Overview of Results from the MISSE 9-15 Polymers and Composites Experiment 1-4 (PCE 1-4)

Kim K. de Groh
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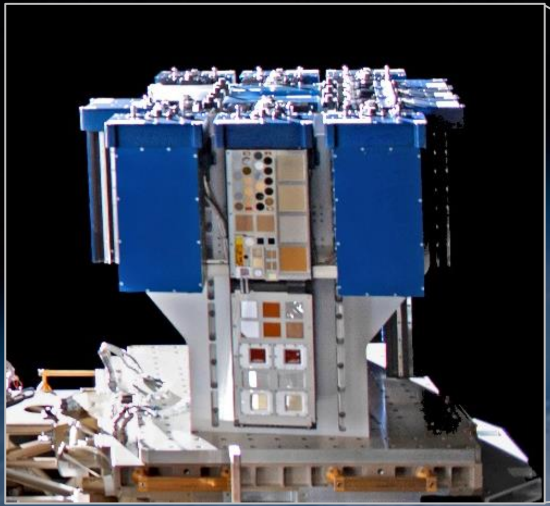
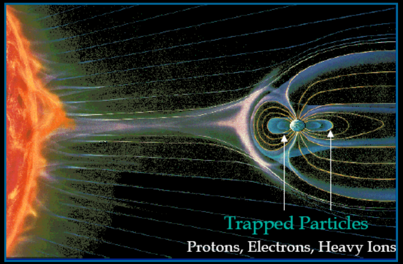
Cleveland, Ohio USA



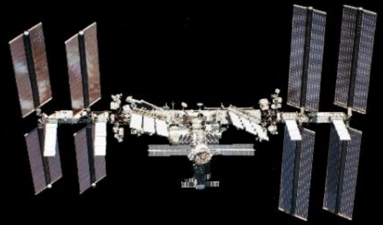
MISSE-Flight Facility (MISSE-FF)

Presented at the joint 16th International Symposium on Materials in Space Environment (ISMSE-16) and 14th International Conference on Protection of Materials and Structures in Space Environment (ICPMSE-14)
October 7-11, 2024 in Saint-Raphael, France

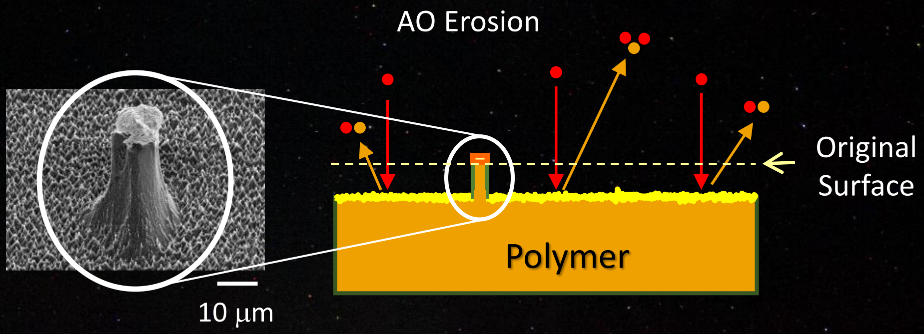


Many harmful threats in the space environment

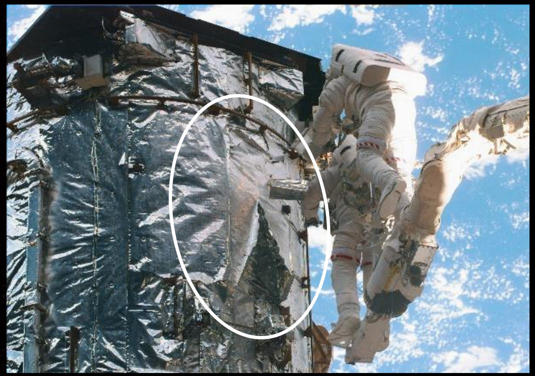
Space Environmental Threats



- Atomic oxygen (AO) (reactive oxygen atoms)
  - Erosion
  - Optical property changes
- Solar radiation (ultraviolet (UV), x-rays)
- Charged particle radiation (electrons, protons)
- Cosmic rays (energetic nuclei)
  - Polymer embrittlement
  - Enhanced erosion
  - Optical property changes
- Temperature extremes & thermal cycling
  - Enhanced embrittlement
  - Enhanced erosion
- Micrometeoroids & orbital debris (particles)
  - Impact site effects

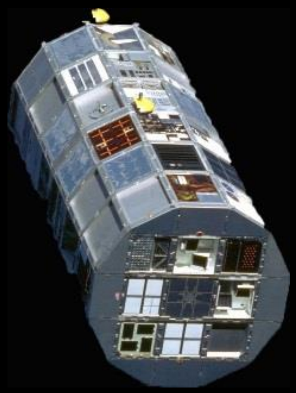


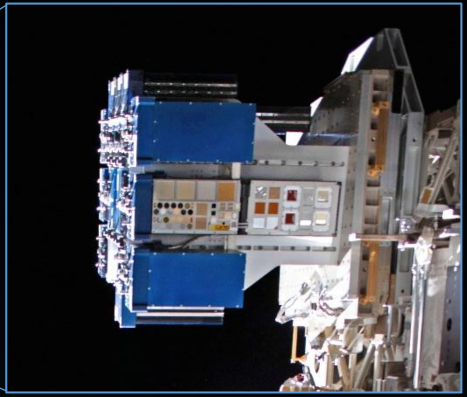
Radiation embrittlement



Hubble Servicing Mission 2 (SM2)
6.8 years of space exposure

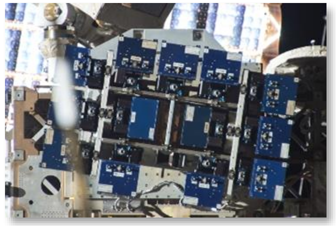
Space Environmental Effects Flight Experiments
Skylab to the International Space Station





MISSE-Flight Facility

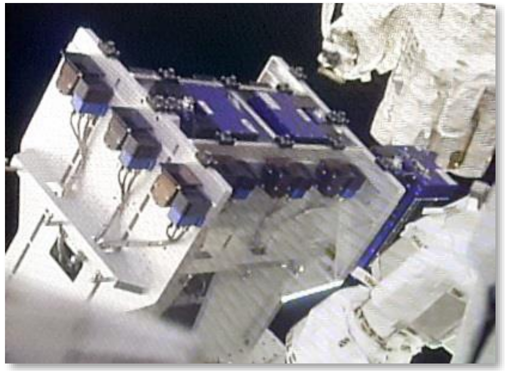
ISS-56
October 2018



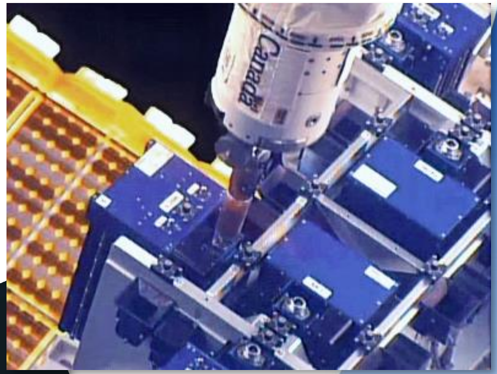
Materials International Space Station Experiment-Flight Facility (MISSE-FF)

Aegis Aerospace (formerly Alpha Space)

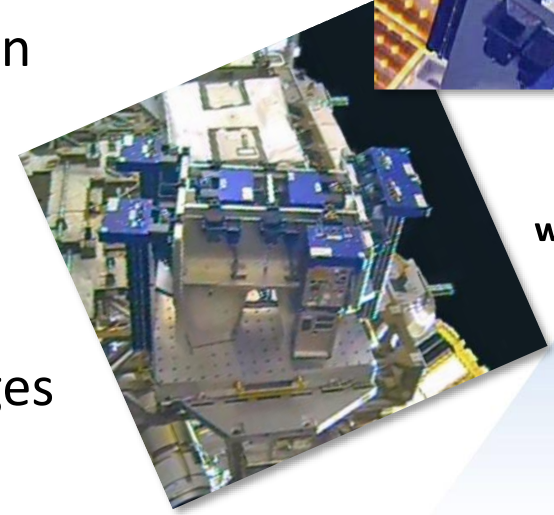
- The MISSE-FF is an ISS permanent external material science platform that is modular and robotically serviceable
  - *Provides ram, wake, zenith and nadir exposures*
  - *Launched aboard SpaceX CRS-14 on April 2, 2018*
  - *Installed on ELC-2 Site 3 on April 8, 2018 (+8 degree pitch)*
  - *Inaugural MISSE-9 experiments were deployed April 19, 2018*
- Modular design allows *MISSE Sample Carriers* (MSCs) with experiments to be added/replaced at different times
- Supports active experiments
- 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-FF being moved to ELC-2



Robotic insertion of a MSC



MISSE-FF with 5 MSCs

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

Polymers and Composites Experiment 1-4 (PCE 1-4)

Principal Investigator (PI): Kim de Groh (NASA GRC)
Co-Investigator: Bruce Banks (SAIC/GRC)

- NASA Glenn has 4 experiments with **365 flight samples** flown on the MISSE-FF
  - *MISSE-9 (138), MISSE-10 (43), MISSE-12 (86*), MISSE-13 (98) & MISSE-15 (42 re-flight*)*
- **Objective**: Study the performance of polymers, composites and spacecraft component materials in the harsh LEO space environment
- 47 Sample Collaborators from 21 Organizations:
  - *Government: NASA GRC, LaRC, GSFC, MSFC & DoD (AFRL, NRL)*
  - *Academia: Univ. of Rome T.V., Univ. of Akron, Johns Hopkins Univ., Michigan State Univ.*
  - *Industry: Ball Aerospace, Acktar Ltd, redhouse studios llc., NeXolve, RST Inc., etc.*
- Wide variety of flight samples:
  - *Spacecraft polymers & composites, shape memory alloys & shape memory polymer composites, cosmic ray shielding & melanin composites for radiation durability, docking seals, thermal & conductive coatings, tensile samples, contamination samples, etc.*
- Provides critical space environmental durability data for LEO, lunar and low Mars orbit (LMO) spacecraft and space structures
  - *Improved predictions of spacecraft component lifetimes in space*
  - *Improvements to Glenn's atomic oxygen erosion models*

MISSE-FF Expt.	Flight Direction	# of Samples	Total
MISSE-9 PCE-1	Ram	39	138
	Wake	52	
	Zenith	47	
MISSE-10 PCE-2	Ram	21	43
	Zenith	10	
	Nadir	12	
MISSE-12 PCE-3	Ram	30	86
	Wake	42*	
	Zenith	14	
MISSE-13 PCE-4	Wake	39	98
		26	
	Zenith	33	
MISSE-15 PCE-3 Wake Re-flight	Wake	*42 Reflight**	*N/A*

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

Flight Orientations & Environmental Exposures

Ram:

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

Wake:

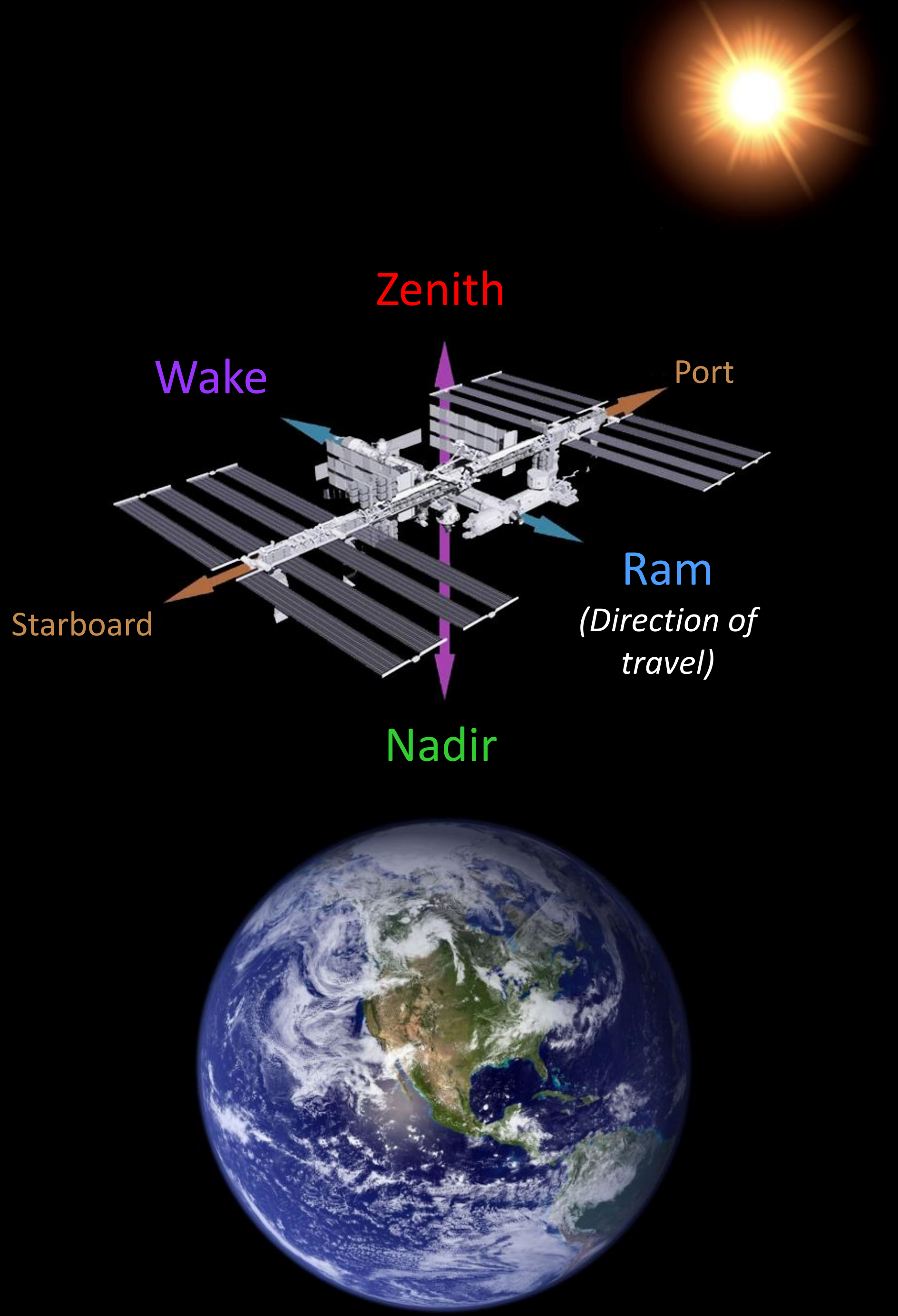
- *Facing away from the direction of travel (i.e. aft pointing or trailing edge)*
- *Essentially no AO & moderate solar exposure*

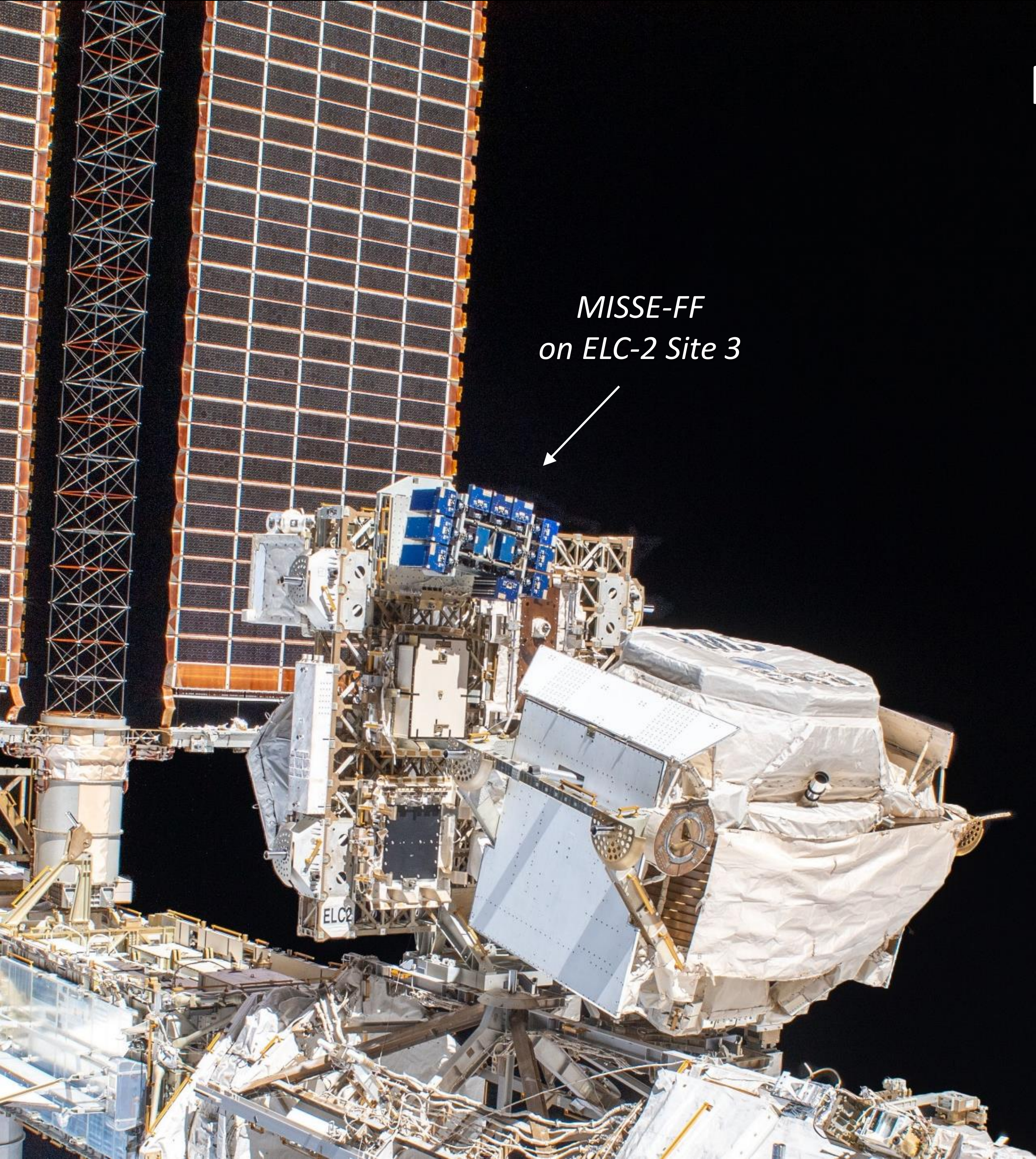
Zenith:

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

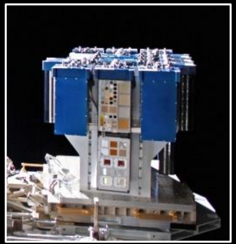
Nadir:

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





PCE 1-4 Samples Include:



- *AO fluence (F)*
  - *Kapton H witness samples*
  - *AO Photo Monitors*
- *On-orbit contamination*
- *AO erosion yield (E_y)*
- *Optical properties*
- *Tensile properties*
  - *MISSE-9 wake (38) & zenith (24)*
  - *MISSE-13 wake (24)*
- *Radiation & functional durability, etc.*
  - *Shape Memory Alloys (SMA)*
  - *Shape Memory Polymer Composites (SMPC)*
  - *Melanin composites*
  - *ITO conductive coatings*
- *"Unique" samples*
  - *AO Scattering chambers*
  - *Solar sail materials*
  - *Specialty coatings*
  - *Docking seal (S383-70 silicone) samples*
  - *Etc.*

MISSE-9
Polymers and Composites Experiment-1 (PCE-1)

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

Co-Investigator: Bruce Banks (SAIC/GRC)

Sample Collaborators: Henry de Groh, Sylvie Crowell, Stephanie Vivod & Jessica Cashman (NASA GRC), Maryann Meador (GRC Retired), Austin Whitt & Sadeq Malakooti (HX5 GRC), Loredana Santo & Fabrizio Quadrini (University of Rome "Tor Vergata"), Genevieve Devaud, John Fleming, Julia Deyanova & Daniela Torres (BAE), & Lawrence Drzal (Michigan State University)

Experiment Description:

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

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 & shape memory polymer composites*
5. *Use the flight data to improve AO predictive models (erosion and scattering)*

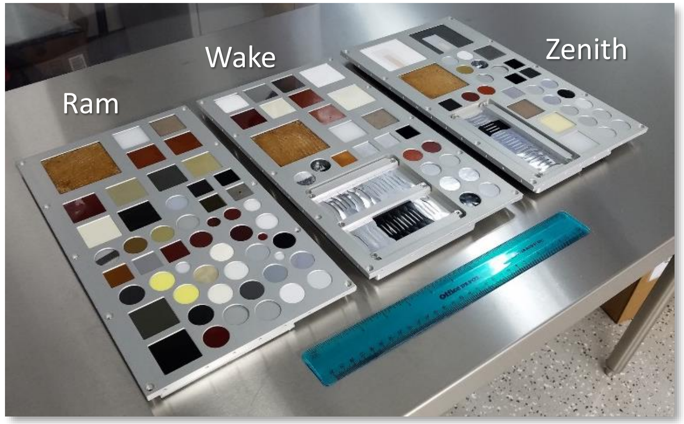
Pre-flight photograph of the PCE-1 samples in the M9 R2 (left), M9 W3 (center) and M9 Z3 decks (right)

Expected Results:

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

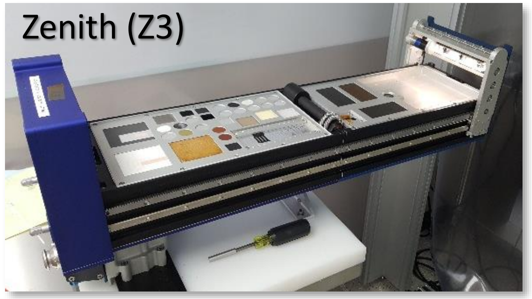
Polymers and Composites Experiment-1 (PCE-1)

Integration of the 138 PCE-1 samples into the MISSE-9 Decks



Aegis Aerospace
August 4, 2017

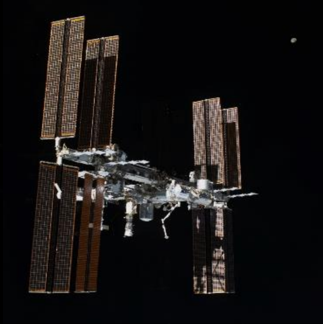
Ram	Wake	Zenith
(R2 MSC 3-MS)	(W3 MSC 8-MS)	(Z3 MSC 5-MS)



Pre-flight full MSC photos courtesy of Aegis Aerospace

Polymers and Composites Experiment (PCE)

Ram (R2) Pre-flight & On-Orbit Images



Pre-flight Image

On-Orbit Image Composite

On-orbit images taken April 23, 2018

On-orbit sample photos courtesy of NASA and Aegis Aerospace

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

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

Co-Investigator: Bruce Banks (SAIC/GRC)

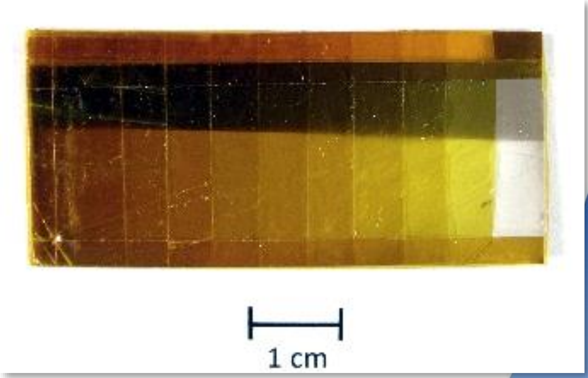
Sample Collaborators: Sylvie Crowell (NASA GRC), Loredana Santo & Fabrizio Quadrini (University of Rome "Tor Vergata"), Genevieve Devaud, John Fleming, Julia Deyanova & Daniela Torres (BAE), Robert Bryant (NASA LaRC) & Jin Ho Kang (NIA/LaRC)

Experiment Description:

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

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 and 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 MAPTIS database*



M10R-R1 AO Photo Monitor

M10N-C4 90° Kapton (Au & NaCl)

Expected Results:

- AO fluence and contamination data in ram, zenith & nadir directions (AO fluence vs. time - 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-12
Polymers and Composites Experiment-3 (PCE-3)

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

Co-Investigator: Bruce Banks (SAIC/GRC)

Collaborators: Santo Padula II, Othmane Benafan, Sharon Miller, Theresa Benyo*, Andrew Trunek*, Henry de Groh, Sylvie Crowell, Stephanie Vivod & Jessica Cashman (NASA GRC), Sadeq Malakooti (HX5 GRC), Loredana Santo & Fabrizio Quadrini (Univ. of Rome), Genevieve Devaud, John Fleming, Julia Deyanova & Daniela Torres (BAE), Dina Katsir (Acktar Ltd.), Ben Jensen (Surrey), Dave Wilt (AFRL), Kathleen Spaner & Ronald DeMeo (RST, Inc.)

Experiment Description:

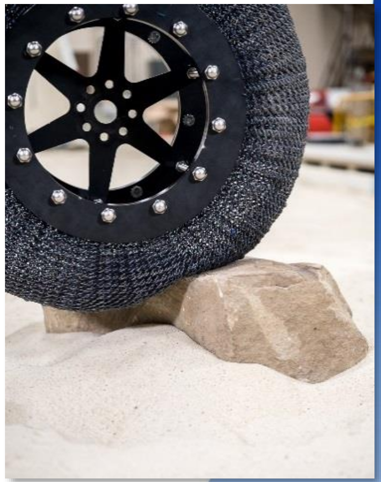
- Passive experiment with 86 samples flown in ram, wake & zenith orientations
  - 30 Ram, 42 Wake & 14 Zenith
- Pre-flight & post-flight data are measured in ground-facilities

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*

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 materials & solar cell cover slides after radiation 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-13
Polymers and Composites Experiment-4 (PCE-4)

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

Co-Investigator: Bruce Banks (SAIC/GRC)

Collaborators: Othmane Benafan, Santo Padula II, Sharon Miller, Sylvie Crowell, Theresa Benyo*, Andrew Trunek*, Henry de Groh, Pat Dunlap, Stephen Gerdts & Tiffany Williams (GRC), Sadeq Malakooti (HX5 GRC), Janice Mather (UA), Loredana Santo & Fabrizio Quadrini (Univ. of Rome), Genevieve Devaud, John Fleming, Julia Deyanova & Daniela Torres (BAE), Joe Matus & Les Johnson (MSFC), Brandon Framer & D. Lynn Rodman (NeXolve)

Experiment Description:

- Passive experiment with 98 samples flown in wake & zenith orientations
  - 65 Wake & 33 Zenith
- Pre-flight & post-flight data are measured in ground-facilities

Primary Objectives:

1. *Determine optical and mechanical property degradation of spacecraft materials in LEO*
2. *Determine the functionality of shape memory alloys (SMAs), shape memory polymer composites (SMPCs), melanin-based composites and elastomer seal samples after space radiation exposure*
3. *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*
4. *Determine AO fluence and contamination for wake and zenith MISSE-13 flight orientations*
5. *Use data to improve AO predictive models & archive data in MISSE MAPTIS database*

Pre-flight photograph of the PCE-4 flight samples in the M13 Z2 (left) and M13 W1 decks (center & right)

Expected Results:

- Changes in optical, thermal & tensile properties
- Functionality of SMAs, SMPCs, melanin-based materials and elastomer seal samples after space radiator exposure
- AO fluence and contamination data in wake and zenith flight direction
- LEO E_y values as a function of AO fluence & solar irradiation

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

NASA/TM-20205008863

Provides tables of the 365 PCE 1-4 samples & PCE 1-4 pre-flight sample collaborators

"MISSE-Flight Facility Polymers and Composites Experiment 1-4 (PCE 1-4)" by Kim K. de Groh & Bruce A. Banks, NASA/TM-20205008863, February 2021

NTRS website:

https://ntrs.nasa.gov/api/citations/20205008863/downloads/TM-20205008863%2003.29.21.pdf

NASA/TM-20205008863

MISSE-Flight Facility
Polymers and Composites Experiment 1-4 (PCE 1-4)

Kim K. de Groh
Glenn Research Center, Cleveland, Ohio

Bruce A. Banks
Science Applications International Corporation, Cleveland, Ohio

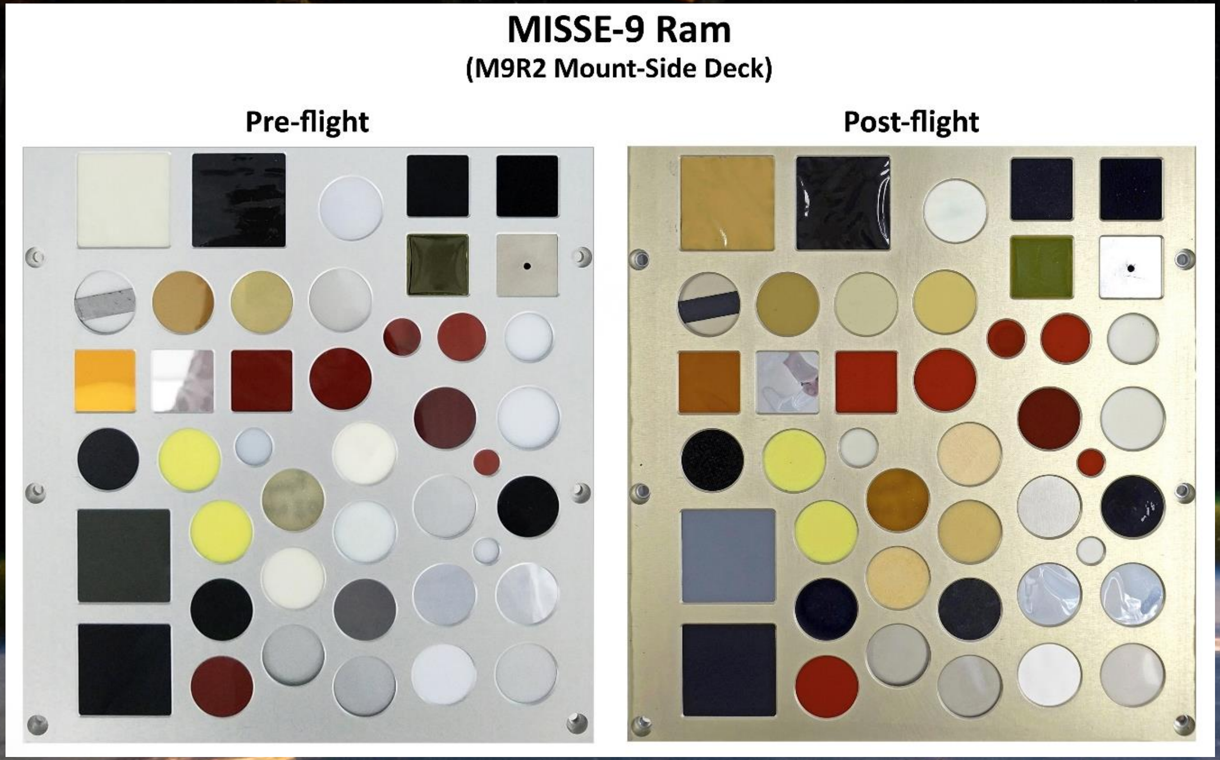
February 2021

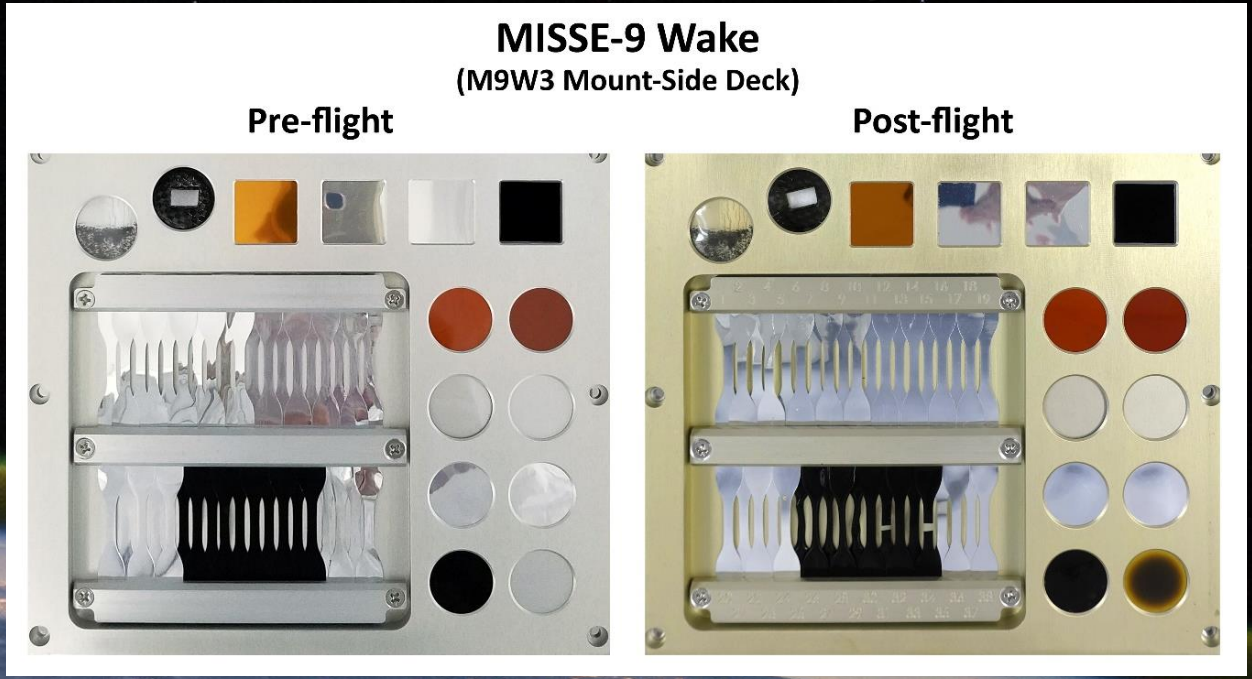
PCE 1-4 Missions

MISSE-FF Experiment	Flight Direction	Number of Samples	MISSE Sample Carrier (MSC)	Launch Mission	Return Mission	De-integration & Sample Return to GRC
MISSE-9 PCE-1	Ram	39	R2 (MSC 3) MS	SpaceX-14 April 2, 2018	SpaceX-19 January 7, 2020	February 2020
	Wake	52	W3 (MSC 8) MS		SpaceX-17 June 3, 2019	July 2019
	Zenith	47	Z3 (MSC 5) MS			
MISSE-10 PCE-2	Ram	21	R1 (MSC 11) MS	NG-10 November 17, 2018	SpaceX-21 January 13, 2021*	August 2021
	Zenith	10	Z2 (MSC 10) MS		SpaceX-20 April 7, 2020	August 2021
	Nadir	12	N3 (MSC 13) MS			
MISSE-12 PCE-3	Ram	30	R2 (MSC 4) SS	NG-12 November 2, 2019	SpaceX-21 January 13, 2021*	September 2021
	Wake**	42	W3 (MSC 6) MS			
	Zenith	14	Z1 (MSC 18) MS			
MISSE-13 PCE-4	Wake	39	W1 (MSC 5) SS	SpaceX-20 March 6, 2020	SpaceX-21 January 13, 2021*	September 2021
		26	W1 (MSC 5) MS			
	Zenith	33	Z2 (MSC 19) MS			
MISSE-15 PCE-3 Wake Re-flight**	Wake	42	W1 (MSC 10) MS	SpaceX-23 August 29, 2021	SpaceX-25 August 20, 2022	January 2023

MS: Mount side deck; SS: Swing side deck
***January 13, 2021 EST (January 14, 2021 UTC)**
****The PCE-3 wake samples were re-flown as part of the MISSE-15 mission**

PCE 1-4 Post-flight Analyses





PCE 1-4 Post-flight Analyses
Space Environmental Exposure

- Post-flight images
  - *Flight vs. back-up (control) sample images (visible light & 365 nm UV light)*
- Dehydrated mass of all AO fluence, AO E_y and optical samples
- Worked with Aegis Aerospace to determine the mission exposure details for each PCE 1-4 MISSE Sample Carrier (MSC)
  - *Launch & return missions and dates*
  - *MISSE-FF installation & retrieval dates*
  - *Time on MISSE-FF, Space Vacuum and Direct Space Exposure Durations*
- Calculated the AO fluence (AO F) for each mission's flight orientation*

AO Fluence computed from Kapton H mass loss

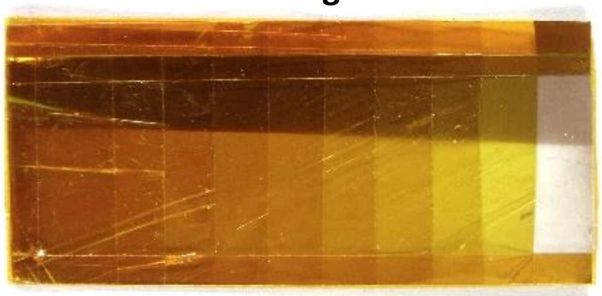
$$F_k = \frac{\Delta M_k}{A_k \rho_k E_k}$$

Where: ΔM_k = **Mass loss of Kapton H (g)**
A_k = **Exposed area of Kapton H (cm^2)**
ρ_k = **Density of Kapton H (1.427 g/cm^3)**
E_k = **LEO erosion yield of Kapton H (3.0 x 10^{-24} cm^3/atom)**

M9R-R1 F
AO Photo Monitor

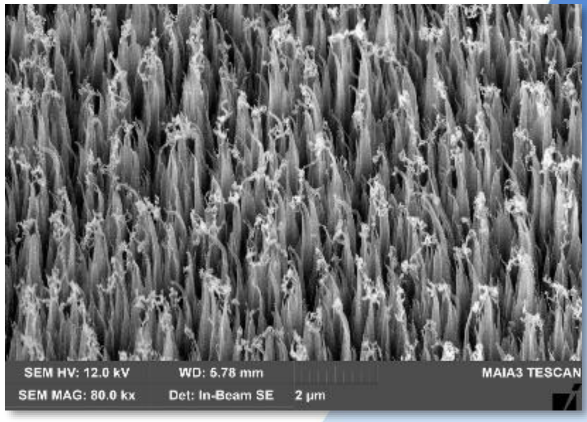
1 cm

Pre-flight



Post-flight

M12R-S1 F AO Photo Monitor



(45° Tilt)

➢ *The mission exposure details are provided in "Space Environment Exposure of the MISSE 9-15 Polymers and Composites Experiment 1-4 (PCE 1-4)," NASA/TM-20240000755, Feb. 2024.*

Most AO fluence values were based on **dehydrated mass loss*

PCE 1-4 Mission Exposure Summary

MISSE-FF Experiment	Flight Direction	MISSE Sample Carrier (MSC)	Launch Mission	Installed on MISSE-FF	Retrieved from MISSE-FF	Return Mission	Space Vacuum Duration (Years)	Time on MISSE-FF (Years)	Direct Space Exposure Duration (Years)	Atomic Oxygen Fluence (atoms/cm^2)^	Mission Equivalent Sun Hours (ESH)^^
MISSE-9 PCE-1	Ram	R2 (MSC 3) MS	SpaceX-14 April 2, 2018	April 18, 2018	Nov. 11, 2019	SpaceX-19 Jan. 7, 2020	1.59	1.57	0.77	3.44E+20	952.3
	Wake	W3 (MSC 8) MS		April 18, 2018	April 26, 2019	SpaceX-17 June 3, 2019	1.07	1.02	0.54	4.46E+16	634.6
	Zenith	Z3 (MSC 5) MS		April 19, 2018			1.07	1.02	0.54	3.19E+18	555.7
MISSE-10 PCE-2	Ram	R1 (MSC 11) MS	NG-10 Nov. 17, 2018	Jan. 4, 2019	Nov. 25, 2020	SpaceX-21 Jan. 13, 2021*	1.93	1.90	1.17	3.93E+20	1445.4
	Zenith	Z2 (MSC 10) MS			March 18, 2020	SpaceX-20 April 7, 2020	1.25	1.20	0.69	4.84E+18	702.0
	Nadir	N3 (MSC 13) MS					1.25	1.20	0.48	6.94E+18	102.3
MISSE-12 PCE-3	Ram	R2 (MSC 4) SS	NG-12 Nov. 2, 2019	Nov. 11, 2019	Nov. 25, 2020	SpaceX-21 Jan. 13, 2021*	1.07	1.04	0.89	2.97E+20	1104.0
	Wake	W3 (MSC 6) MS			Nov. 27, 2020		1.07	1.05	0**	0	0
	Zenith	Z1 (MSC 18) MS			Nov. 26, 2020		1.07	1.05	0.45	*≈1.67E+18*	465.4
MISSE-13 PCE-4	Wake	W1 (MSC 5) MS/SS	SpaceX-20 March 6, 2020	March 18, 2020	Nov. 27, 2020	SpaceX-21 Jan. 13, 2021*	0.72	0.70	0.44	2.65E+18	515.6
	Zenith	Z2 (MSC 19) MS			Nov. 26, 2020		0.72	0.70	0.46	2.24E+18	467.9
MISSE-15 PCE-3 Wake Re-flight**	Wake	W1 (MSC 10) MS	SpaceX-23 Aug. 29, 2021	Dec. 28, 2021	Aug. 2, 2022	SpaceX-25 Aug. 20, 2022	0.71	0.60	0.44	4.77E+18	511.7

MS: Mount side deck; SS: Swing side deck
*January 13, 2021 EST (January 14, 2021 UTC)
**The PCE-3 wake samples were re-flown as part of the MISSE-15 mission
^ AO fluence was computed from dehydrated Kapton H mass loss, except for MISSE-12 zenith which was based on erosion morphology of the M12Z-S1 Photographic AO Fluence Monitor
^^ Mission Equivalent Sun Hours (ESH) from Aegis Aerospace's "MISSE MSC UV Equivalent Sun Hours Calculation" Report (A. Goode, August 17, 2022-C03)

Reference: de Groh, K. K. and Banks, B. A., "Space Environmental Exposure of the MISSE 9-15 Polymers and Composites Experiment 1-4 (PCE 1-4)," NASA/TM-20240000755, February 2024.

MSCs are closed for contamination avoidance during visiting vehicles, etc.

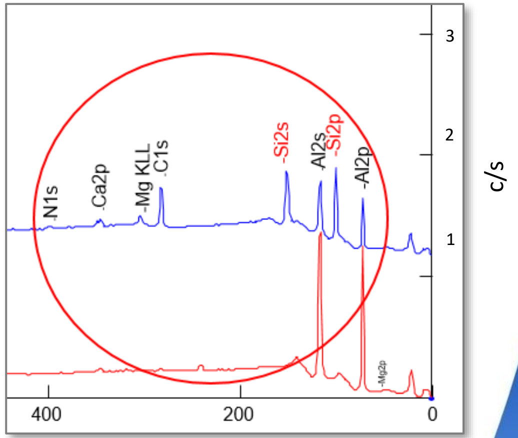
PCE 1-4 Post-flight Analyses

Contamination Analyses with Dorothy Lukco (HX5, LLC) & Sylvie Crowell (NASA GRC)

- X-ray photoelectron spectroscopy (XPS) analysis of contamination samples
  - *25 contamination samples: 13 flight & 12 control samples*
- Optical properties of PCE 1-4 contamination flight and control samples
  - *Total Reflectance (TR) , Total Transmittance (TT) & Solar Absorptance (SA)*

➢ *The results are provided in "Analyses of the MISSE 9-15 Polymers and Composites Experiment 1-4 (PCE 1-4) Contamination Samples," NASA/TM-20240000941, Feb. 2024*
  - *Includes flight vs. control sample images, XPS & optical data*

MISSE-12 Ram Al_2O_3
Flight & Control



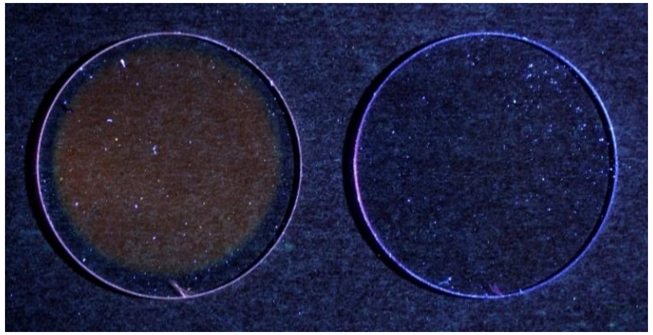
Binding Energy

MISSE-12 Wake (M12W-C3 F)
Al_2O_3

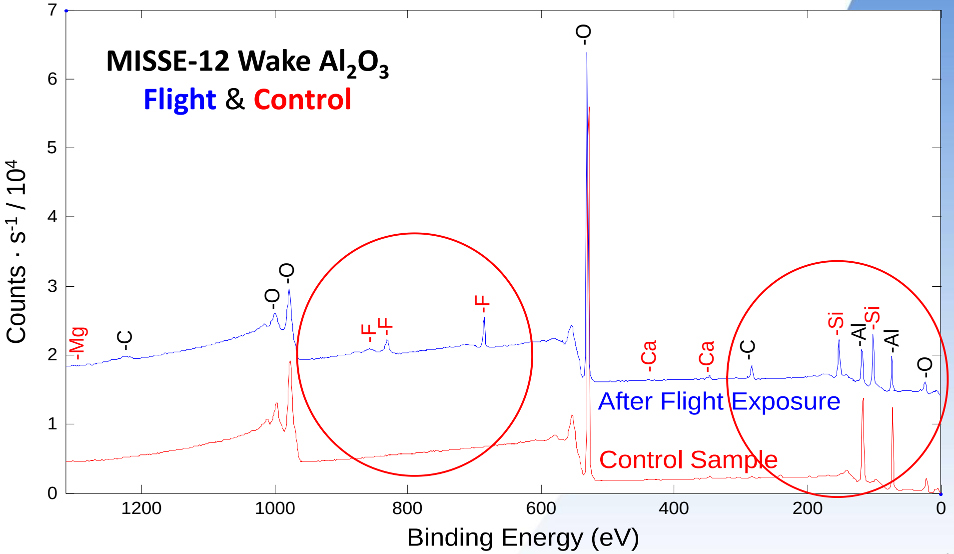
Flight
Control

Visible Light Image

Flight
Control



UV Light Image
showing contamination in the flight sample



PCE 1-4 Contamination Samples

Si Atomic Concentrations

MISSE-FF Flight Sample ID	Flight Orientation	Material	Time on MISSE-FF (Years)	Direct Space Exposure Duration (Years)	Si Atomic Concentration (at.%)	Si Atomic Concentration per Year (at.%/Year)
MISSE-9						
M9R-C6 F	Ram	Al_2O_3	1.57	0.77	**6.0**	7.8
M9R-C27 F	Ram	MgF_2	1.57	0.77	**4.4**	5.7
M9W-C3 F	Wake	Al_2O_3	1.02	0.54	**1.7**	3.1
M9Z-C3 F	Zenith	Al_2O_3	1.02	0.54	**1.5**	2.8
M9Z-C18 F	Zenith	MgF_2	1.02	0.54	**1.8**	3.3
MISSE-10						
M10R-C4 F	Ram	Al_2O_3	1.9	1.17	**8.4**	7.2
M10N-C5 F	Nadir	Al_2O_3	1.2	0.48	**8.1**	**16.9**
M10Z-C5 F	Zenith	Al_2O_3	1.2	0.69	**6.6**	9.6
MISSE-12						
M12R-C3 F	Ram	Al_2O_3	1.04	0.89	**15.1**	**17.0**
M12W-C3 F	Wake	Al_2O_3	1.05	0**	**N/A**	N/A
M12Z-S2 F	Zenith	SMA NiTi	1.05	0.45	**6.2**	**13.8**
MISSE-13						
M13W-C4 F	Wake	FEP/Al	0.7	0.44	**1.6**	3.6
M13Z-C4 F	Zenith	FEP/Al	0.7	0.46	**2.2**	4.8
MISSE-12 & MISSE-15 Re-flight**						
M12W-C3 F	Wake	Al_2O_3	1.04 + 0.6	0.44	**15.1**	**34.3**

No Si was detected on the back-up (control) samples

Except:

M10N-C5 B: <0.1 at.% Si (Al_2O_3)

M9Z-C18 B: 1.7 at.% Si (MgF2)

Ref: *de Groh, K. K., Lukco, D., Crowell, S. F., Gregor, S. J. and Banks, B.A., "Analyses of the MISSE 9-15 Polymers and Composites Experiment 1-4 (PCE 1-4) Contamination Samples," NASA TM/20240000941, February 2024.*

PCE 1-4 Post-flight Analyses
LEO AO Erosion Yield (E_y) Values

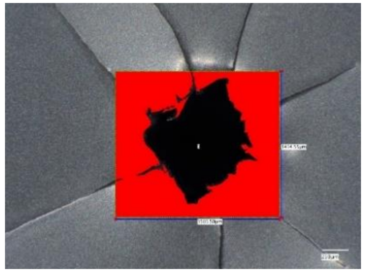
- LEO atomic oxygen (AO) erosion yield (E_y) of flight samples
  - *Determined the AO E_y for* ***150 flight samples***
  - *The Ey for the majority of samples was determined based on* ***dehydrated mass loss***
  - *AO Fluence was determine based on Kapton H mass loss*
  - *Erosion depth was used to compute Ey for MISSE-9 ram HOPG (M9R-C22 F)*
- Optical Microscopy (OM) and SEM imaging
  - *Zygo, Keyence OM and Hitachi FESEM imaging of various samples*
  - *Surface area of impact sites have been accounted for*

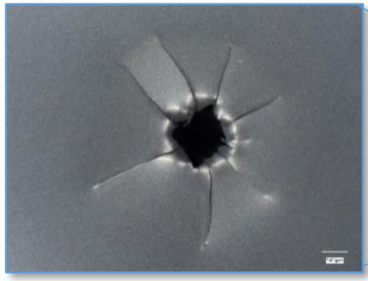
E_y computed from Mass Loss

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

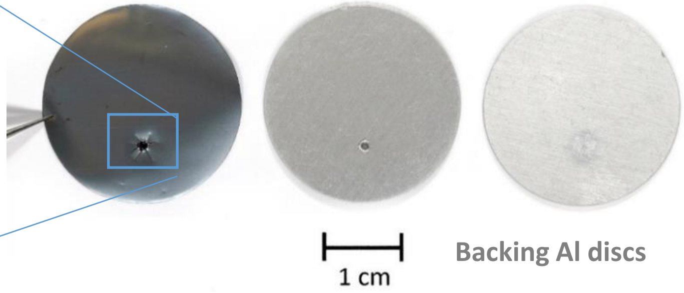
where: ΔM_s = Sample Mass loss (g)
A_s = Sample exposed area (cm^2)
ρ_s = Sample density (g/cm^3)
F = AO fluence ($atom/cm^2$)

Area deducted from exposed surface area (black)

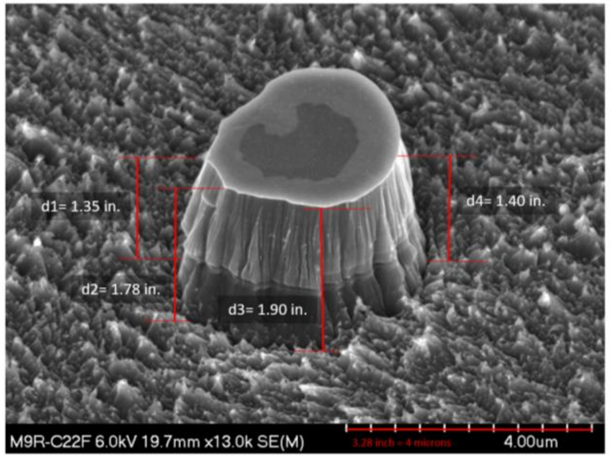




StaMet/Kapton XC Flight Sample (M12R-C12 F)



MISSE-9 Ram (M9R-C22 F)
Highly Oriented Pyrolytic Graphite (HOPG)



HOPG erosion depth measurements (13kX and 45° tilt)

➢ *PCE 1-4 AO Ey paper "Erosion Results from the MISSE 9-15 Polymers and Composites Experiment 1-4 (PCE 1-4)" has been written and is being finalized*
  - *Includes AO Ey data with dehydrated mass loss, exposed surface area, sample density and mission AO fluence*
  - *Includes select flight vs. control sample, OM & SEM images*

PCE 1-4 Post-flight Analyses

Tensile Data with Austin Whitt (HX5|GEARS)

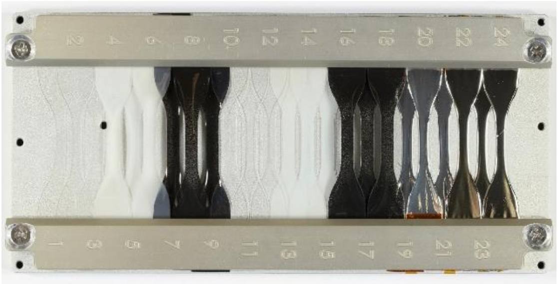
MISSE-9
Wake Samples
(Post-flight)

- Tensile testing of flight and control tensile samples
  - *233 thin film tensile samples: 116 flight & 117 control samples*

MISSE Mission	Flight Samples	Control Samples	Total # Samples
MISSE-8 Zenith	30	22	52
MISSE-9 Wake	38*	38	76
MISSE-9 Zenith	24	17	41
MISSE-13 Wake	24	40	64
Total	**116**	**117***	**233**

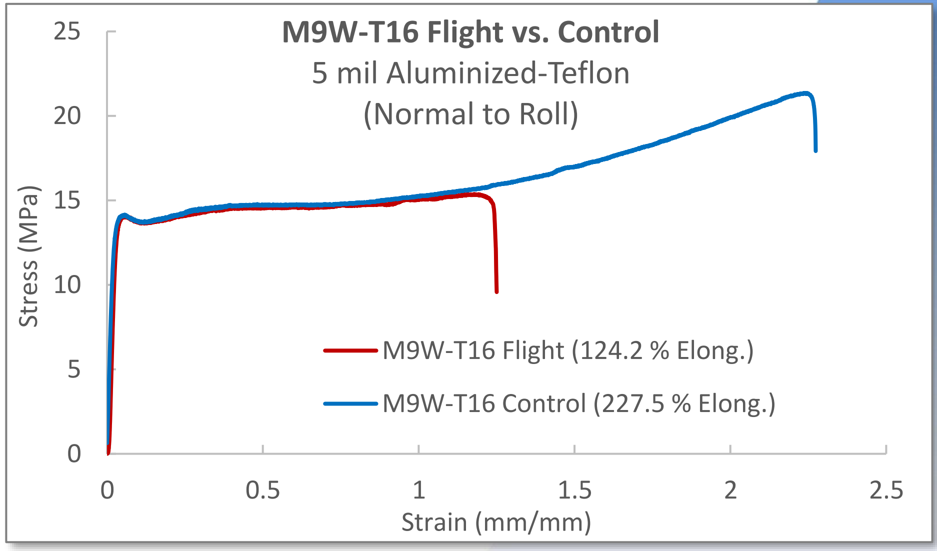
ASTM D638-08 Type V

MISSE-13 Wake Samples (Post-flight)



  - *The majority of samples are Teflon FEP with various thicknesses and coatings*

- Tensile Test Data:
  - *2 MISSE-9 wake carbon coated FEP (C-FEP) samples broke on-orbit**
  - *230 samples successfully tested:*
    - *114 Flight Samples: 30 M8 Zenith, 36 M9 Wake, 24 M9 Zenith & 24 M13 Wake*
    - *116 Control Samples: 21 M8 Zenith, 38 M9 Wake, 17 M9 Zenith & 40 M13 Wake*
      - ** System error with 1 control sample*
  - *Ave. reductions for MISSE-9 - 5 mil Al-FEP:*
    - *Wake: 48% decrease elongation*
    - *Zenith: 67% decrease in elongation*



Teflon fluorinated ethylene propylene (FEP)

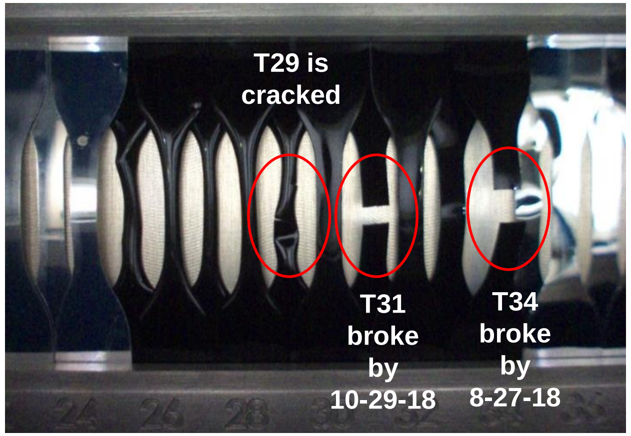
MISSE-9 Polymers and Composites Experiment-1 (PCE-1)
Wake (W3) On-Orbit Images

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!

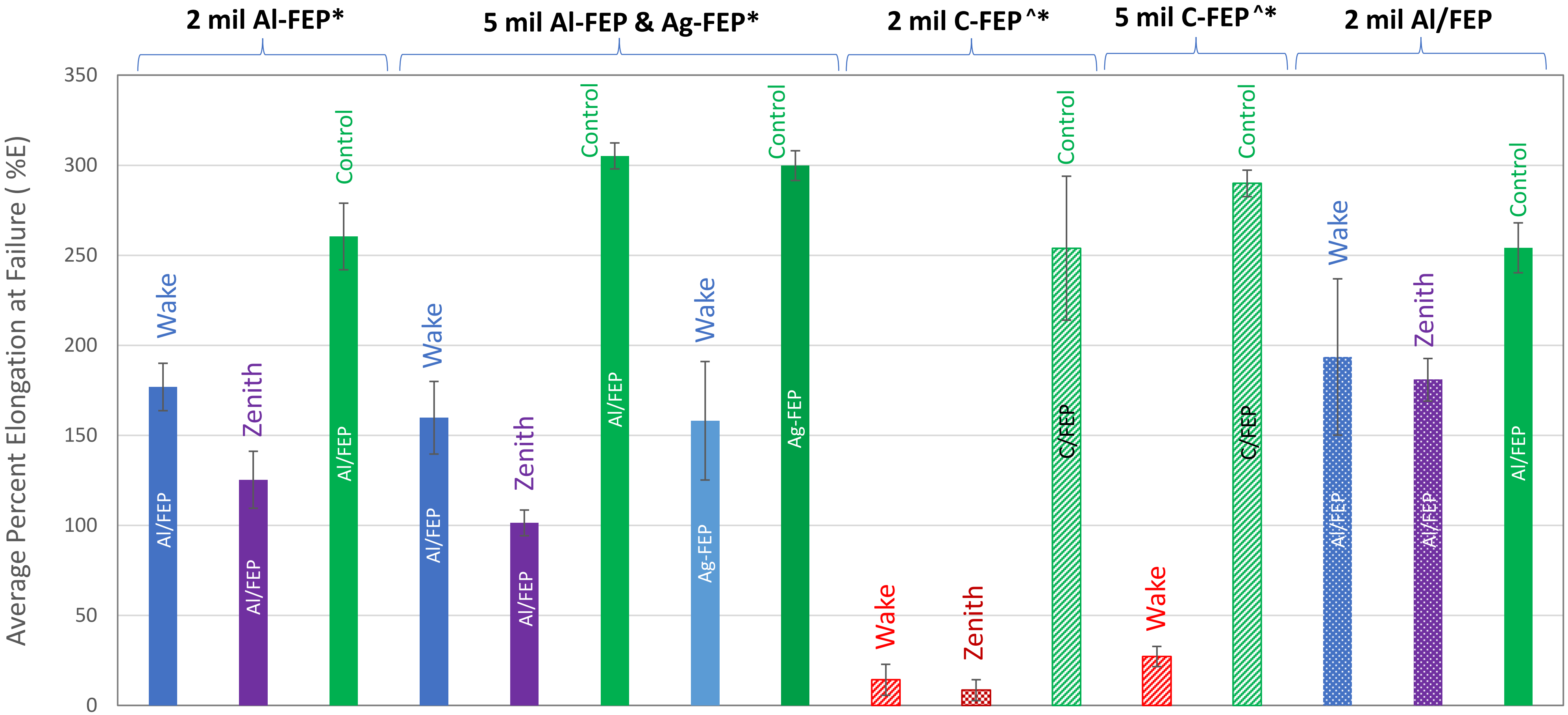


- Wake tensile sample M9W-T34 (carbon back-surface painted 5 mil Teflon FEP (FEP/C)) broke on-orbit after **≤5 months** of space exposure
- M9W-T31 (5 mil FEP/C) broke after **≤7 months** of space exposure & M9W-T29 (2 mil FEP/C) is cracked
- The black coating causes the sample to passively heat to a 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*

On-orbit sample photos courtesy of NASA and Aegis Aerospace

MISSE-9 Wake and Zenith Tensile Data

0.54 Years Direct Space Exposure



* Teflon FEP is space facing ^ Carbon-back surface painted FEP (black)

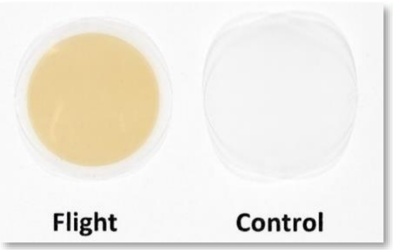
❖ *Flight data is not consistent with ESH estimates provided by Aegis Aerospace*

➢ *MISSE-8, MISSE-9 and MISSE-13 tensile results paper "Effect of Space Exposure on the Tensile Properties of MISSE Teflon Flight Samples," NASA/TM-TBD 2024 (title may change) has been written and is being finalized*

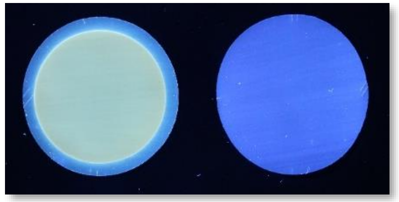
PCE 1-4 Post-flight Analyses

Optical Properties with Sylvie Crowell (NASA GRC)

M9Z-C12
Polyvinylidene fluoride (PVDF)



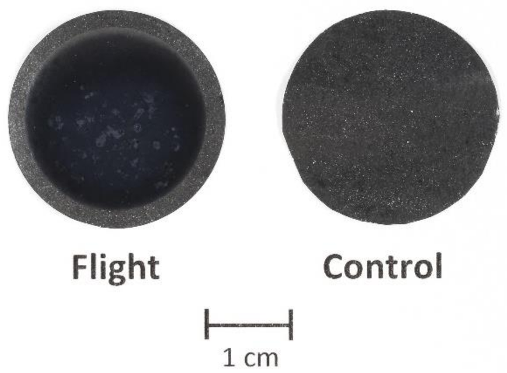
UV Light (365 nm)

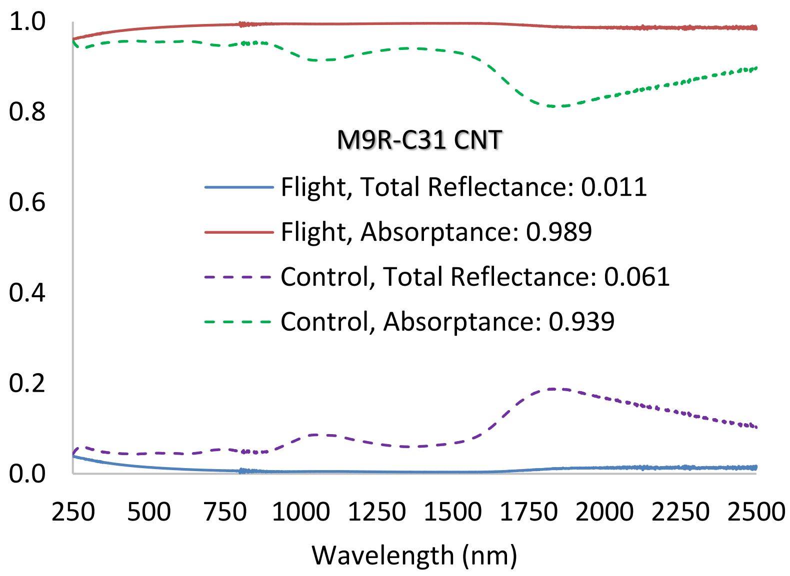


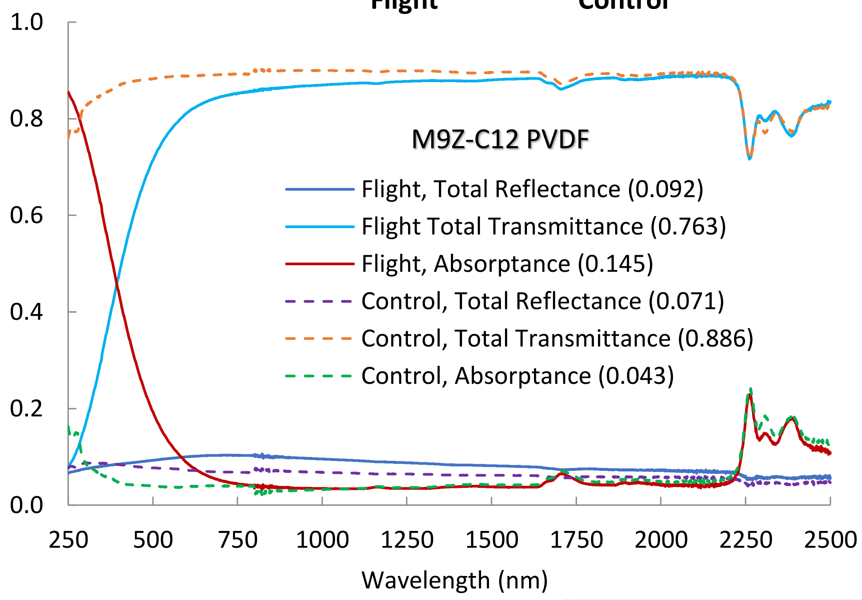
Flight Control

- Optical properties of flight and control samples – ***in progress***
  - *Total Reflectance (TR), Total Transmittance (TT) & Solar Absorptance (SA)*
    - *Cary 5000 UV-Vis-NIR Spectrophotometer with a DRA-2500 integrating sphere*
  - *The majority of PCE 1-4 samples have been scanned & processed*
    - *120 flight samples completed & 24 being processed*

MISSE-9
Carbon Nanotube (CNT) Buckypaper
(M9R-C31)



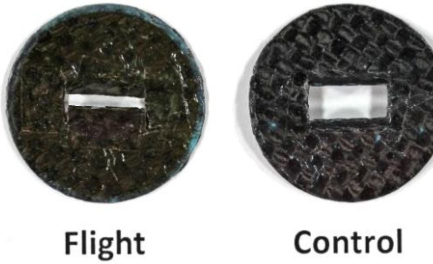




- *We will be writing a NASA TM paper with all PCE 1-4 optical data in the near future*
  - *TM to include flight vs. control sample images & optical data (TR, TT & SA)*

PCE 1-4 Post-flight Analyses

- Post-flight Analyses by PCE 1-4 Sample Collaborators – *Completed & On-going*
  - *BAE, Systems, Inc.*: *Specialty coatings including Z307 black paint, Ball Infrared Black (BIRB) paint, Magic Black, Fractal Black, Vantablack CX2, Vantablack (S-IR)**
  - *University of Rome - Tor Vergata*: *Shape Memory Polymer Composites (SMPCs)* for functionality assessment for space structures and cosmic ray shielding (CRS) samples* for radiation durability assessment (Composites Communication paper, 2024)*
  - *Michigan State University:* *Graphene nanoplatelets (GnP) paper*
  - *Melanin Team (GRC, U. of Akron, JHU, redhouse):* *Melanin and mycelium composites for radiation protection**
  - *NASA LaRC:* *Polyethylene naphthalate (PEN) & LaRC radiation resistant polyimide (RPI) solar sail materials**
  - *NASA GRC Aerogel Team*: *Low and high density polyimide aerogels for AO and radiation durability assessment**
  - *NASA GRC Seals Team*: *Uncoated and coated docking seal (S383-70 silicone) samples for AO and UV durability assessment*
  - *Othmane Benafan & Santo Padula (NASA GRC)*: *Shape Memory Alloys (SMAs) to assess the radiation durability for space-based solid-state actuation and structural components (i.e., rovers, bearing alloys)*
  - *Tiffany Williams & Witold Fuchs (NASA GRC)*: *Polyphenylsulfone (PPSU) with and without BN additives to assess radiation durability for 3D-printable composites* (MRS Advances paper, 2024)*
  - *Henry de Groh (NASA GRC)*: *Indium tin oxide (ITO) conductive coatings for optical and electrical performance and durability (TM-20240002413, March 2024)*
  - *Sharon Miller (NASA GRC)*: *ISS Replacement Array and Crew Vehicle materials*
  - *Emily Naim (NASA GRC)*: *Spacecraft polymers flown in both unstressed and under folding stress configurations*



M9Z-C17 SMPC

** Conference presentations*

PCE 1-4 Sample Results - Papers

- *Santo, L., Quadrini, F., Bellisario, D., de Groh, K. and Banks, B., "Shape Memory Polymer Composites and Cosmic Ray Shielding Materials in Open Space," Extended Abstract of the Applied Space Environments Conference (ASEC), May 13-17, 2019, Los Angeles, CA.*
- *de Groh, K. K. and Banks, B.A., "Space Environmental Effects and NASA Glenn's MISSE-Flight Facility (MISSE-FF) Experiments," Proceedings of the Applied Space Environments Conference (ASEC), May 13-17, 2019, Los Angeles, CA; NASA TM-2020-220475, Feb. 2020.*
- *de Groh, K. K. and Banks, B. A., "MISSE-Flight Facility Polymers and Composites Experiment 1-4 (PCE 1-4)," NASA TM-20205008863, Feb. 2021.*
- *Williams, T. S., Fuchs, W. K., Nguyen, B. N., de Groh K. K., and Santiago, D., "Exposure of Polyphenylsulfone and Polyphenylsulfone-Hexagonal Boron Nitride Composite Films in LEO Wake Environment," MRS Advances (2024).*
- *de Groh, K. K. and Banks, B. A., "Space Environmental Exposure of the MISSE 9-15 Polymers and Composites Experiment 1-4 (PCE 1-4)," NASA/TM-20240000755, February 2024.*
- *de Groh, K. K., Lukco, D., Crowell, S. F., Gregor, S. J. and Banks, B. A., "Analyses of the MISSE 9-15 Polymers and Composites Experiment 1-4 (PCE 1-4) Contamination Samples," NASA/TM-20240000941, February 2024.*
- *de Groh III, H. C., de Groh, K. K., Gregor, S. J. and Banks, B.A. "Space Exposure of Indium Tin Oxide Coatings," NASA/TM-20240002413, March 2024.*
- *Santo, L., Quadrini, F., Bellisario, D., Iorio, L., Proietti, A. and de Groh, K. K., "Effect of the LEO Space Environment on the Functional Performances of Shape Memory Polymer Composites," Composites Communication, 48 (2024) 101913.*
- *de Groh, K. K. and Banks, B. A., "Erosion Results from the MISSE 9-15 Polymers and Composites Experiment 1-4 (PCE 1-4)," NASA/TM 2024 TBD.*
- *Mathers, J. L., de Groh, K. K. and de Groh III, H. C., "Testing of Sunscreen Protected Silicone Seals from MISSE-12 and MISSE-13 On-Orbit Flights," NASA/TM 2024 TBD.*
- *Malakooti, S., Vivod, S. L., de Groh, K. K., Cashman, J. L., Meador, MA., Scheiman, D. A., Salem, J. A. and McCorkle, L.S, "Space Environment Exposure Effects on Polyimide Aerogels," Submitted to the journal Polymer Degradation and Stability (2024)*
- *de Groh, K. K., Whitt, A. and Banks, B.A., "Effect of Space Exposure on the Tensile Properties of MISSE Teflon Flight Samples," NASA/TM 2024 TBD 2024.*

PCE 1-4 Sample Results - Conference Presentations

- **ISSRDC 2022:**
  - *"Shape Memory Polymer Composites After Long-term Exposure in Space Environment by the MISSE Facility," L. Santo, F. Quadrini, D. Bellisario, L. Iorio and K. K. de Groh, presented at the ISSRDC 2022 Conference, July 25-28, 2022, Washington D.C.*
  - *"Melanin-based biomaterials for radiation shielding and harvesting applications in space," T. Benyo, A. Casadevall, R. JB Cordero, K. K. de Groh, A. Dhinojwala, Q. Dragotakes, C. Maurer, S. Singla and A. Trunek, presented at the ISSRDC 2022 Conference, July 25-28, 2022, Washington D.C.*
- **ISMSE-15 2022:**
  - *"Initial Results of the MISSE-Flight Facility Polymers and Composites Experiment 1-4 (PCE 1-4)," K. K. de Groh, B. A. Banks, A. S. Mills and L. Santo, presented at the joint 15th International Symposium on Materials in the Space Environment (ISMSE-15) and 13th International Conference on Protection of Materials from the Space Environment (ICPMSE-13), held Sept. 18–23, 2022 in Leiden, The Netherlands.*
- **MRS 2023 Spring Meeting:**
  - *"Low Earth Orbit (LEO) Exposure Effects on Polyimide Aerogels During MISSE Missions," S. Malakooti, A. E. Tokarz, J. L. Cashman, K. K. de Groh and S. L. Vivod, presented at the 2023 MRS Spring Meeting, April 10-14, 2023 in San Francisco, CA.*
  - *"Exposure of Polyphenylsulfone and Polyphenylsulfone-Hexagonal Boron Nitride Composite Films in LEO Wake Environment," T. Williams, W. Fuchs, B. Nguyen, K. de Groh and D. Santiago, presented at the 2023 MRS Spring Meeting, April 25, 2023 (virtual) in San Francisco, CA.*
- **ISSS 2023:**
  - *"Space Environmental Damage Assessment on Sail/Deorbit Materials in Low Earth Orbit" J. H. Kang, K. Gordon, R. Bryant, W. K. Wilkie, K. de Groh, et al, presented at the 6th International Symposium on Space Sailing, June 5-9, 2023, New York, NY.*
- **SPE 2024:**
  - *Santo, L, Quadrini, F. and de Groh, K. K., "Space Application of Polyethylene for Cosmic Ray Shielding," invited presentation at the Society of Plastics Engineering (SPE) International Polyolefins Conference, February 18-21, 2024, Galveston, TX.*
- **2024 SEM Annual Conference:**
  - *Malakooti, S., Vivod, S. L. and de Groh, K. K., "Durability of Polyimide Aerogels in The Space Environment," presented at The 2024 SEM Annual Conference and Exposition on Experimental and Applied Mechanics, June 3 - 6, 2024, Vancouver, WA.*
- **NSMMS/CRASTE 2024:**
  - *Deyanova, J. E., Torres, D., Fleming, J., Devaud, G. and de Groh, K. K., "Effect of the MISSE Space Environment on Specialized Materials," presented at the 2024 NSMMS & CRASTE Joint Symposium, June 24-27, 2024, Madison, WI.*

Summary & Conclusions

- NASA Glenn's Polymers and Composites Experiment 1-4 (PCE 1-4) with 365 flight samples were successfully exposed to the space environment on the MISSE-Flight Facility (MISSE-FF)
  - *MISSE-9 PCE-1 (138 samples: 39 ram, 52 wake & 47 zenith)*
  - *MISSE-10 PCE-2 (43 samples: 21 ram, 10 zenith & 12 nadir)*
  - *MISSE-12 PCE-3 (86 samples: 30 ram, 42 wake* & 14 zenith)*

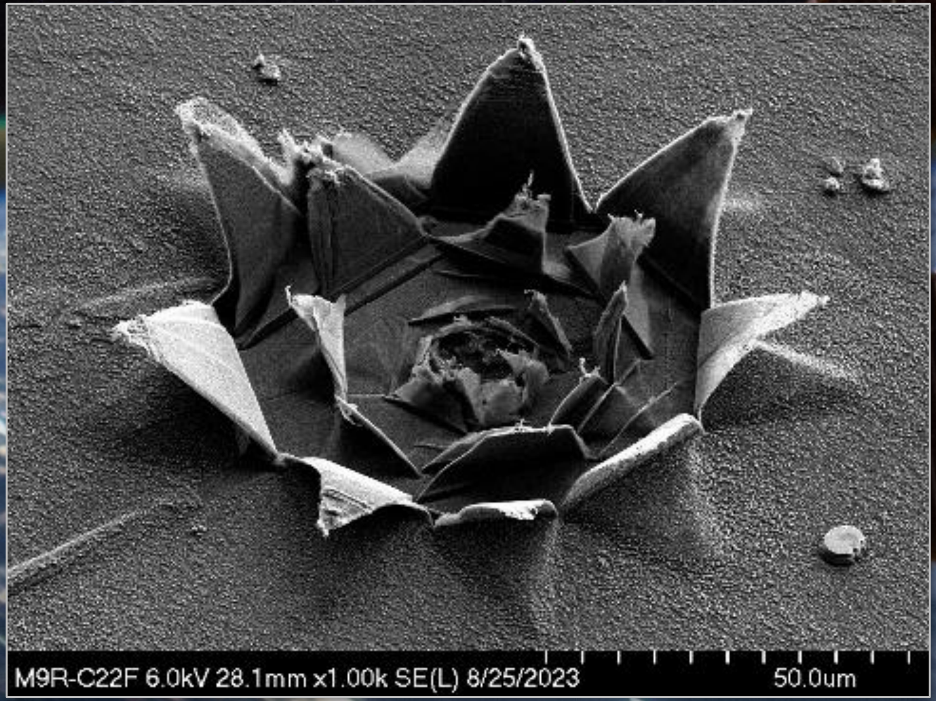
    **The 42 wake samples were re-flown as part of the MISSE-15 mission*
  - *MISSE-13 PCE-4 (98 samples: 65 wake & 33 zenith)*
- We have 47 sample collaborators from 21 organizations
- The primary objective of these experiments is to determine the AO and radiation durability of spacecraft polymers, composites and specialty coatings
  - *In addition, each experiment has a wide variety of materials and numerous additional sample objectives*
- Samples have been analyzed for:
  - *AO fluence (NASA TM-20240000755) & on-orbit contamination (NASA TM-20240000941)*
  - *AO erosion yield (150 samples; NASA TM-2024 being finalized)*
  - *Tensile properties (2 broke on-orbit & 230 samples successfully tested; NASA TM being finalized)*
  - *Optical properties (144 PCE 1-4 samples; NASA TM to be written)*
  - *Radiation & functional durability, and other properties by PCE 1-4 sample collaborators*
- The results from the PCE 1-4 experiments will provide spacecraft designers with AO and radiation performance and durability data needed for developing durable spacecraft components

Acknowledgements

I am very grateful for the cooperative research efforts with all my PCE 1-4 sample collaborators

This work is supported by NASA's Biological and Physical Sciences (BPS) Division

HOPG Impact site (1kX and 45° tilt)



Extra Slides

Polymers and Composites Experiment-1 (PCE-1)

MISSE-9 Ram
(M9R2 Mount-Side Deck)

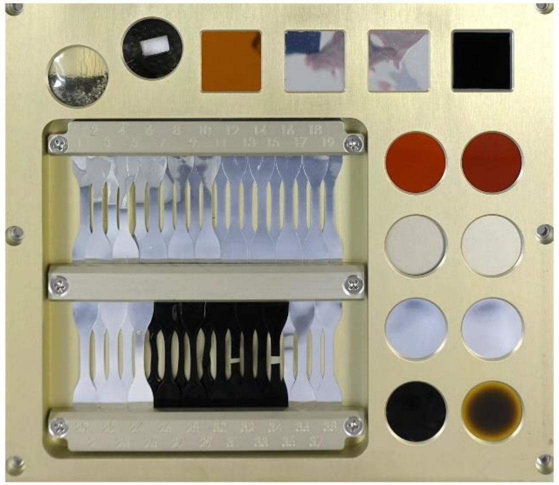
Pre-flight

Post-flight

MISSE-9 Wake
(M9W3 Mount-Side Deck)

Pre-flight

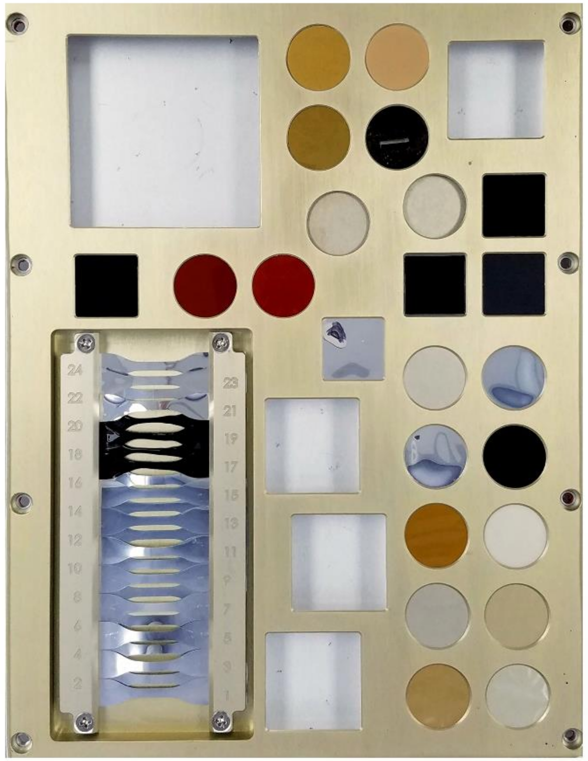
Post-flight



MISSE-9 Zenith
(M9Z3 Mount-Side Deck)

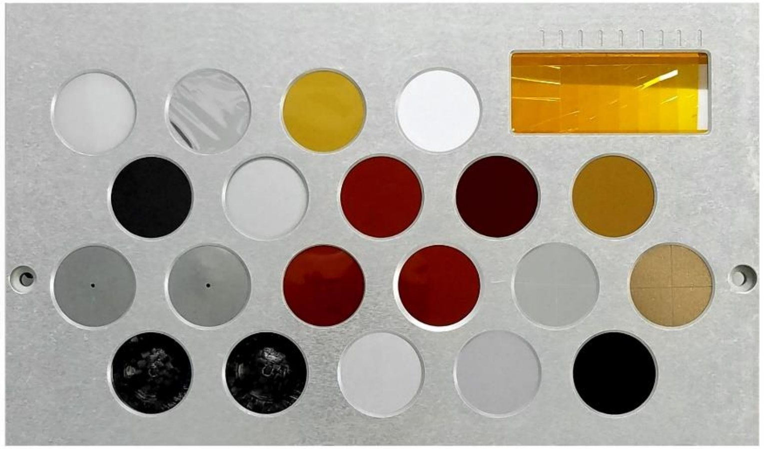
Pre-flight

Post-flight

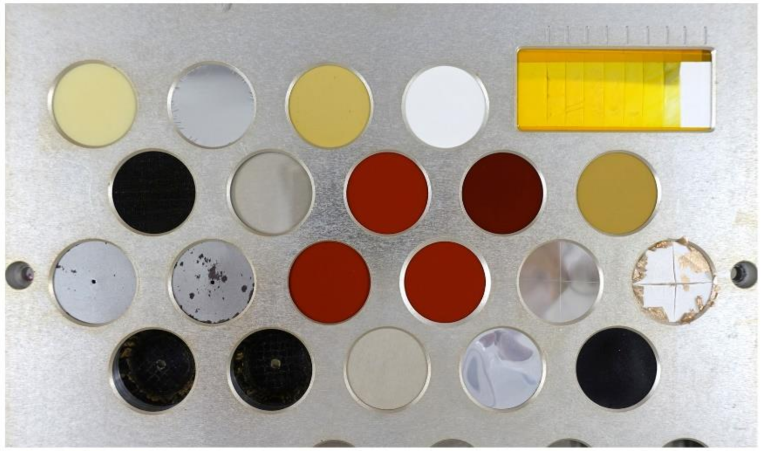


MISSE-10 Ram
(M10R1 Mount-Side Deck)

Pre-flight



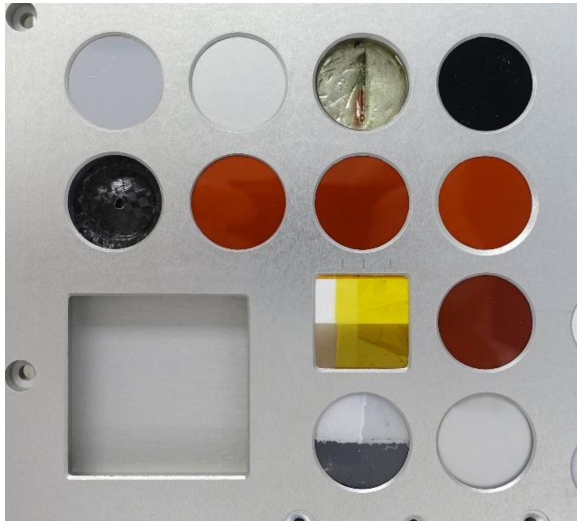
Post-flight



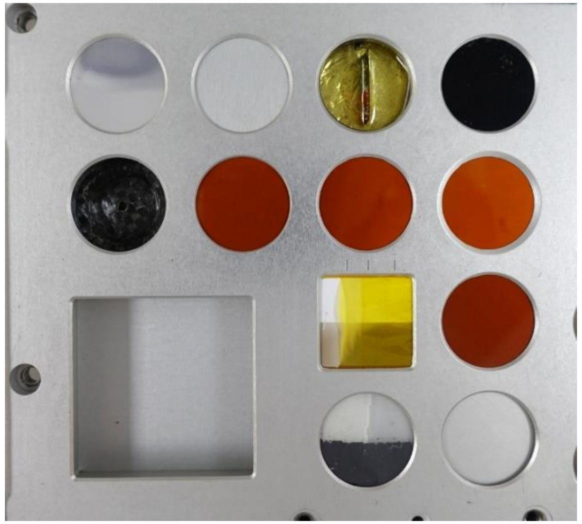
Polymers and Composites Experiment-2 (PCE-2)

MISSE-10 Nadir
(M10N3 Mount-side Deck)

Pre-flight

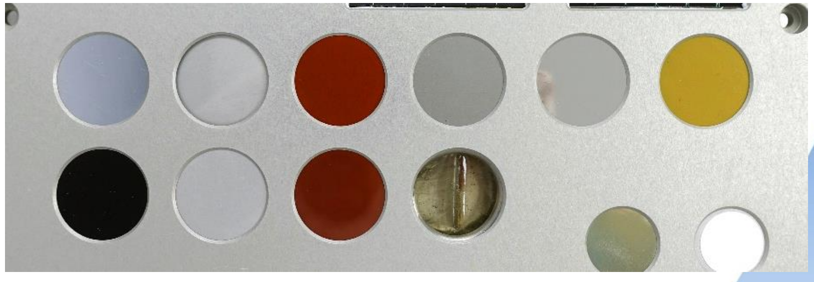


Post-flight



MISSE-10 Zenith
(M10Z2 Mount-side Deck)

Pre-flight



Post-flight

Polymers and Composites Experiment-3 (PCE-3)

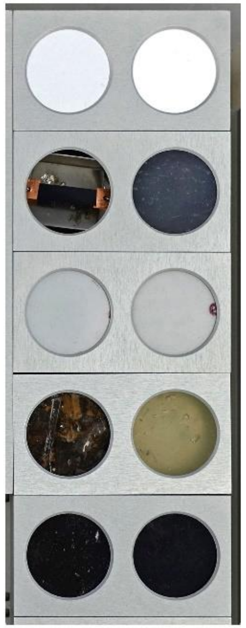
MISSE-12 Ram
(M12R2 Mount-Side Deck)

Pre-flight

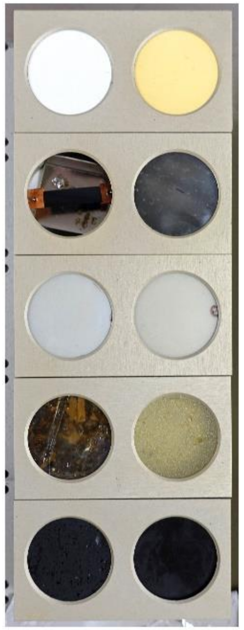
Post-flight

MISSE-12 Zenith
(M12Z1 Mount-Side Deck)

Pre-flight

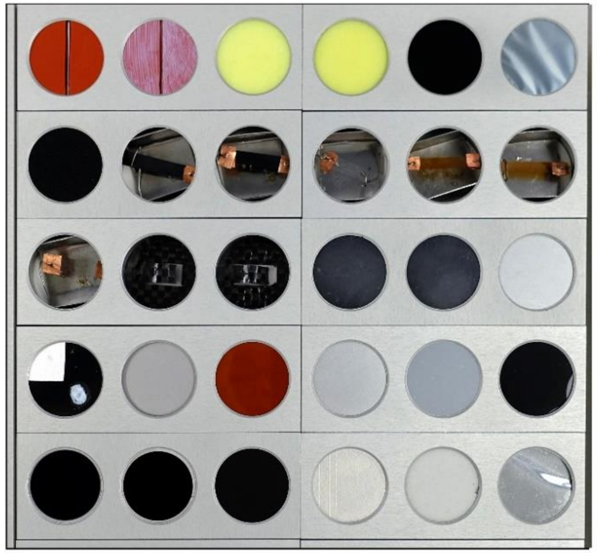


Post-flight



MISSE-12/MISSE-15 Wake *
(M12W3/M15W1 Mount-Side Deck)

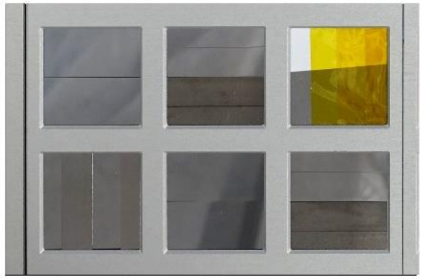
Pre-flight



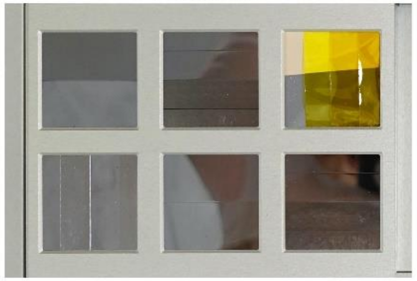
Post-flight

MISSE-12/MISSE-15 Wake *
(M12W3/M15W1 Mount-Side Deck)

Pre-flight



Post-flight



** The MISSE-12 wake carrier never opened during the MISSE-12 mission, thus the 42 wake samples were re-flown as part of the MISSE-15 mission in the wake direction.*

Polymers and Composites Experiment-4 (PCE-4)

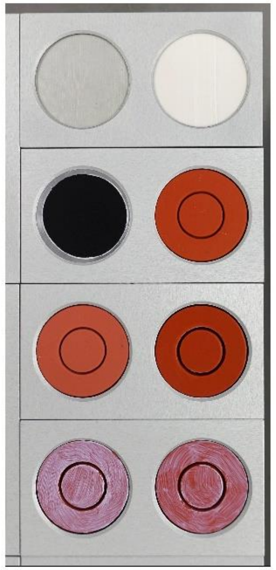
MISSE-13 Wake
(M13W1 Mount-Side Deck)

Pre-flight

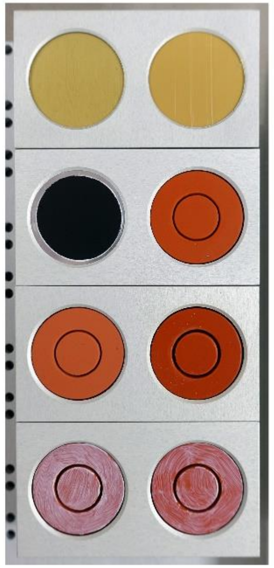
Post-flight

MISSE-13 Wake
(M13W1 Mount-Side Deck)

Pre-flight

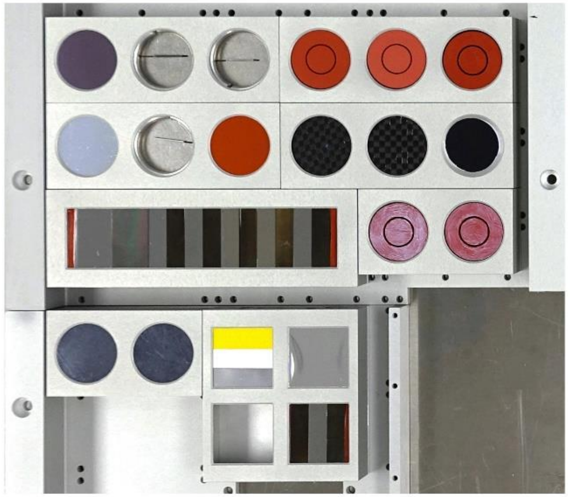


Post-flight

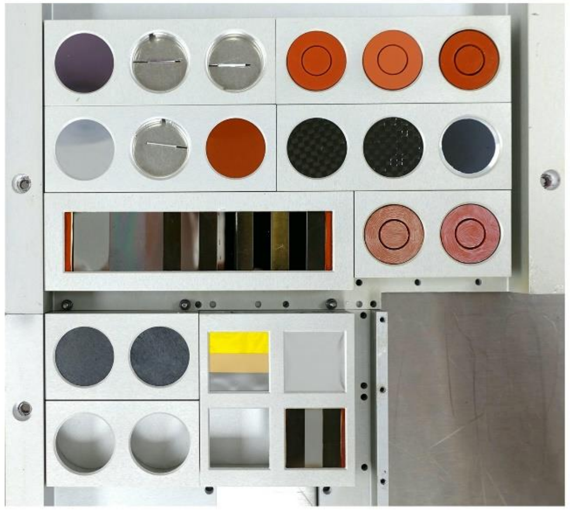


MISSE-13 Zenith
(M13W1 Mount-Side Deck)

Pre-flight



Post-flight



MISSE-13 Wake
(M13W1 Swing-Side Deck)

Pre-flight

Post-flight