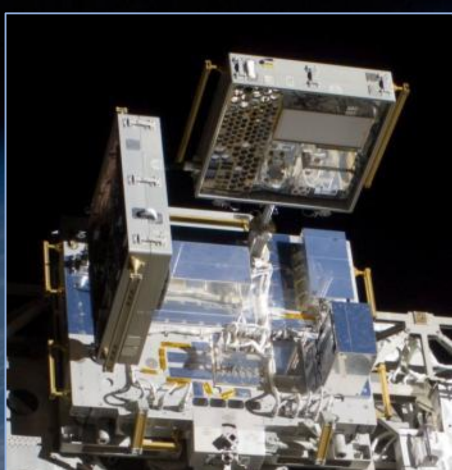
Effect of 1.5 Years of Space Exposure on Tensile and Optical Properties of Spacecraft Polymers

Kim K. de Groh[1], Bruce A. Perry[2], Bruce A. Banks[3], Halle A. Leneghan[4], Olivia C. Asmar[4] and Athena Haloua[4]

[1]NASA Glenn Research Center, Cleveland, OH
[2]Ohio Aerospace Institute, Brook Park, OH
[3]SAIC at NASA Glenn, Cleveland OH
[4]Hathaway Brown School, Shaker Heights, OH

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

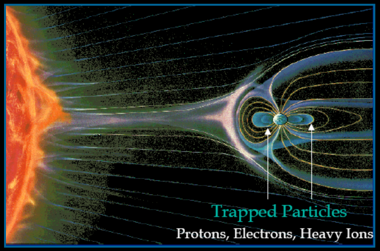


MISSE 7A & 7B

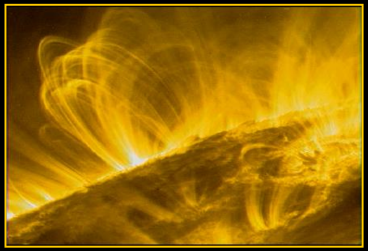
April 2010
(STS-131)

Outline

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

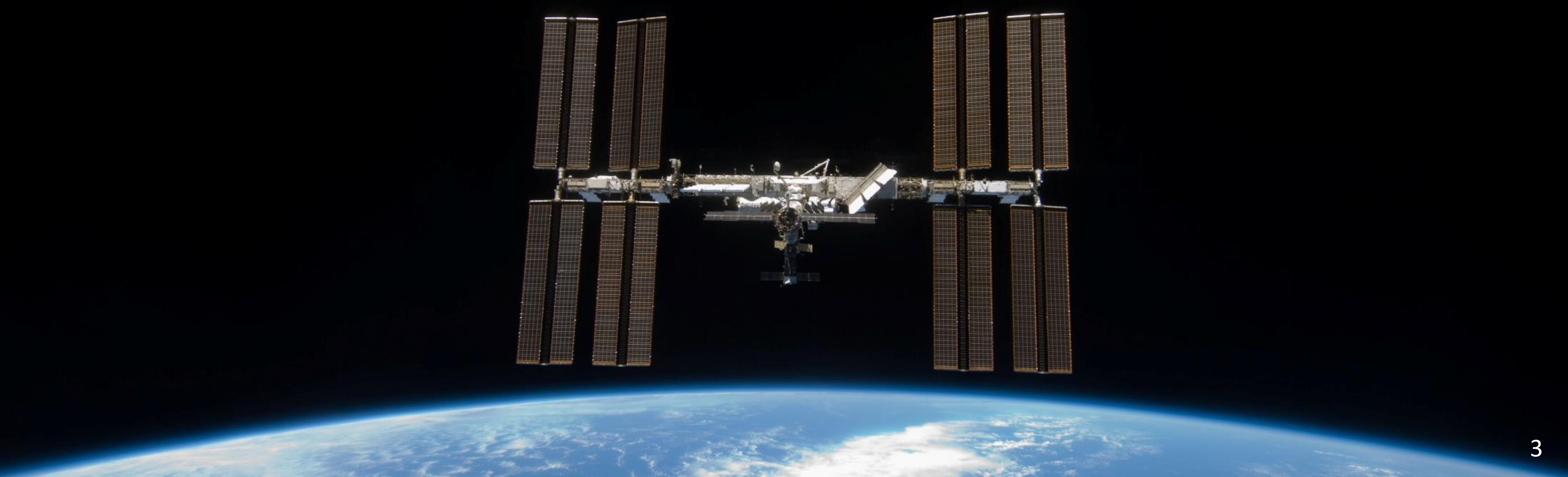


The Space Environment

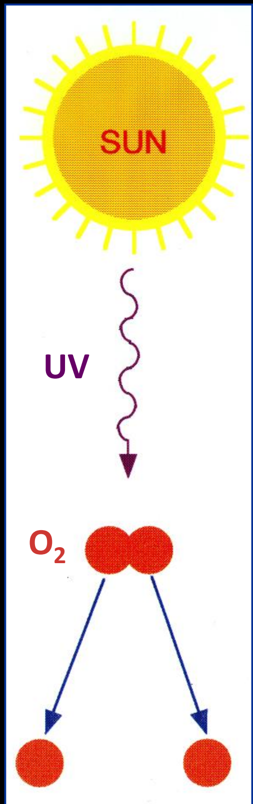


In low Earth orbit (LEO) environmental threats include:

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



Atomic Oxygen (AO)

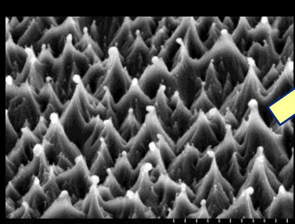


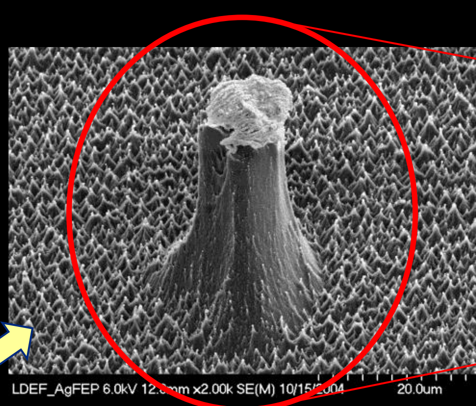
Atomic Oxygen

- AO is the predominant species in LEO (≈180-650 km)
- It is formed by photodissociation of molecular oxygen (O_2) by short wavelength energetic UV radiation
- At ram impact velocities (7.66 km/s) the average impact energy is 4.5 eV
- AO oxidizes certain spacecraft materials such as polymers, resulting in gas formation - so *the material erodes away...*

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

Ram AO erosion causes "cone" formation





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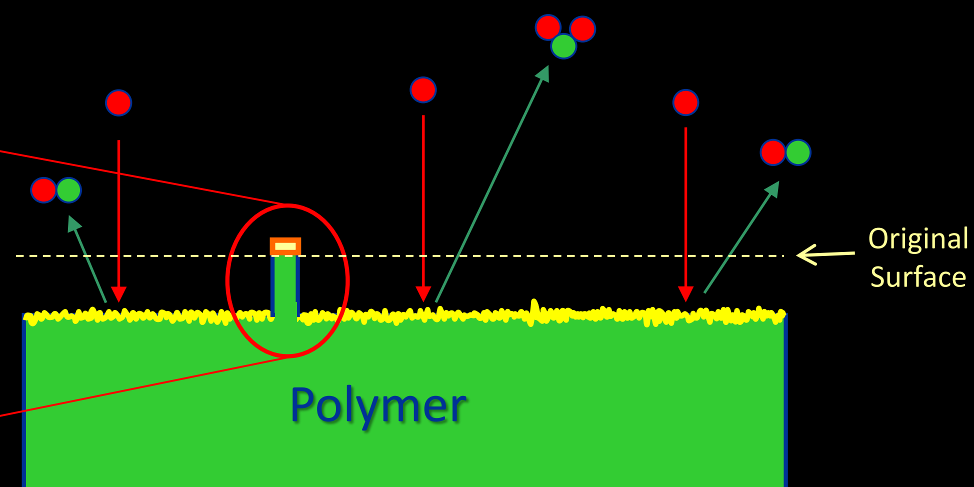
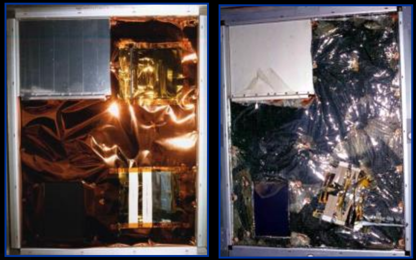


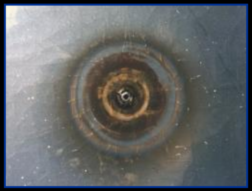
Space Environment Induced Degradation

Radiation induced darkening

Pre-flight Post-flight

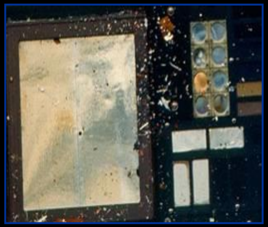


AO erosion of Kapton blanket

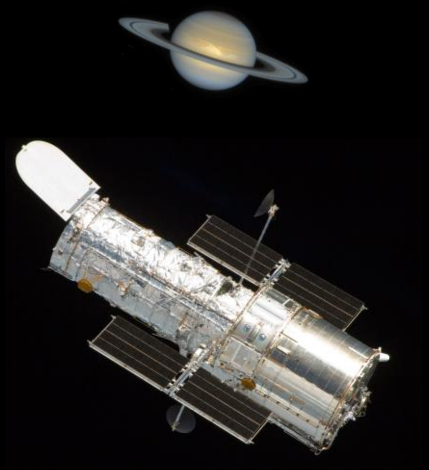


Impact site

Long Duration Exposure Facility **(LDEF)**
5.8 yrs in space

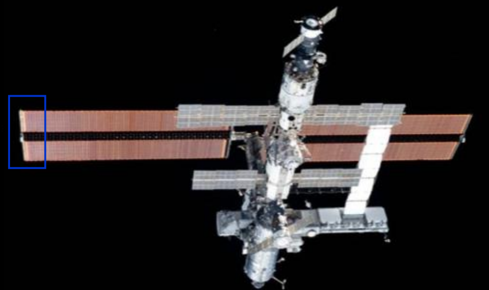


Debris generation



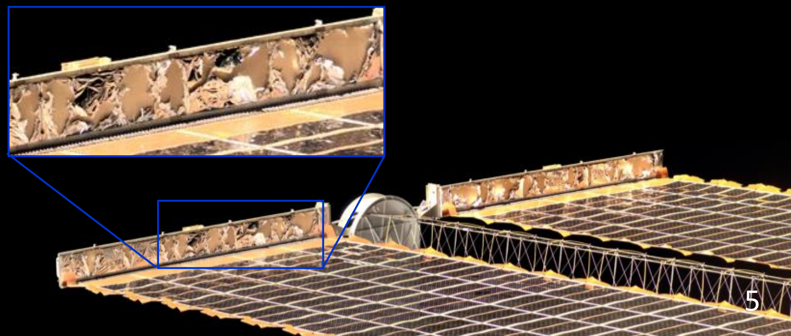
Hubble Space Telescope (HST)

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



International Space Station (ISS)
2001

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



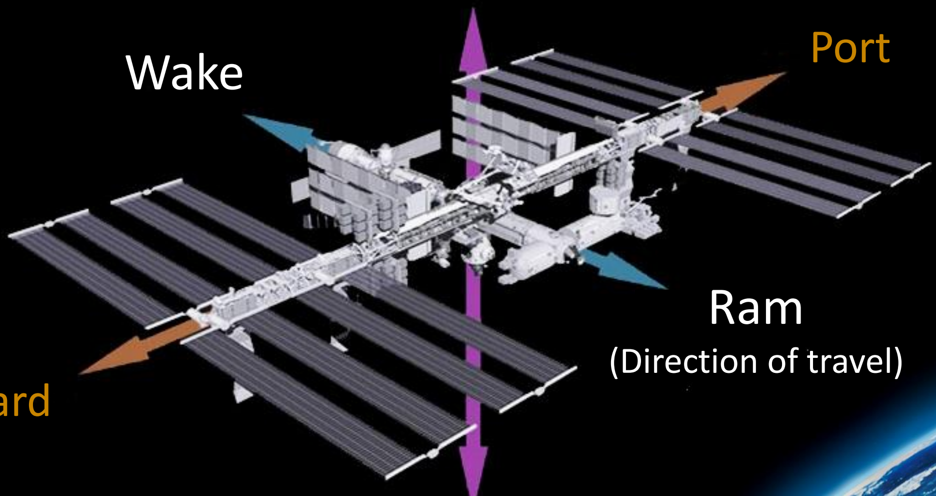
Materials International Space Station Experiment (MISSE)

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).

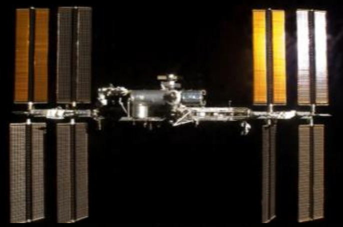
The PECs were positioned in either a *ram/wake orientation* or a *zenith/nadir orientation*.

Objective:

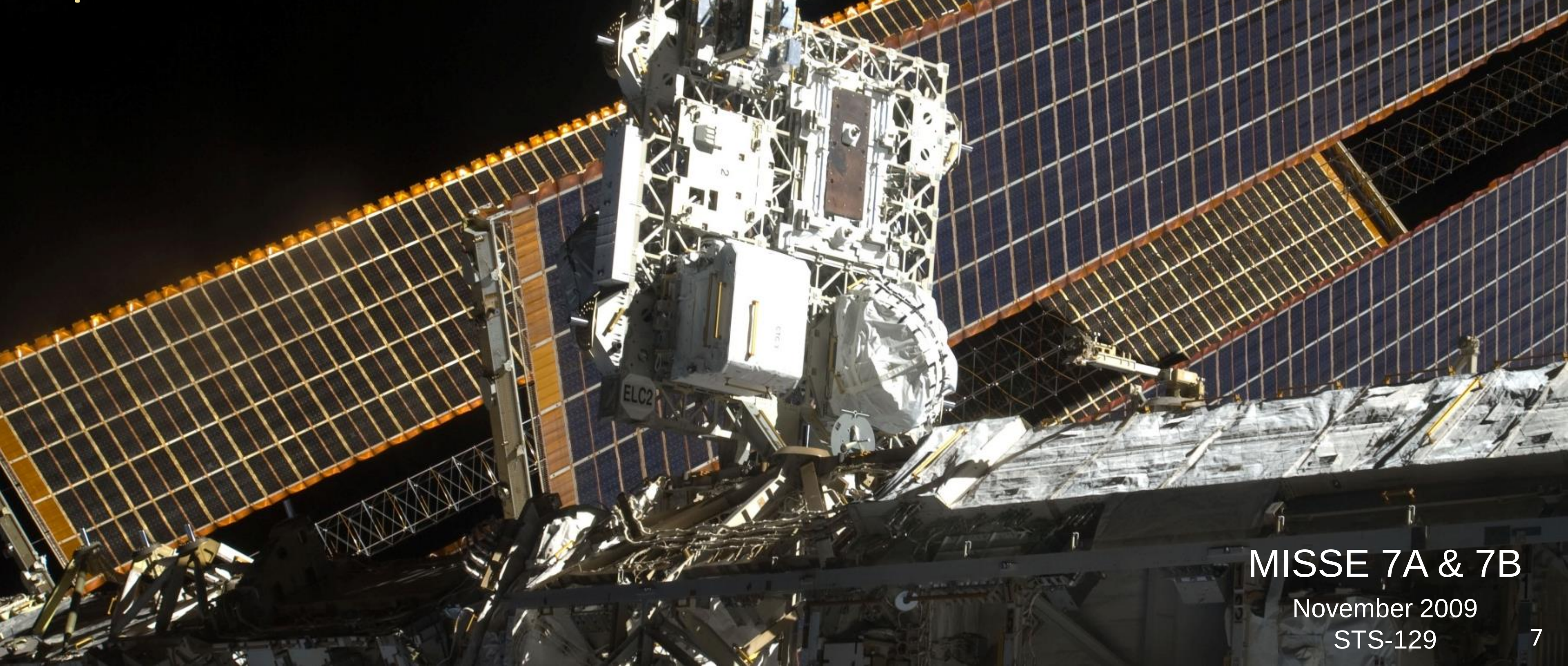
To test the stability and durability of materials and devices in the space environment



MISSE 7A & 7B



PI: Phil Jenkins/Naval Research Laboratory (NRL)
Experiment type: Active & Passive
Orientation: 7A - Zenith/Nadir, 7B - Ram/Wake
ISS Location: EXPRESS Logistics Carrier 2 (ELC 2)
Deployed: November 23, 2009 (STS-129)
Retrieved: May 20, 2011 (STS-134)
Exposure: 1.49 Years



MISSE 7A & 7B
November 2009
STS-129

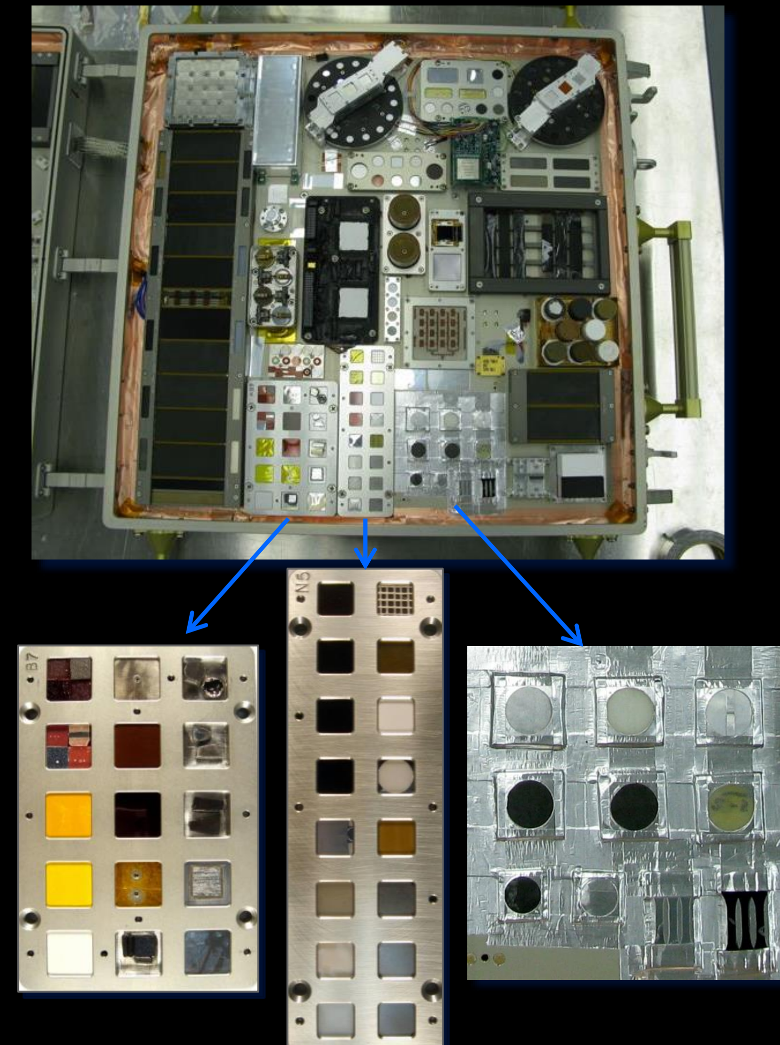
MISSE 7B Polymers Experiment

The MISSE 7B Polymers Experiment is a passive experiment that contained 44 samples flown in ram or wake flight orientations on MISSE 7B

Objectives:

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

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



Pre-flight photo of the ram side if MISSE 7B with images of B7-R & NR-5 trays and taped samples

MISSE 7A Zenith Polymers Experiment

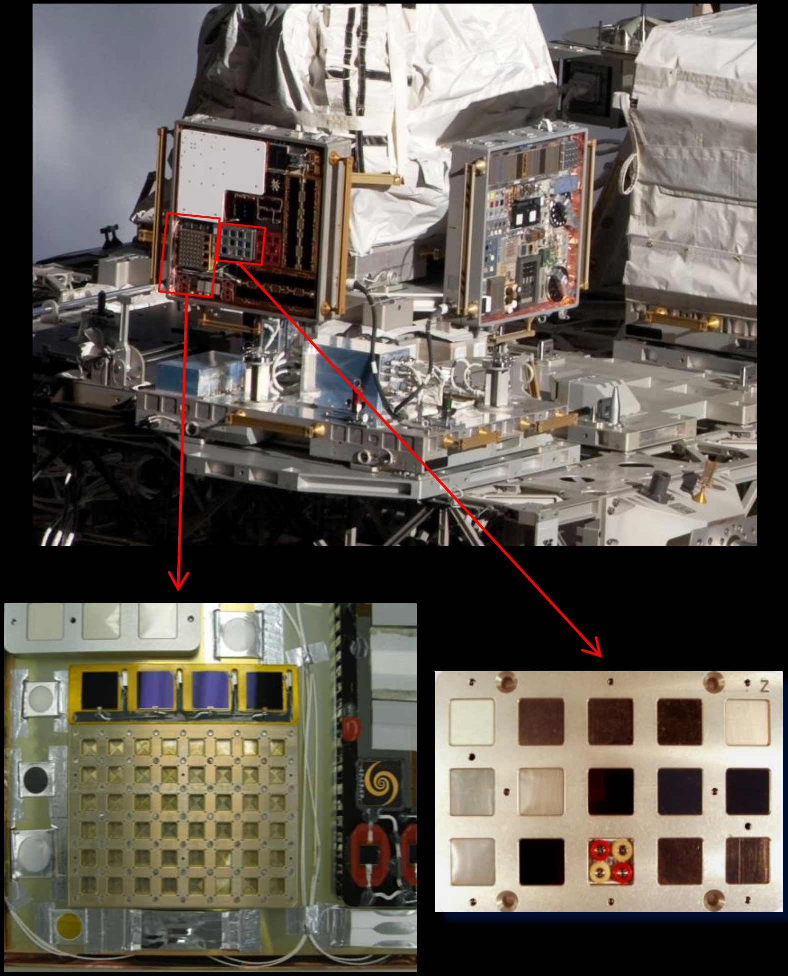
The MISSE 7A Zenith Polymers Experiment is a passive experiment that contained 25 samples flown in a zenith flight orientation on MISSE 7A

Objectives:

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

- 25 samples were flown in the zenith orientation, exposing them to *high solar radiation & grazing AO*
  - *15 samples in the "Z" tray (1" x 1" samples)*
  - *10 samples in Al holders taped to the baseplate*
- 6 tensile samples were also flown in a nadir orientation
- Kapton H® was flown for AO fluence determination

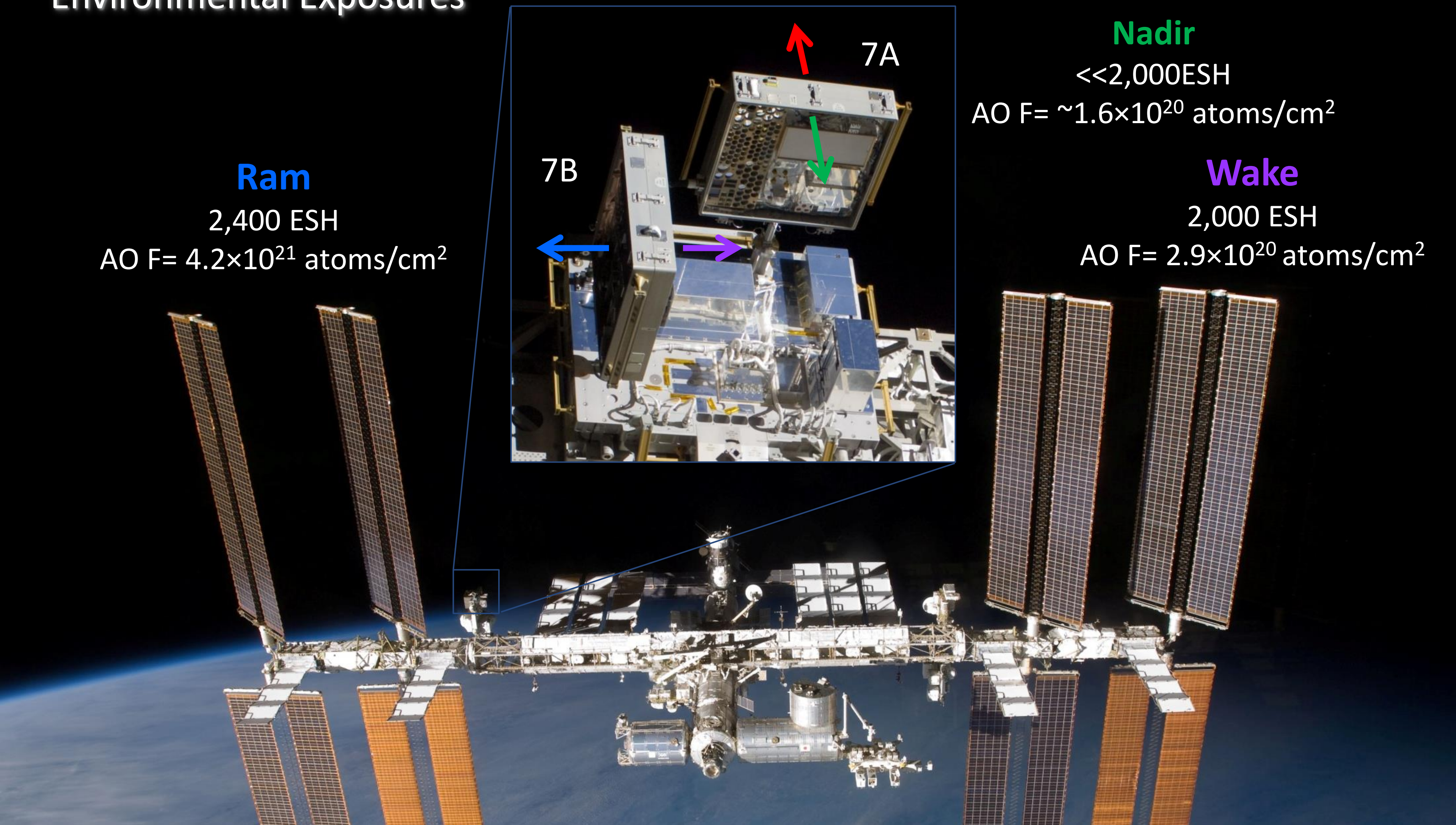
MISSE 7A (left) on the ISS



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

MISSE 7A & 7B

Environmental Exposures



Environment data references:

1. Yi, G. T., et al., NASA TM-2013-217848

2. Finckenor, M. M., et al. 2012 NSMMS, Tampa, FL, June 2012

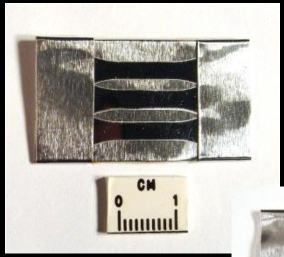
Effect of 1.5 Years of Ram, Wake, Zenith and Nadir Space Exposure on Tensile Properties of Teflon

MISSE 7 Tensile Samples Experiment

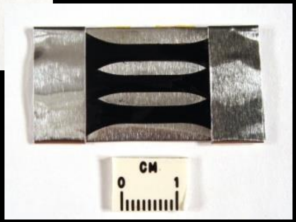
19 Tensile Samples

GRC Sample ID	Sample	Thickness (mil)	# Samples	Purpose	MISSE Location
E7	Back surface aluminized fluorinated ethylene propylene (Al-FEP)	2	3	To determine embrittlement of FEP	7B Ram
E23	Carbon paint back-surface coated FEP (C-FEP)	2	3	Effect of heating on the embrittlement of FEP	7B Ram
E6	Al-FEP	2	2	To determine embrittlement of FEP	7B Wake
E8	Expanded-polytetrafluoroethylene (ePTFE)	44	2	To determine embrittlement of ePTFE	7A Zenith
E12	Al-FEP	2	3	To determine embrittlement of FEP	7A Zenith
H2	Al-FEP	2	3	To determine embrittlement of FEP	7A Nadir
H3	Al-FEP	2	3	To determine embrittlement of FEP	7A Nadir

Ram Samples

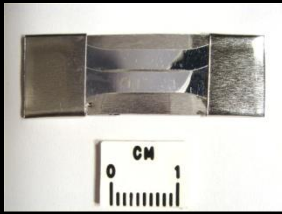


E7



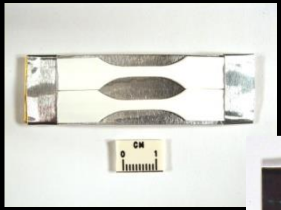
E23

Wake Samples

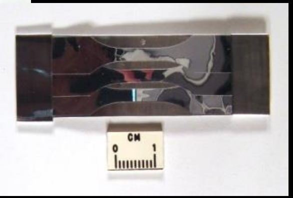


E6

Zenith Samples



E8



E12

Nadir Samples

H2

H3

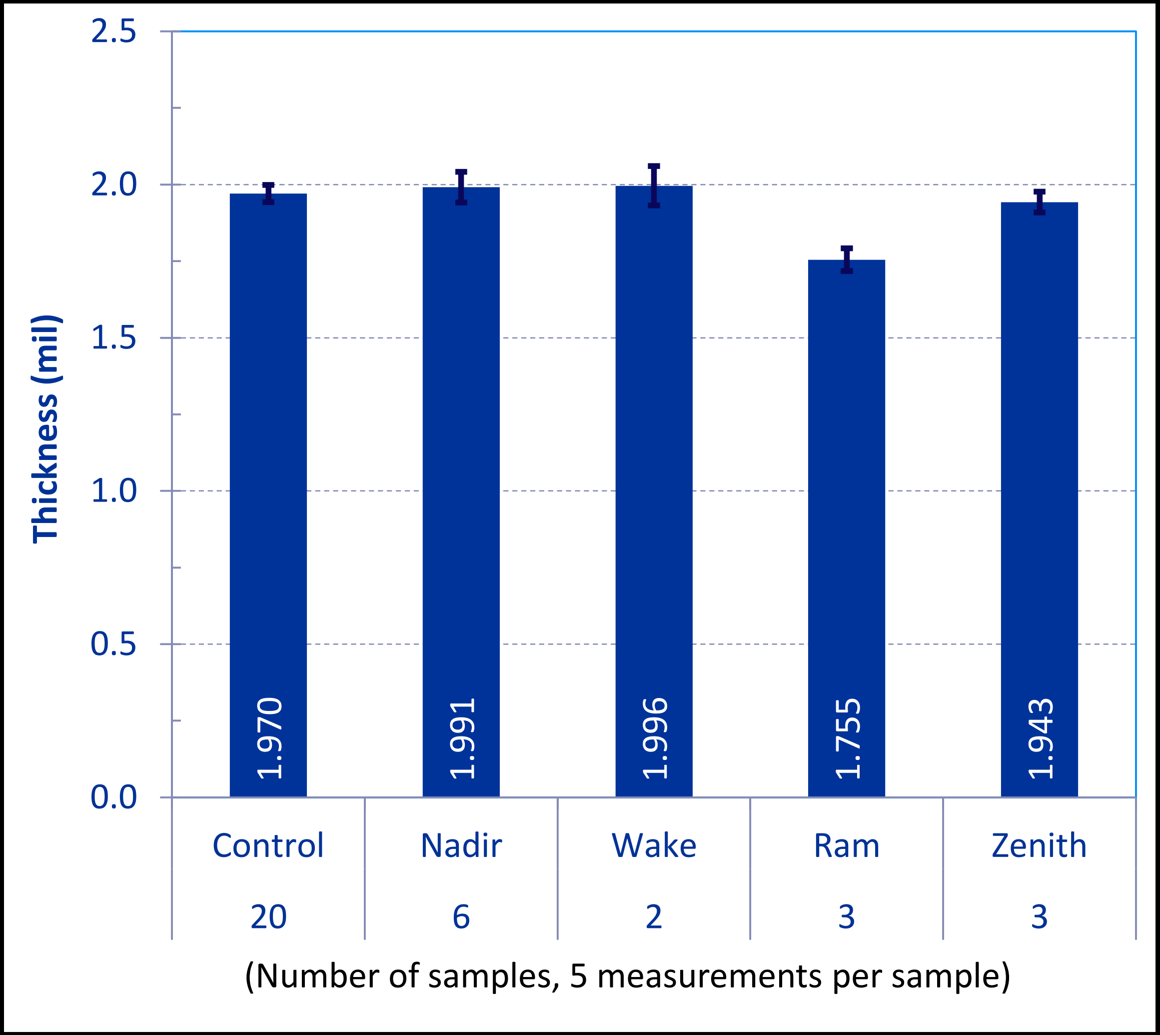
Pre-flight photos

Experimental Procedures

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

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

Thickness Measurements
2 mil Aluminized-FEP (Al-FEP)



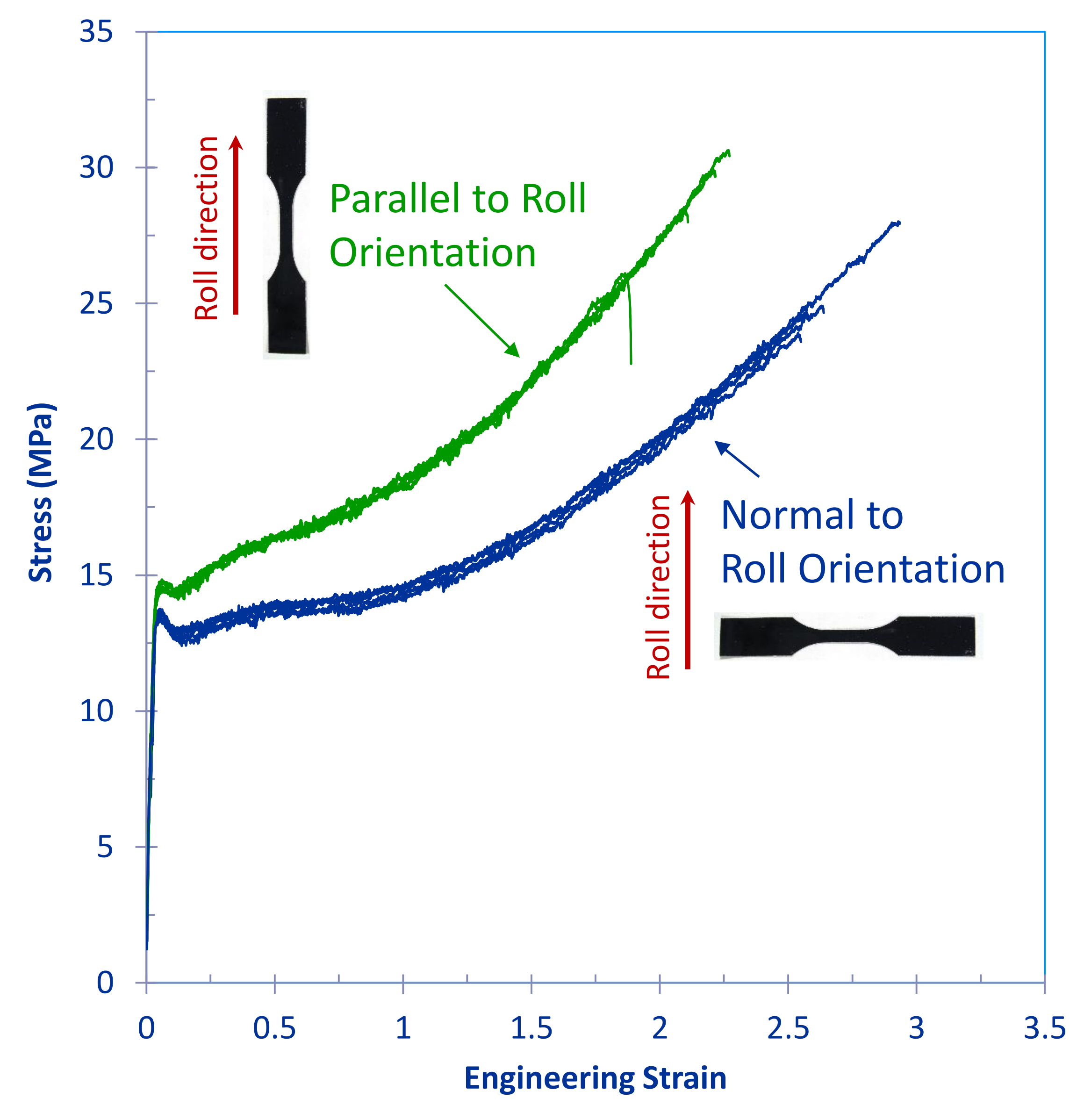
2-mil Al-FEP:

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

Tensile Properties

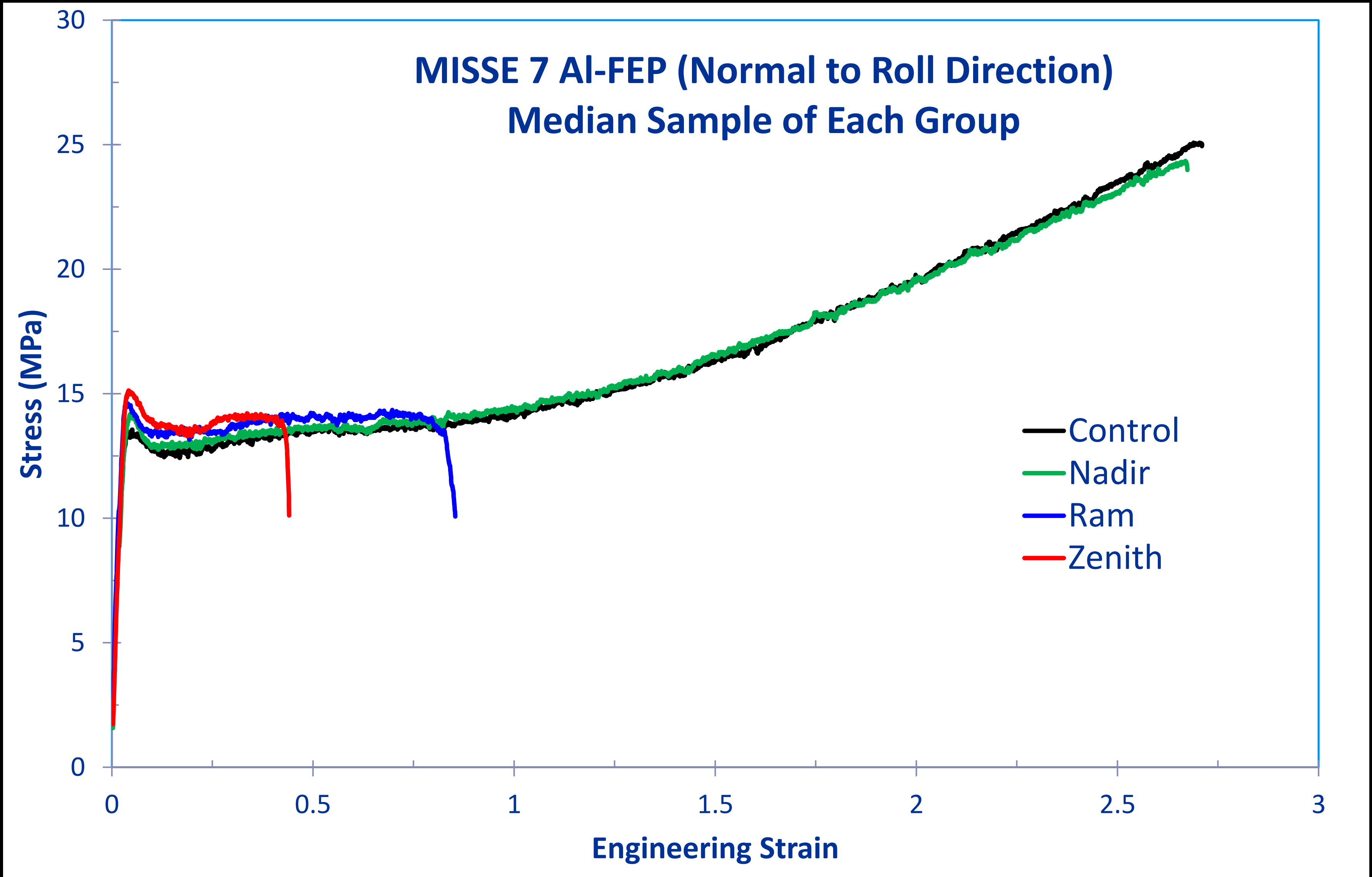
Pristine Al-FEP (2 mil thick)

- A clear difference was observed between samples punched out parallel and normal to the roll direction
- Therefore, comparisons were only made between samples punched in the same orientation
- The “punch orientation” of the MISSE samples was not known, but was determined based on which type of stress-strain curve the samples produced



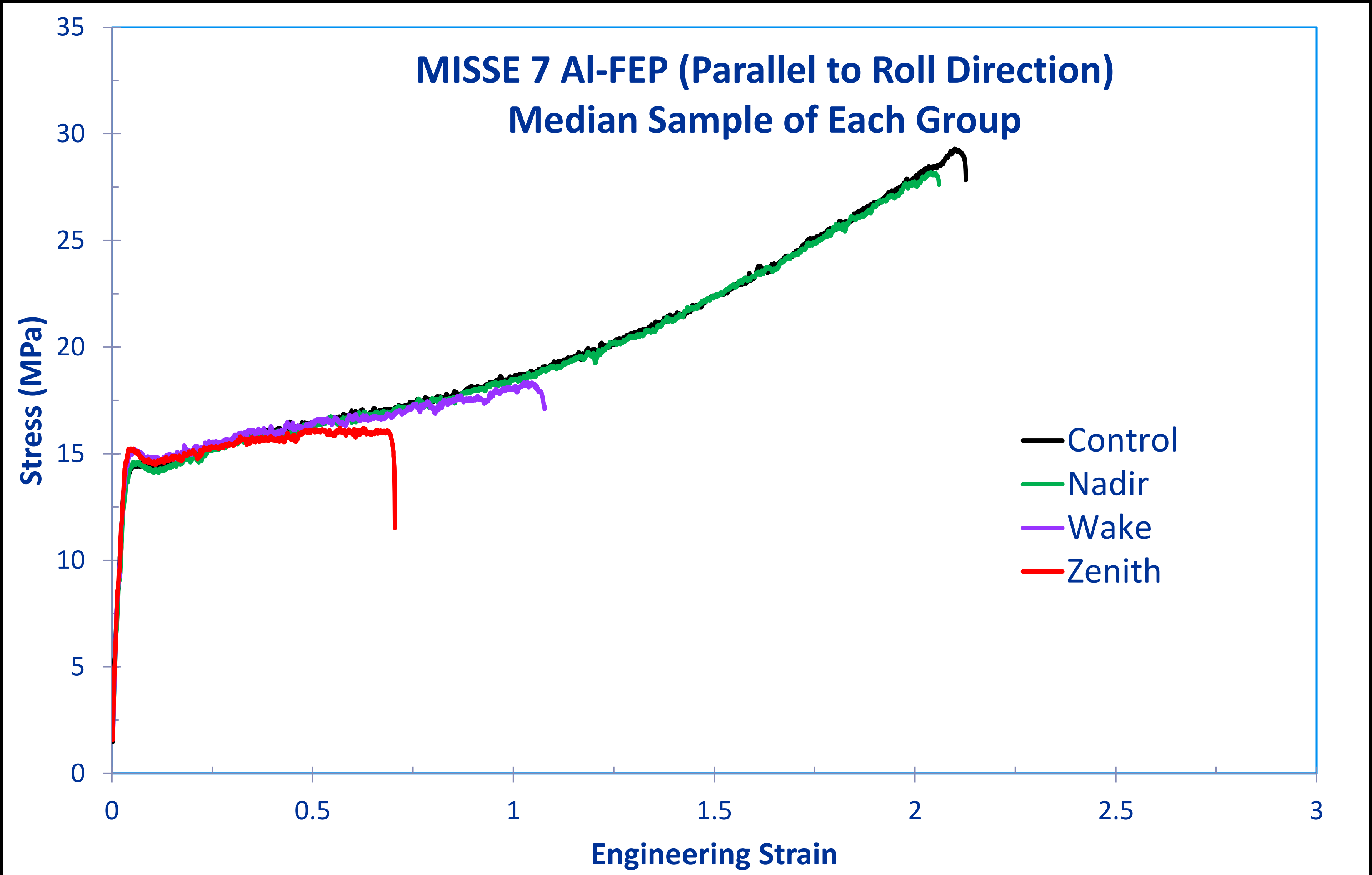
MISSE 7 Tensile Samples Experiment

Al-FEP Tensile Data



MISSE 7 Tensile Samples Experiment

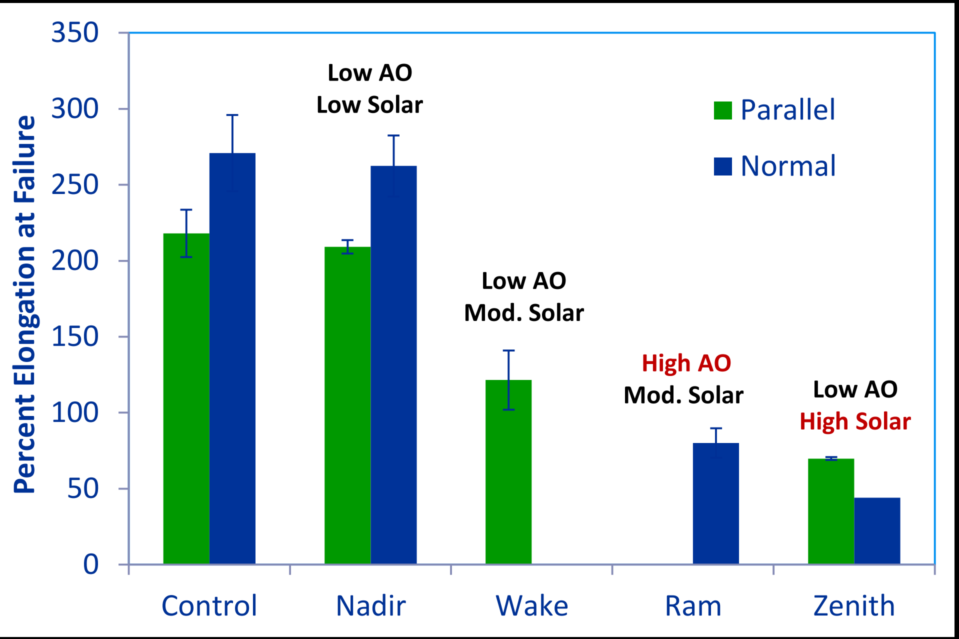
Al-FEP Tensile Data

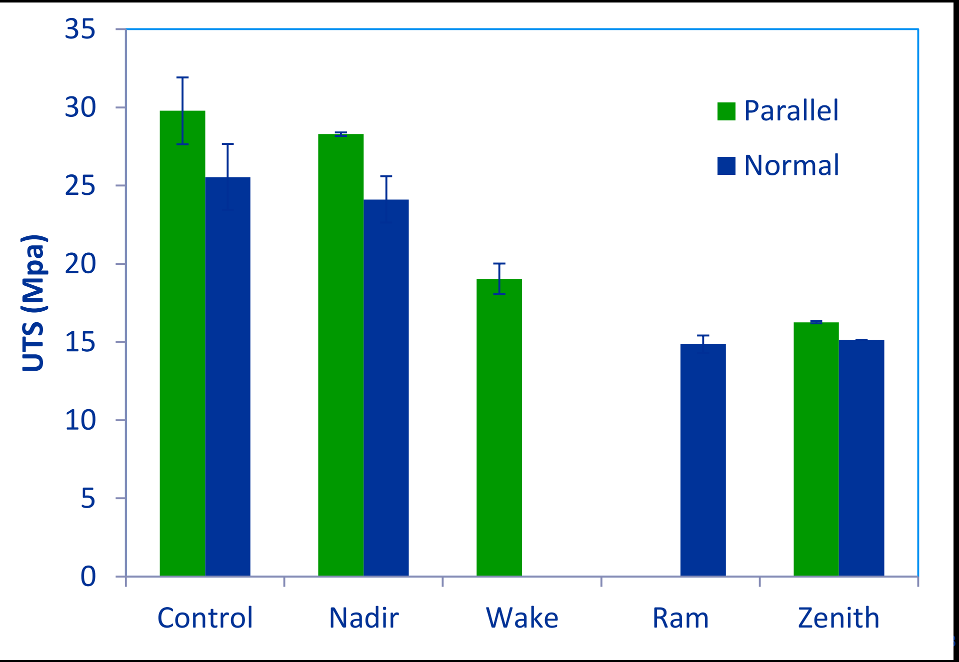


MISSE 7 Al-FEP Tensile Data

Roll Direction	Exposure	# Samples	Average UTS (MPa)	Average E%	St. Dev. UTS (MPa)	St. Dev. E%
Parallel	Control	7	29.8	218.1	2.1	15.6
	Nadir	2	28.3	209.1	0.1	4.5
	Wake	2	19.0	121.5	1.0	19.5
	Ram	-	-	-	-	-
	Zenith	2	16.3	69.8	0.1	1.0
Normal	Control	12	25.5	270.9	2.1	25.0
	Nadir	4	24.1	262.4	1.5	20.1
	Wake	-	-	-	-	-
	Ram	3	14.9	80.0	0.6	9.7
	Zenith	1	15.1	44.1	-	-

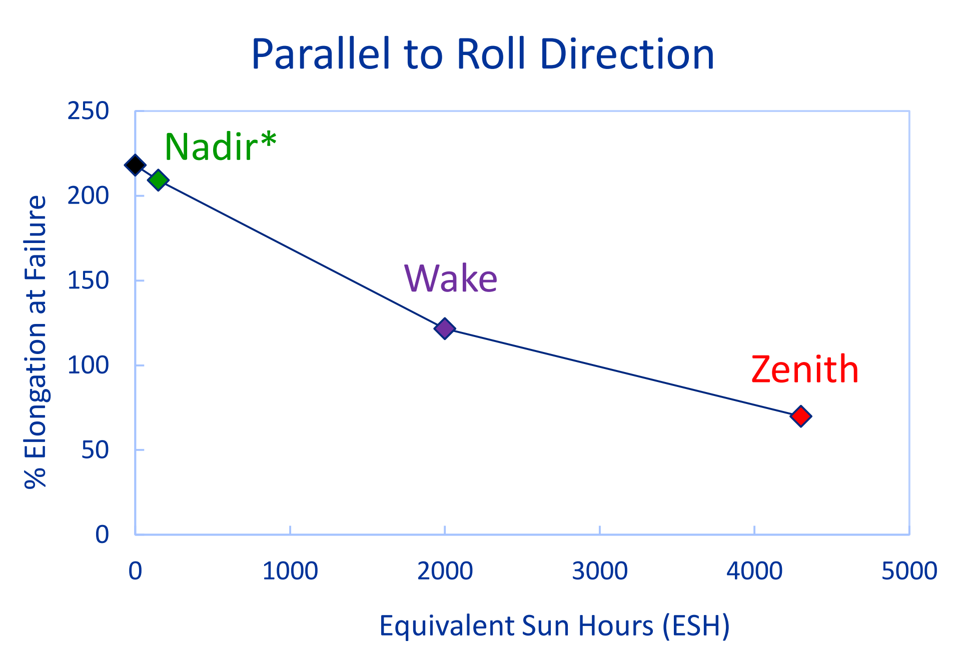
UTS: Ultimate Tensile Strength

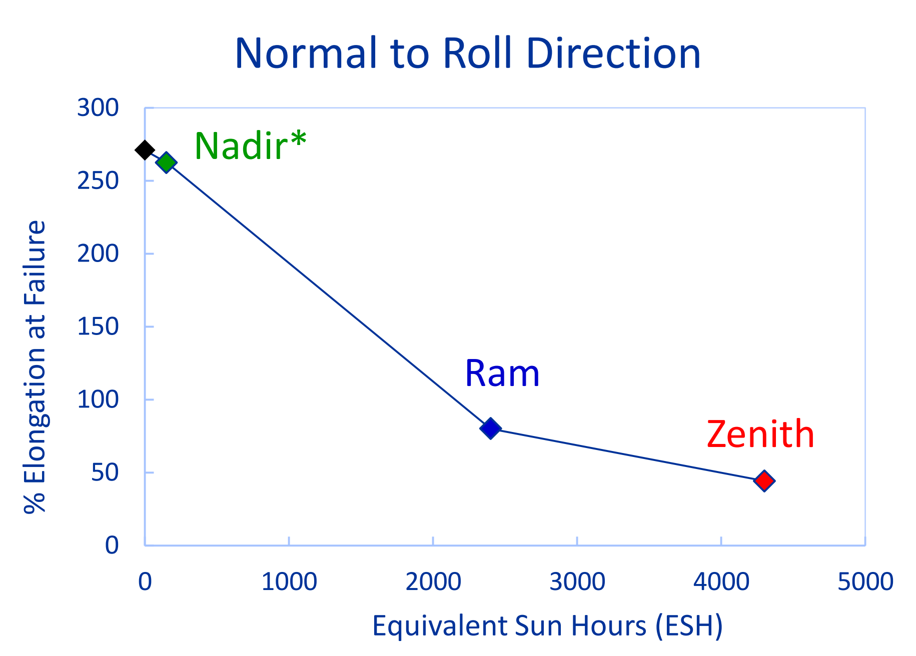




MISSE 7 Al-FEP

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





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

Nadir	Wake	Ram	Zenith
150 ESH*	2,000 ESH	2,400 ESH	4,300 ESH
AO F= ~1.6×10^{20} atoms/cm^2	2.9×10^{20} atoms/cm^2	4.2×10^{21} atoms/cm^2	1.6×10^{20} atoms/cm^2

MISSE 7 Tensile Samples Experiment

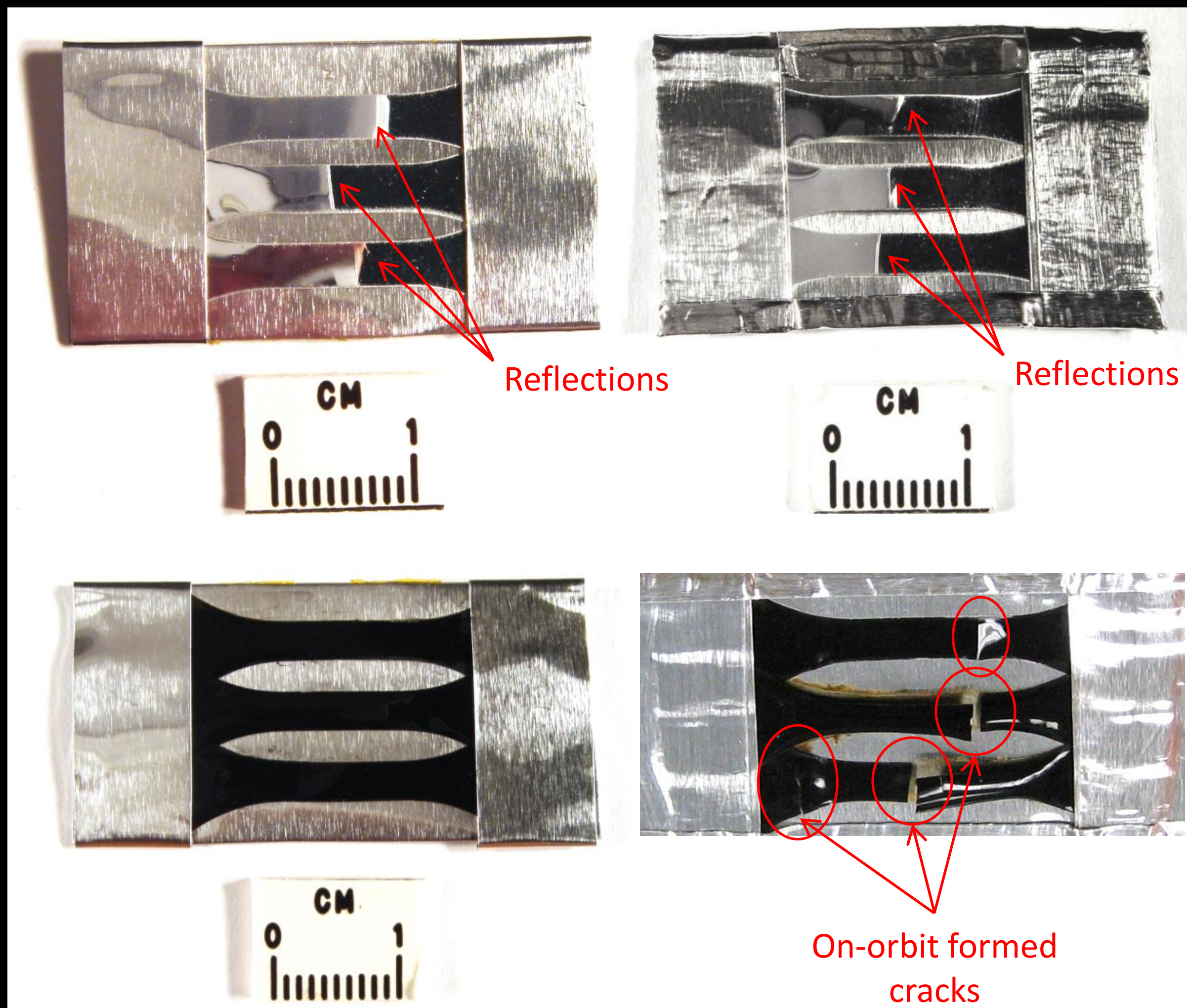
Al-FEP & C-FEP Ram Samples

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

Pre-Flight | Post-Flight

E7: Al-FEP

E23: C-FEP



<u>Control</u>
UTS: 25.5 MPa
Elongation: 271%

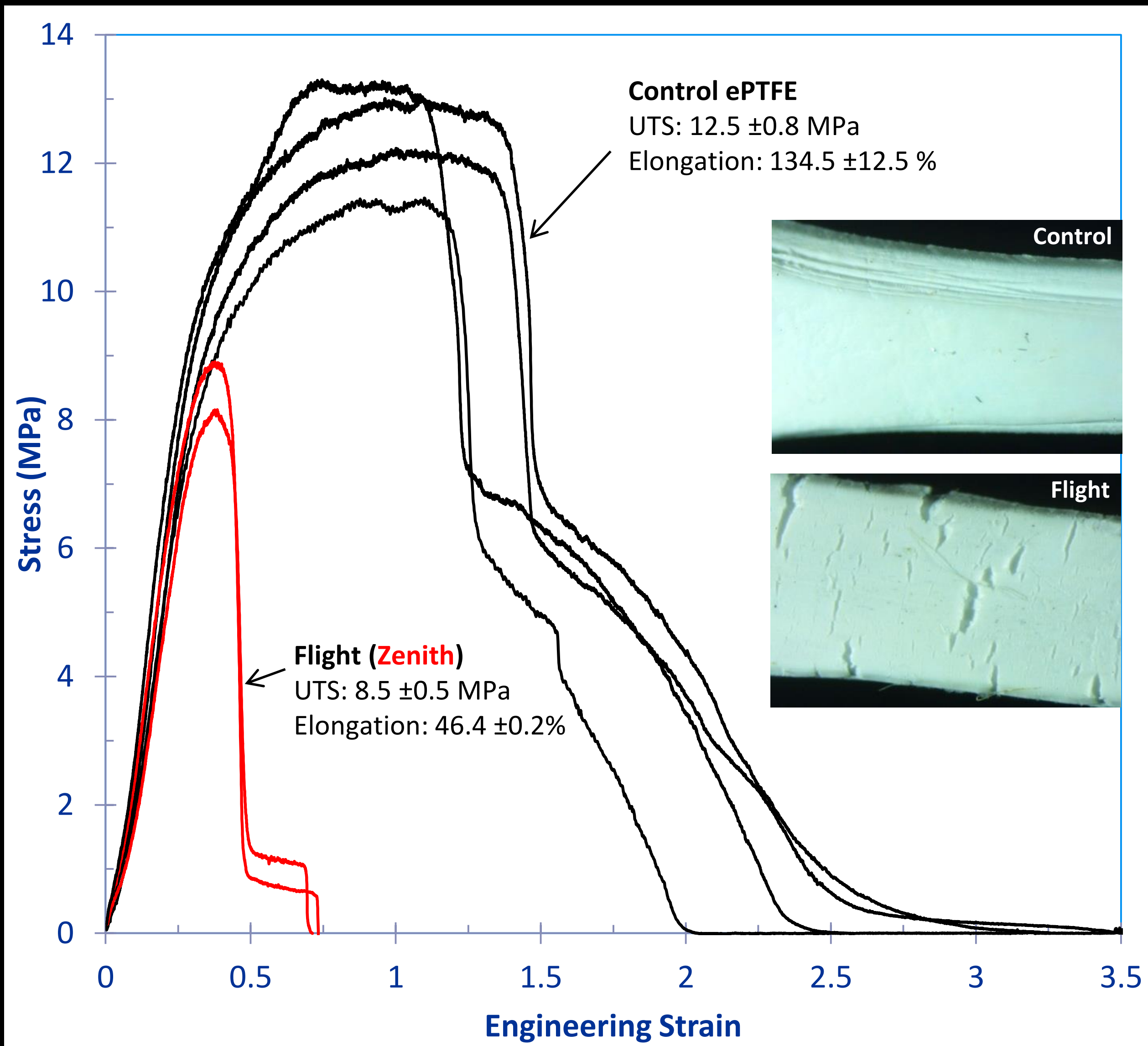
<u>E7</u>
UTS: 14.9 MPa
Elongation: 80%

<u>Control</u>
UTS: 15.1 MPa
Elongation: 232%

<u>E23</u>
UTS: 0 MPa
Elongation: 0%
(Cracked on-orbit)

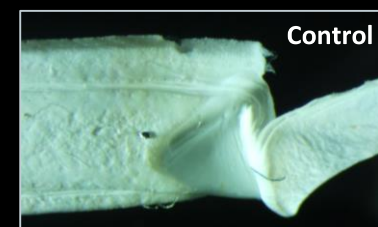
Tensile Strength

Expanded Polytetrafluoroethylene (ePTFE)

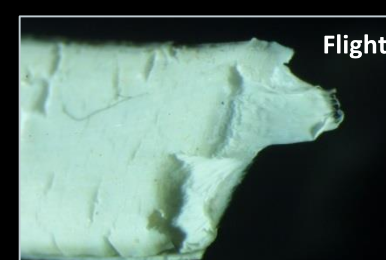


The ePTFE has two layers – both appear to have the same properties, but the back is smooth & the front is textured

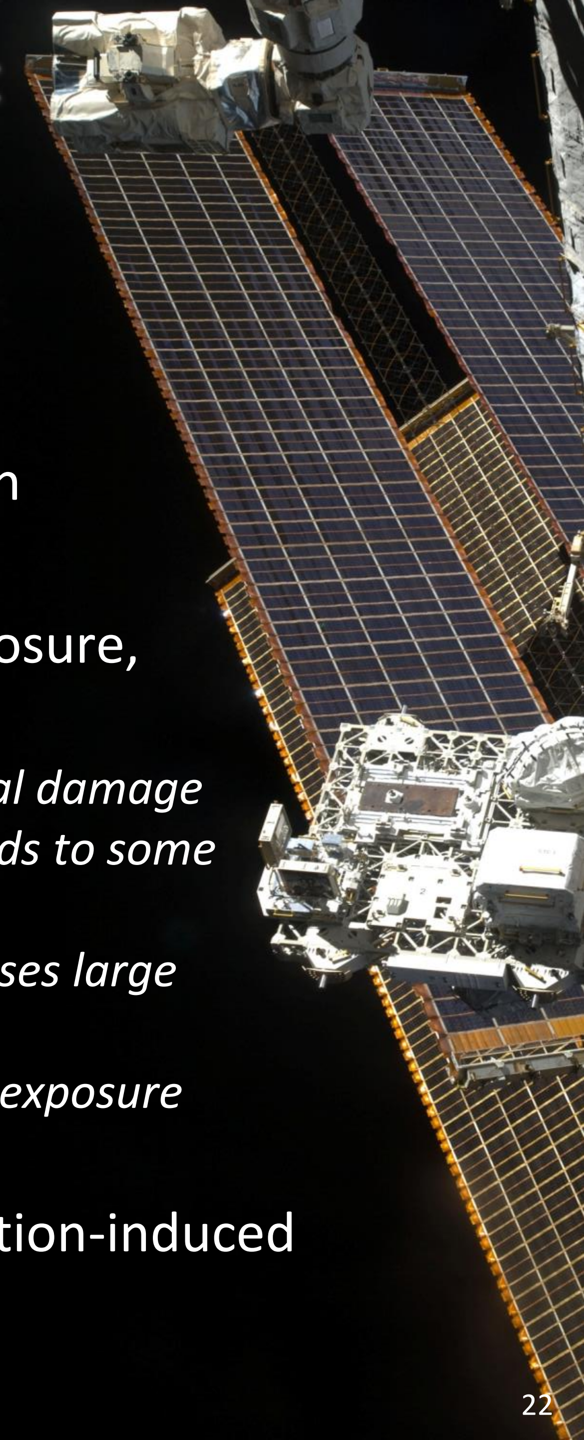
The back layer of control samples broke first & the front layer elongated forming a very thin fibre:



Both layers of flight samples broke nearly simultaneously & cracking was apparent on the front layer prior to break



MISSE 7 Tensile Samples Experiment
Conclusions



- Tensile properties were obtained for 16 MISSE 7 tensile flight samples (3 cracked while on-orbit)
- Prolonged exposure to the space environment can cause catastrophic degradation of 2-mil Al-FEP
- Extent of degradation is highly dependent on exposure, determined by surface orientation:
  - *Nadir: low AO & low radiation exposure cause minimal damage*
  - *Wake: low AO fluence & moderate solar exposure leads to some embrittlement*
  - *Ram: high AO fluence & moderate solar exposure causes large thickness loss & significant embrittlement*
  - *Zenith: high solar radiation exposure & moderate AO exposure leads to extensive embrittlement*
- On-orbit heating has a significant impact on radiation-induced degradation of FEP

The Effect of 1.5 Years of Zenith Space Exposure on Optical Properties of Spacecraft Polymers

MISSE 7A & 7B

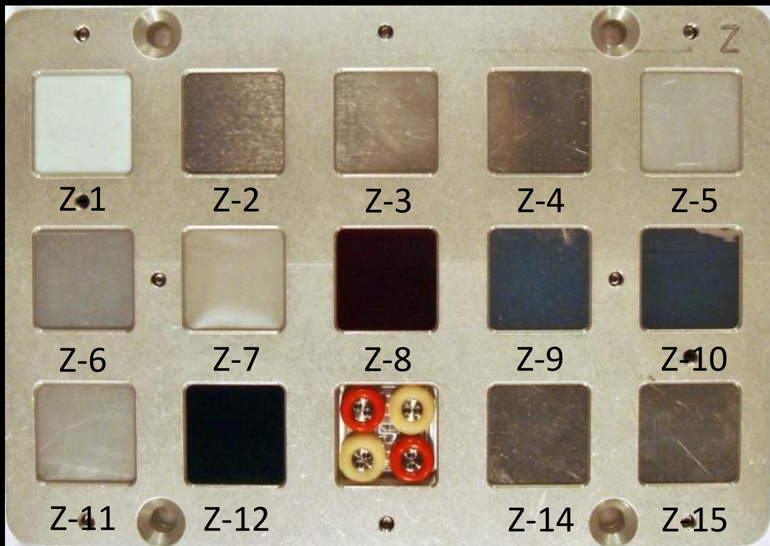
April 2010
(STS-131)

Optical Procedures

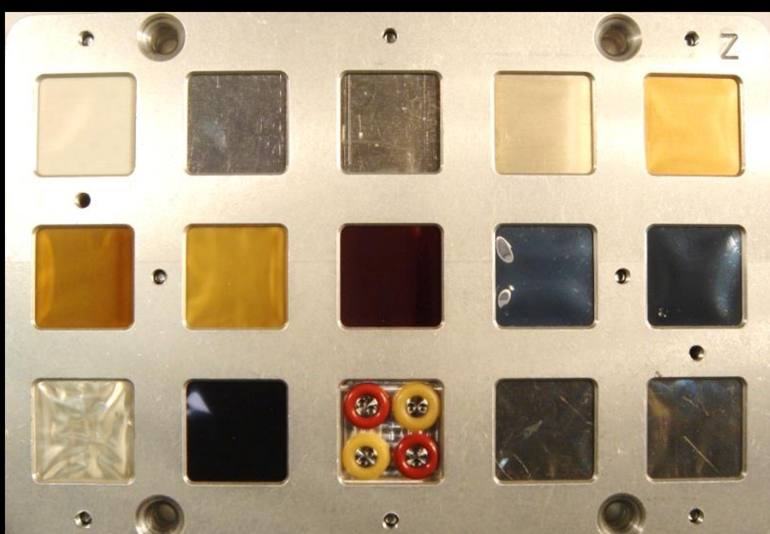
- Optical properties were obtained using a Cary 5000 UV-Vis-NIR Spectrophotometer operated with an integrating sphere
- Total and diffuse reflectance (TR , DR) and total and diffuse transmittance (TT, DT) were obtained from 250 nm to 2500 nm
  - Data was obtained post-flight on both the flight and control samples
- Specular reflectance (SR) and specular transmittance (ST) were computed using the following equations:
  - SR = TR - DR
  - ST = TT - DT
- An Excel macro was utilized to compute the integrated Air Mass Zero (AM0) solar absorptance (α_S) using TR and TT:
  - $\alpha_S = 1 – (TR + TT)$
- Data from the flight and control samples were compared to determine effect of LEO space exposure on the optical properties of the polymers

MISSE 7A Zenith Polymers Experiment Samples

Z-Tray Pre-Flight

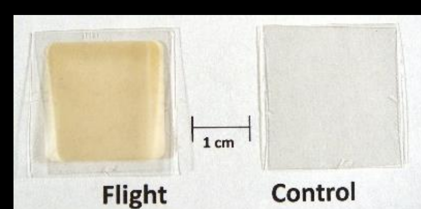


Z-Tray Post-Flight

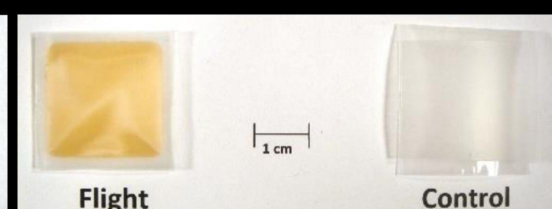


ID	Material (Abbreviation)	Trade Name	Thickness (mils)	# of Layers
Z-1	Polytetrafluoroethylene (PTFE)	Chemfilm DF-100	5	1
Z-2	Fluorinated ethylene propylene (FEP)	Teflon FEP	5	1
Z-3	Chlorotrifluoroethylene (CTFE)	Kel-F	5	2
Z-4	Ethylene-tetrafluoroethylene (EFTE)	Tefzel ZM	5	2
Z-5	Polyvinylidene fluoride (PVDF)	Kynar 740	3	2
Z-6	Ethylene-chlorotrifluoroethylene (ECTFE)	Halar 300	3	3
Z-7	Polyvinyl fluoride (PVF)	Clear Tedlar	3	12
Z-8	Polyimide (PI, PMDA)	Kapton H	1	3
Z-9	Aluminized-FEP (Al-FEP)*	Aluminized-Teflon	2	1
Z-10	Silvered-FEP (Ag-FEP)*	Silvered-Teflon	5	1
Z-11	Polyethylene (PE)	PE	5	8
Z-12	Si/Kapton E/vapor deposited Al	Si/Kapton E/ VDA	2	1
Z-14	Al_2O_3/FEP	Al_2O_3/FEP	2	1
P13**	Polyvinyl alcohol (PVOH)	PVOH	1.5	12
E9**	Polypropylene (PP)	PP	20	1

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



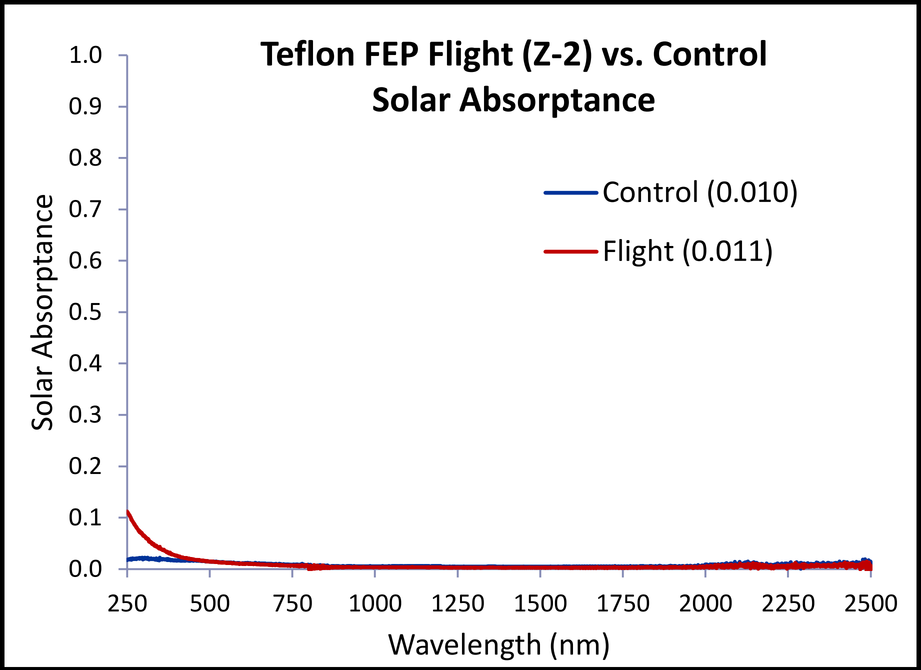
Z-4 ETFE (Tefzel)

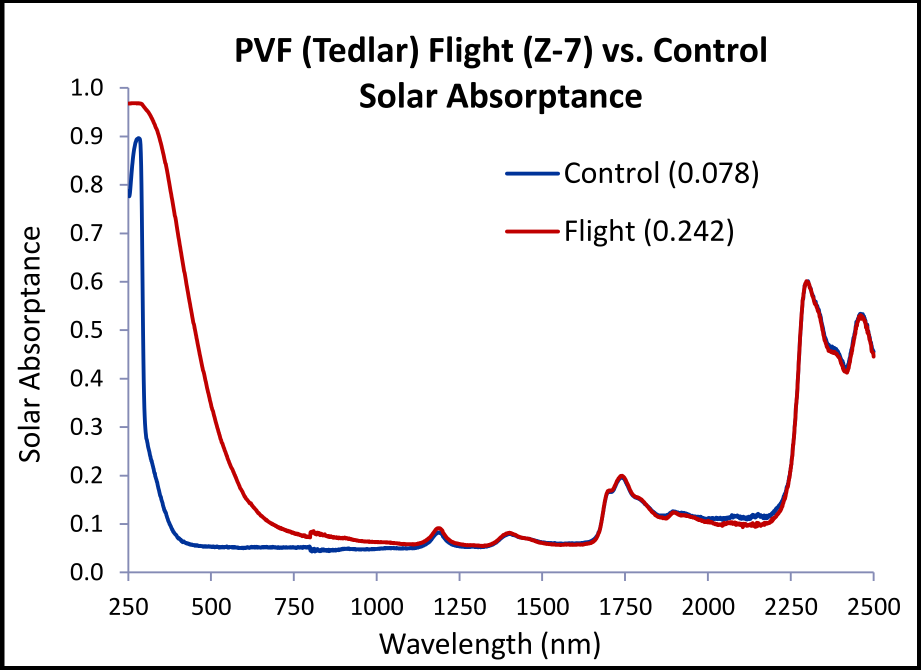


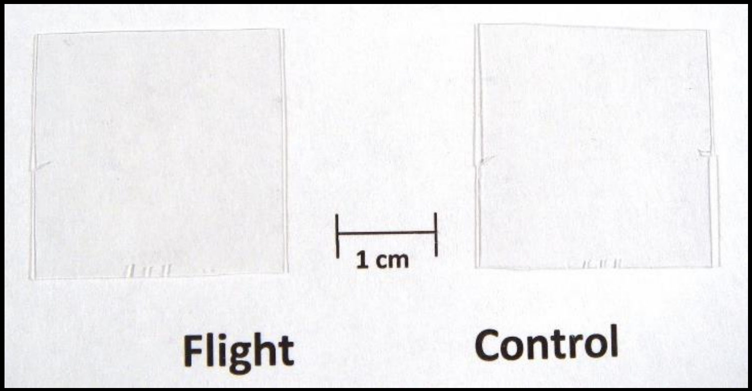
Z-5 PVDF (Kynar)

Examples of MISSE 7 Zenith Polymer Samples

Solar Absorptance Spectra

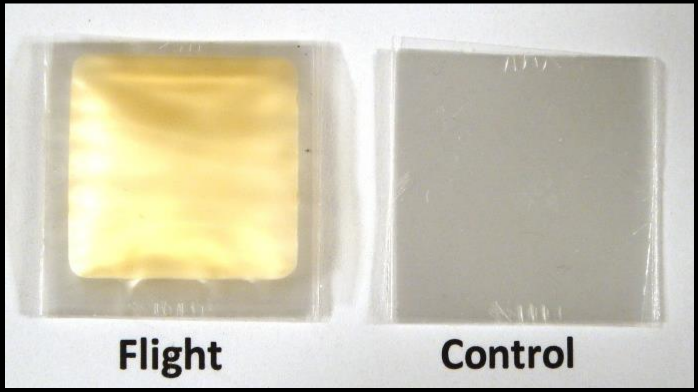






Z-2 FEP (Teflon) flight sample looks clear like control

Solar absorptance change is essentially zero



Z-7 PVF (Tedlar) flight sample looks yellow

Solar absorptance increase of 0.164

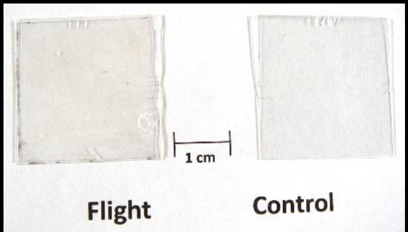
Zenith Polymers Optical Property Data

MISSE ID	Material	Thickness (mils)	# Layers	Flight vs Control	TR	DR	SR	TT	DT	ST	α_S	$\Delta\ \alpha_S$
Z-1	Polytetrfluoroethylene (PTFE), Teflon	5	1	Flight	0.135	0.124	0.011	0.808	0.339	0.469	0.057	**0.001**
				Control	0.144	0.134	0.010	0.800	0.340	0.460	0.056	
Z-2	Fluorinated ethylene propylene (FEP), Teflon	5	1	Flight	0.049	0.029	0.020	0.939	0.028	0.911	0.011	**0.001**
				Control	0.051	0.019	0.032	0.939	0.030	0.909	0.010	
Z-3	Chlorotrifluoroethylene (CTFE), Kel-F	5	2	Flight	0.113	0.047	0.066	0.844	0.020	0.824	0.042	0.021
				Control	0.118	0.012	0.106	0.861	0.018	0.843	0.021	
Z-4	Ethylene-tetrafluoroethylene (ETFE), Tefzel	5	2	Flight	0.104	0.069	0.035	0.809	0.333	0.475	0.087	0.072
				Control	0.107	0.013	0.093	0.878	0.022	0.856	0.015	
Z-5	Polyvinylidene fluoride (PVDF), Kynar	3	2	Flight	0.105	0.097	0.008	0.713	0.568	0.145	0.182	0.119
				Control	0.117	0.106	0.010	0.820	0.651	0.169	0.063	
Z-6	Ethylene-chlorotrifluoroethylene (ECTFE), Halar	3	3	Flight	0.138	0.127	0.011	0.623	0.492	0.131	0.239	**0.189**
				Control	0.177	0.06	0.177	0.774	0.145	0.629	0.050	
Z-7	Polyvinyl fluoride (PVF), Clear Tedlar	3	12	Flight	0.366	0.343	0.240	0.392	0.342	0.051	0.242	**0.164**
				Control	0.453	0.327	0.127	0.468	0.342	0.127	0.078	
Z-8	Polyimide, Kapton H	1	3	Flight	0.182	0.126	0.056	0.351	0.174	0.177	0.467	0.029
				Control	0.201	0.030	0.170	0.361	0.028	0.333	0.438	
Z-9	Aluminized-FEP (FEP/Al)	2	1	Flight	0.783	0.159	0.623	0	0	0	0.217	0.061
				Control	0.844	0.435	0.409	0	0	0	0.156	
Z-10	Silverized-FEP (FEP/Ag)	5	1	Flight	0.867	0.320	0.547	0	0	0	0.133	0.052
				Control	0.919	0.053	0.865	0	0	0	0.081	
Z-11	Polyethylene (PE)	5	8	Flight	0.356	0.324	0.032	0.556	0.337	0.219	0.088	0.017
				Control	0.399	0.284	0.115	0.530	0.324	0.207	0.071	
Z-12	Si/2 mil Kapton E/Al	2	1	Flight	0.579	0.037	0.542	0	0	0	0.421	**-0.002**
				Control	0.576	0.042	0.535	0	0	0	0.423	
Z-14	Al_2O_3/FEP	2	1	Flight	0.117	0.092	0.026	0.817	0.022	0.795	0.066	0.025
				Control	0.132	0.045	0.087	0.826	0.027	0.799	0.041	
P13	Polyvinyl alcohol (PVOH) *(Sample is cracked & not flat)*	1.5	6	Flight	0.414	0.403	0.010	0.383	0.374	0.009	0.203	**0.124**
				Control	0.377	0.303	0.074	0.544	0.509	0.035	0.079	
E9	Polypropylene (PP)	20	1	Flight	0.083	0.048	0.035	0.796	0.350	0.446	0.121	0.050
				Control	0.086	0.042	0.045	0.842	0.356	0.486	0.071	

MISSE 7 vs. MISSE 2
Solar Absorptance Changes

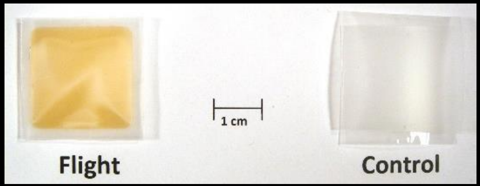
MISSE Environmental Exposure	MISSE 2 [Waters 2009]	MISSE 7	
Flight Orientation	Ram	Zenith	
Solar Exposure (ESH)	6,300	4,300	
AO Fluence (atoms/cm^2)	8.43×10^{21}	1.6×10^{20}	
Material	**F vs. C $\Delta \alpha_s$**	**F vs. C $\Delta \alpha_s$**	**MISSE 7 vs. 2**
Polyimide, Kapton H	0.077	0.029	+0.048
Chlorotrifluoroethylene (CTFE), Kel-F	0.105	0.021	+0.084
Ethylene-tetrafluoroethylene (ETFE), Tefzel	0.095	0.072	+0.023
Ethylene-chlorotrifluoroethylene (ECTFE), Halar	0.116	0.189	-0.073
Fluorinated ethylene propylene (FEP), Teflon	0.004	0.001	+0.003
Polytetrfluoroethylene (PTFE), Teflon	-0.011	0.001	-0.012
Polyvinylidene fluoride (PVDF), Kynar	0.153	0.119	+0.034
Polyvinyl fluoride (PVF), Clear Tedlar	0.095	0.164	-0.069

MISSE 2 CTFE (2-E5-39)



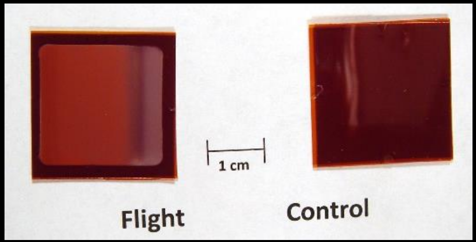
MISSE 7 CTFE (Z-3)

MISSE 2 PVDF (2-E5-46)



MISSE 7 PVDF (Z-5)

MISSE 2 Kapton H (2-E5-33)

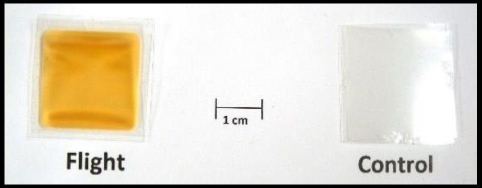


MISSE 7 Kapton H (Z-1)

MISSE 7 vs. MISSE 2
Solar Absorptance Changes

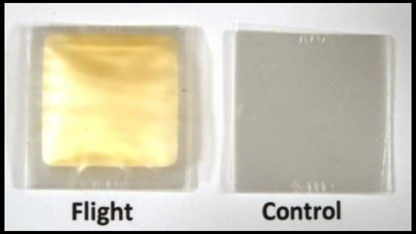
MISSE Environmental Exposure	MISSE 2 [Waters 2009]	MISSE 7	
Flight Orientation	Ram	Zenith	
Solar Exposure (ESH)	6,300	4,300	
AO Fluence (atoms/cm^2)	8.43×10^{21}	1.6×10^{20}	
Material	**F vs. C $\Delta\ \alpha_s$**	**F vs. C $\Delta\ \alpha_s$**	**MISSE 7 vs. 2**
Polyimide, Kapton H	0.077	0.029	+0.048
Chlorotrifluoroethylene (CTFE), Kel-F	0.105	0.021	+0.084
Ethylene-tetrafluoroethylene (ETFE), Tefzel	0.095	0.072	+0.023
Ethylene-chlorotrifluoroethylene (ECTFE), Halar	0.116	0.189	-0.073
Fluorinated ethylene propylene (FEP), Teflon	0.004	0.001	+0.003
Polytetrfluoroethylene (PTFE), Teflon	-0.011	0.001	-0.012
Polyvinylidene fluoride (PVDF), Kynar	0.153	0.119	+0.034
Polyvinyl fluoride (PVF), Clear Tedlar	0.095	0.164	-0.069

MISSE 2 ECTFE (2-E5-40)



MISSE 7 ECTFE (Z-6)

MISSE 2 PVF (2-E5-10)



MISSE 7 PVF (Z-7)

MISSE 7 Zenith Polymers
Optical Property Data Conclusions

- Optical properties of 15 MISSE 7 Zenith Polymers Experiment flight samples were obtained post-flight and compared to control samples
  - *Total, diffuse, and specular reflectance and transmittance were obtained and the AM0 solar absorptance (α_s) for each sample was computed*
- Absorptance increases varied from ~0 to 0.189:
  - *~0: FEP (Z-2), PTFE (Z-1) & Si coated Kapton E (Z-12)*
  - *0.124: PVOH (P13), 0.164: PVF (Z-7) & 0.189: ECTFE (Z-6)*
- A comparison of the $\Delta\alpha_s$ of polymers flown on MISSE 2 and MISSE 7 indicated that some materials are more sensitive to AO erosion (i.e. Kapton H, CTFE & PVDF), while others are more sensitive to solar radiation degradation (i.e. PVF & ECTFE)
- Samples with high increases in solar absorptance should be avoided, or protected, when considering materials for thermal control or other exterior spacecraft applications

Summary & Conclusions

- The MISSE 7A Zenith Polymers Experiment and MISSE 7B Polymers Experiment were successfully flown & retrieved
- Tensile properties of 16 Teflon flight samples were obtained (3 cracked on-orbit) & compared with control samples
  – Prolonged exposure to the space environment can cause catastrophic degradation of 2-mil Al-FEP
  – Extent of degradation is highly dependent on exposure, determined by surface orientation:
    - *Nadir exposure results in minimal degradation*
    - *Zenith exposure results in extensive embrittlement*
  – Temperature plays a key role in the radiation-induced degradation of FEP
- Optical properties of 15 zenith flight samples were obtained post-flight and compared to control samples
  – Absorptance increases varied from ~0 to 0.189
  – Comparison of $\Delta\alpha_s$ of polymers flown on MISSE 2 and MISSE 7 indicate that the optical properties of some materials appear more sensitive to AO erosion, while others appear more sensitive to solar radiation degradation

Acknowledgements

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

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

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