holder geometry*
- LEO Ey of 17 samples were determined based on:
  - *Mass loss, density, surface area & AO fluence*
- Ey of FEP was dependent on orientation, hence environmental exposure:
  - *The zenith & wake exposures (high ESH/AO fluence) provided an order of magnitude greater Ey than ram exposure*
  - *FEP Ey increased with a direct correlation to the* ***ESH/AO fluence*** *ratio showing the effect of solar radiation and/or heating due to solar exposure on FEP erosion*
- C-FEP had a significantly higher Ey than FEP or Al-FEP in zenith orientation
  - *Heating has a significant impact on the erosion of FEP*
- MISSE flight data is available in MISSE MAPTIS Database *http://maptis.nasa.gov/*
  - *MAPTIS: Materials and Processing Technical Information System*

Acknowledgements

We would like to express our sincere appreciation to Phil Jenkins (NRL, MISSE 8 Mission PI) for providing the opportunity to fly this experiment as part of the MISSE 8 mission

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Extra Slides

Materials and Processing Technical Information System (MAPTIS) MISSE Database

http://maptis.nasa.gov/

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