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

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI Program provides access to the NASA Technical Report Server—Registered (NTRS Reg) and NASA Technical Report Server—Public (NTRS) thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers, but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., "quick-release" reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question to help@sti.nasa.gov

- Fax your question to the NASA STI Information Desk at 757-864-6500

- Telephone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Program
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

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

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

February 2021

Acknowledgments

We are grateful to the NASA Flight Opportunities program, the International Space Station Program Office and Alpha Space for making these flight opportunities possible. We thank Craig Robinson of NASA Glenn Research Center for his encouragement and constant support of these flight experiments. We very much appreciate all the effort made by Jeff Buell of Alpha Space in providing specific mission exposure dates for each of the experiment carriers. We would like to give a special thank you to Ally Mills of Hathaway Brown School for her assistance with verifying all the mission dates and durations in numerous spreadsheets and this publication. A final thank you to Diane Malarik of NASA Headquarters for recognizing the importance of this work. Originally supported by Glenn Research Center, this work is currently supported by the NASA Space Life and Physical Sciences Research and Applications Division (SLPSRA).

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA STI Program
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
703-605-6000

This report is available in electronic form at http://www.sti.nasa.gov/ and http://ntrs.nasa.gov/

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

Kim K. de Groh
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Bruce A. Banks
Science Applications International Corporation
Cleveland, Ohio 44135

Abstract

Spacecraft in low Earth orbit (LEO) are subjected to harsh environmental conditions, including radiation (cosmic rays, ultraviolet (UV), x-ray and charged particle radiation), micrometeoroids and orbital debris, temperature extremes, thermal cycling, and atomic oxygen (AO). These environmental exposures can result in erosion, embrittlement and optical property degradation of susceptible materials threatening spacecraft performance and durability. To increase our understanding of effects such as AO erosion and radiation induced embrittlement of spacecraft materials, NASA Glenn Research Center has developed a series of experiments that are flown as part of the Materials International Space Station Experiment (MISSE) missions on the exterior of the International Space Station (ISS). These experiments have provided critical space environmental durability data such as AO erosion data of polymers and composites, and radiation induced mechanical property degradation of spacecraft insulation materials, after long term space exposure. In continuing these studies, four Glenn experiments have been flown on ISS's MISSE-Flight Facility (MISSE-FF). These experiments are the Polymers and Composites Experiment-1 (PCE-1) flown as part of the inaugural MISSE-9 mission, the PCE-2 flown as part of the MISSE-10 mission, the PCE-3 being flown as part of the MISSE-12 mission, and the PCE-4 being flown as part of the MISSE-13 mission. This paper provides an overview of space environmental effects on spacecraft materials and Glenn's PCE 1-4 MISSE-FF experiments.

Introduction

Materials used on the exterior of spacecraft are subjected to many environmental threats that can cause degradation. In low Earth orbit (LEO) these threats include visible light photon radiation, ultraviolet (UV) radiation, vacuum ultraviolet (VUV) radiation, x-rays, solar wind particle radiation (electrons, protons), cosmic rays, temperature extremes, thermal cycling, impacts from micrometeoroids and orbital debris (MMOD), on-orbit contamination, and atomic oxygen (AO). These environmental exposures can result in erosion, embrittlement and optical property degradation of susceptible materials threatening spacecraft performance and durability. To increase our understanding of effects such as AO erosion and radiation induced embrittlement of spacecraft materials, since 2001 NASA Glenn Research Center has flown a series of space exposure experiments as part of the Materials International Space Station Experiment (MISSE) missions on the exterior of the International Space Station (ISS). The MISSE 1-8 missions were flown on the Shuttle (2001 to 2013). In the post-Shuttle era, the MISSE experiments (MISSE-9, etc.) are launched on SpaceX Dragon or Northrop Grumman (NG) Cygnus and robotically installed on ISS's external MISSE-Flight Facility (MISSE-FF). This paper provides an overview of space environmental effects on spacecraft materials and Glenn's Polymers and Composites Experiment 1-4 (PCE 1-4) flight experiments flown as part of the MISSE-9, MISSE-10, MISSE-12, and MISSE-13 missions on the MISSE-FF.

Space Environmental Effects

Low Earth Orbit (LEO) Atomic Oxygen Erosion

Although all space environmental exposures can cause degradation to spacecraft components, AO is a particularly serious structural, thermal, and optical threat, especially to exterior oxidizable spacecraft components. Atomic oxygen is formed in the LEO environment through photodissociation of diatomic oxygen (O_2). Short-wavelength (<243 nm) solar radiation has sufficient energy to break the 5.12-eV O_2 diatomic bond in an environment where the mean free path is sufficiently long (~10^8 m) so that the probability of re-association, or the formation of ozone (O_3), is small.[1,2] In LEO, between the altitudes of 180 and 650 km, AO is the most abundant species.[3]

A number of processes can take place when an oxygen atom strikes a spacecraft surface as a result of its orbital velocity and the thermal velocity of the atoms. These include chemical reaction with surface molecules, elastic scattering, scattering with partial or full thermal accommodation, and recombination or excitation of ram species, which consists predominantly of ground-state $O(^3P)$ atomic oxygen atoms.[4] Atomic oxygen can react with polymers, carbon, and many metals to form oxygen bonds with atoms on the exposed surface. For most polymers, hydrogen abstraction, oxygen addition, or oxygen insertion can occur, with the oxygen interaction pathways eventually leading to volatile oxidation products.[5,6] This results in gradual erosion of hydrocarbon or halocarbon material, with the exception of silicone materials, which form a glassy silicate surface layer with AO exposure. Figure 1 shows AO erosion of Teflon™ fluorinated ethylene propylene (FEP) around a small protective particle after 5.8 years of space exposure on the Long Duration Exposure Facility (LDEF). An example of the complete loss of a Kapton® H thermal blanket insulation layer on the LDEF and degradation of other polymeric materials caused by AO erosion in LEO are provided in Figure 2.[2,7]

The most common approach to protecting susceptible spacecraft materials from AO erosion is to coat the material with a thin protective film, such as SiO_x (where x = 1.8 to 2). Even materials with AO protective coatings can be susceptible to AO erosion as a result of microscopic scratches, dust particles, or other imperfections in the substrate surface, which can result in defects or pin windows in the protective coating.[8,9] These coating defects can provide pathways for AO attack, and undercutting erosion of the substrate can occur, even under directed ram AO exposure in LEO. One of the first examples of directed ram AO undercutting erosion in LEO was reported by de Groh and Banks for aluminized-Kapton insulation blankets from the LDEF.[8] Undercutting erosion can be a serious threat to component survivability. An example is shown in Figure 3, where AO undercutting erosion has severely degraded the P6 Truss port solar array wing two-surface aluminized-Kapton blanket box cover on the International Space Station (ISS) after 1 year of space exposure.[10]

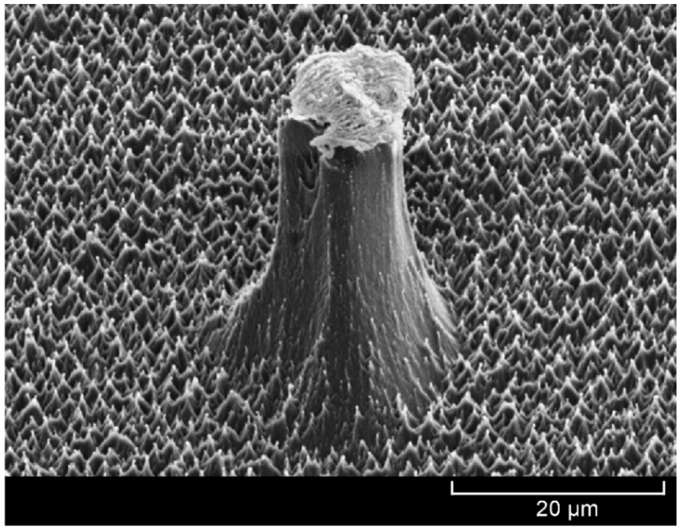


Figure 1. Atomic oxygen erosion of Teflon FEP after 5.8 years of space exposure.[2,7]

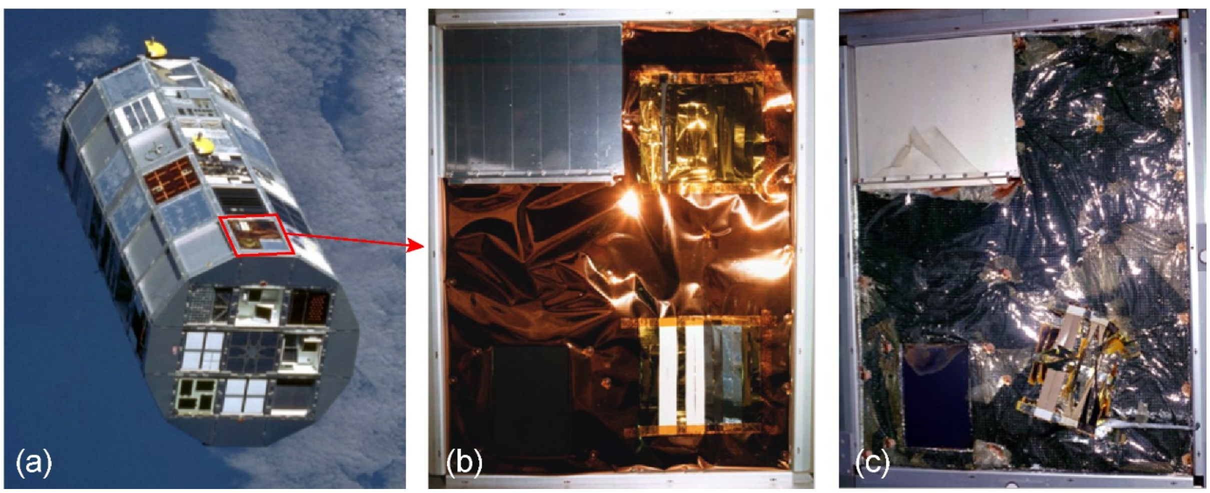


Figure 2. Atomic oxygen erosion of a Kapton insulation blanket from LDEF experiment Tray F-9, located on the leading edge and exposed to direct-ram AO for 5.8 years.[7]
a) LDEF. b) Tray F-9 pre-flight. c) Tray F-9 post-flight.[7]

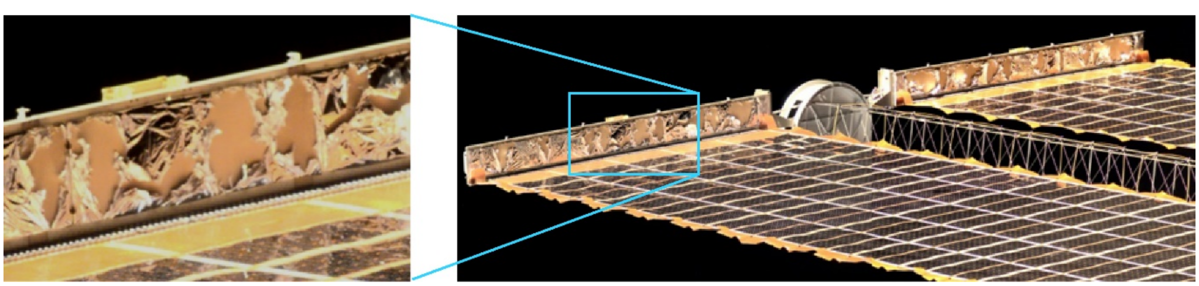


Figure 3. Atomic oxygen undercutting degradation of the P6 Truss solar array wing blanket box cover on the ISS after only 1 year of space exposure.[10]

The sensitivity of a hydrocarbon or halocarbon material to react with AO is quantified by the AO erosion yield, E_y, of the material. The AO E_y is the volume of a material that is removed (through oxidation) per incident oxygen atom and is measured in units of cm^3/atom. As AO erosion in LEO is a serious threat to spacecraft performance and durability, it is essential to know the LEO AO E_y so that the durability of materials being considered for spacecraft design can be predicted.

A common technique for determining the E_y of materials is based on mass loss of flight samples and is calculated using dehydrated mass measurements before and after flight. The E_y of the sample is determined through the following equation:

$$E_y = \frac{\Delta M_S}{\left(A_S \rho_S F\right)} \tag{1}$$

where

E_y = erosion yield of flight sample (cm^3/atom)
ΔM_S = mass loss of the flight sample (g)
A_S = surface area of the flight sample exposed to AO (cm^2)
ρ_S = density of flight sample (g/cm^3)
F = low Earth orbit AO fluence ($atoms/cm^2$)

The AO fluence (F) of a spaceflight mission is often determined through the mass loss of a Kapton H witness sample because Kapton H has a well characterized erosion yield, E_K ($3.0 \pm 0.07 \times 10^{-24}$ cm^3/atom) in the LEO environment.[11–14] Therefore, the AO fluence can be calculated using the following equation:

$$F = \frac{\Delta M_K}{\left(A_K \rho_K E_K\right)} \tag{2}$$

where

F = low Earth orbit AO fluence ($atoms/cm^2$)
ΔM_K = mass loss of Kapton H witness sample (g)
A_K = surface area of Kapton H witness sample exposed to AO (cm^2)
ρ_K = density of Kapton H witness sample (1.4273 g/cm^3)[2,15]
E_K = erosion yield of Kapton H witness sample (3.0×10^{-24} cm^3/atom)[11–14]

Recession measurements can also be used for AO E_y determination based on erosion depth step-heights. The erosion or recession depth (D) can be measured from a protected surface using profilometry, scanning electron microscopy (SEM), optical interferometry, or atomic force microscopy for low-fluence exposures.[16] The recession based E_y can be calculated through the following equation:

$$E_y = \frac{D}{F} \tag{3}$$

where

E_y = erosion yield of flight sample (cm^3/atom)
D = erosion depth of flight sample (cm)
F = low Earth orbit AO fluence (atoms/cm^2)

Hydrocarbon or halocarbon polymers that contain a small amount of metal oxide pigment particles, or ash, can have E_y values that are fluence dependent. This is because AO will erode the polymer content on the surface, leaving a proliferation of inorganic particles that tend to shield the underlying polymer from AO attack. As a result, the E_y of the polymer gradually reduces with fluence. In addition, for any particular ash-filled polymer, the greater the volume fill of the ash particles, the greater the rate of reduction in the E_y with fluence.[17]

Another LEO threat to spacecraft materials is solar UV radiation, which has a typical wavelength of 0.1 to 0.4 µm.[18] Ultraviolet radiation is energetic enough to cause the breaking of organic bonds such as C=C, C=O, and C–H as well as bonds in other functional groups.[5] A molecule is raised to an excited state when an organic molecule absorbs a photon of UV radiation, and bond dissociation can occur if the molecule acquires enough energy at the excited state. Depending on the temperature and physical properties of the materials, the dissociated radical species are reactive intermediates, with the capability of diffusing several atomic distances from their point of origin and can participate in further reactions.[5] Solar radiation often results in bond breakage in materials as well as threats to functionality and stability of the materials. Therefore, solar radiation can impact the erosion of some materials.

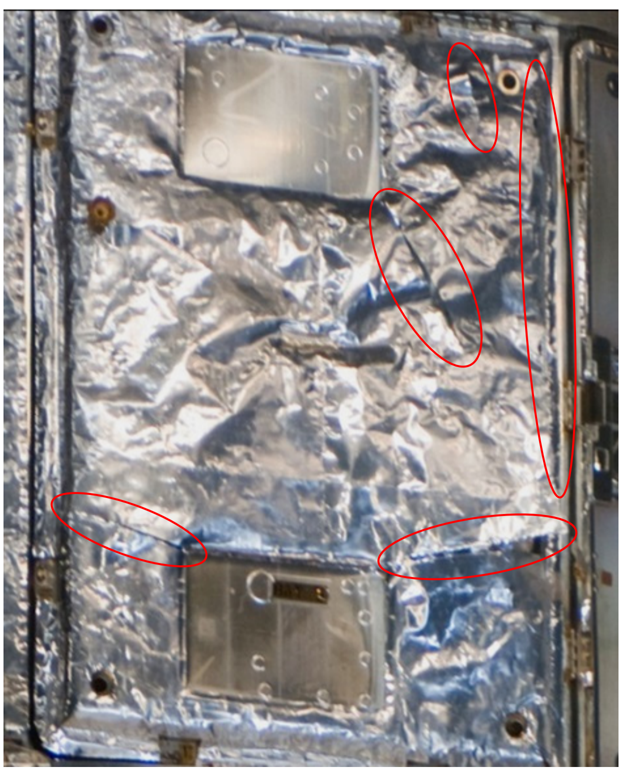
In addition to the structural degradation, AO erosion and solar radiation interaction can also cause optical and thermal property degradation of susceptible spacecraft materials.[2,19] The equilibrium temperature of a spacecraft surface is directly related to its ratio of solar absorptance to thermal emittance. Polymers, such as aluminized-Teflon® fluorinated ethylene propylene (Al-FEP), are often used on the exterior of spacecraft for passive thermal control because they are light weight, flexible and have excellent optical and thermal properties (low solar absorptance and high thermal emittance). Therefore, determining optical property performance and durability in the space environment is important when considering spacecraft design.

Radiation Embrittlement

Radiation in space can be a threat to external spacecraft materials, such as thermal control materials. For example, the metallized Teflon FEP multilayer insulation (MLI) blanket outer layer on the Hubble Space Telescope (HST) has become extremely embrittled in the space environment resulting in severe on-orbit through-thickness cracking. This became evident during the second servicing mission (SM2) after 6.8 years of space exposure where cracking of the 5 mil (127 µm) thick Al-FEP outer layer of the HST MLI blankets was observed on the light shield, forward shell and equipment bays.[20,21] Figure 4 shows two very large cracks in the light shield as observed during SM2.[21] Hundreds of cracks were observed during the following three servicing missions. Figure 5 shows highly degraded HST MLI as imaged during the fifth servicing mission (called SM4) after 19.1 years in space. Figure 5a shows many cracks in the solar facing side (+V3) of the light shield and Figures 5b[22] and 5c[22] show two highly degraded equipment bay MLI blankets (Bay 5 and Bay 8, respectively) prior to removal during SM4.

Figure 4. Large cracks in the HST Light Shield solar facing MLI as observed during SM2, after 6.8 years in space.[21]

a.



b.

c.

Figure 5. On-orbit photos of HST during SM4: a). Many cracks in the solar facing (+V3) surface of the light shield, b). Equipment Bay 5 with large cracks circled, and c). Equipment Bay 8 with large cracks circled.

Teflon FEP insulation pieces retrieved during each of the five HST servicing missions were available for post-retrieval analyses and ground-based space environment simulation tests.[22-32] Analyses conducted by de Groh et al. indicate that the SM4 Bay 8 Al-FEP, which had a significantly higher solar exposure and on-orbit thermal cycling temperature, was more embrittled than the solar-grazed Bay 5 insulation, and was found to fracture like thin brittle glass.[22] The elongation at failure of the Bay 8 MLI FEP outer layer decreased from approximately 250% for pristine FEP to less than 2% for the samples that could be tested.[22] These results highlight the potential negative impact of radiation exposure on spacecraft materials, and the need to understand materials performance and durability in a space radiation environment.

Ground-based environmental durability tests conducted by the Hubble MLI Failure Review Board members indicated that exposing materials in accelerated tests to environmental model predicted spacecraft mission exposures can underestimate the extent of damage that occurs in the space environment.[24,29] Figure 6 shows the results of electron and proton irradiation testing conducted at Goddard Space Flight Center on 5 mil thick FEP, simulating charged particle radiation fluences for various mission years on HST.[24,29] The highly accelerated electron and proton exposure for 100 year fluence levels did not produce as much degradation (as observed in elongation at failure) as witnessed in FEP retrieved from the HST after 9.7 years in LEO.[24,29] Thermal cycling following electron exposure caused additional degradation, but even an equivalent 40 year exposure did not result in as much damage as occurred in Hubble FEP after 9.7 years.[24,29] The reasons for this may include the complex nature of the environmental exposure in space, which is not simulated completely in any ground-based facility, the extreme differences in exposure rates in space and ground tests (slower in-space exposure rates may enable free radicals greater opportunity to degrade the polymers), and inaccuracies in environmental models.

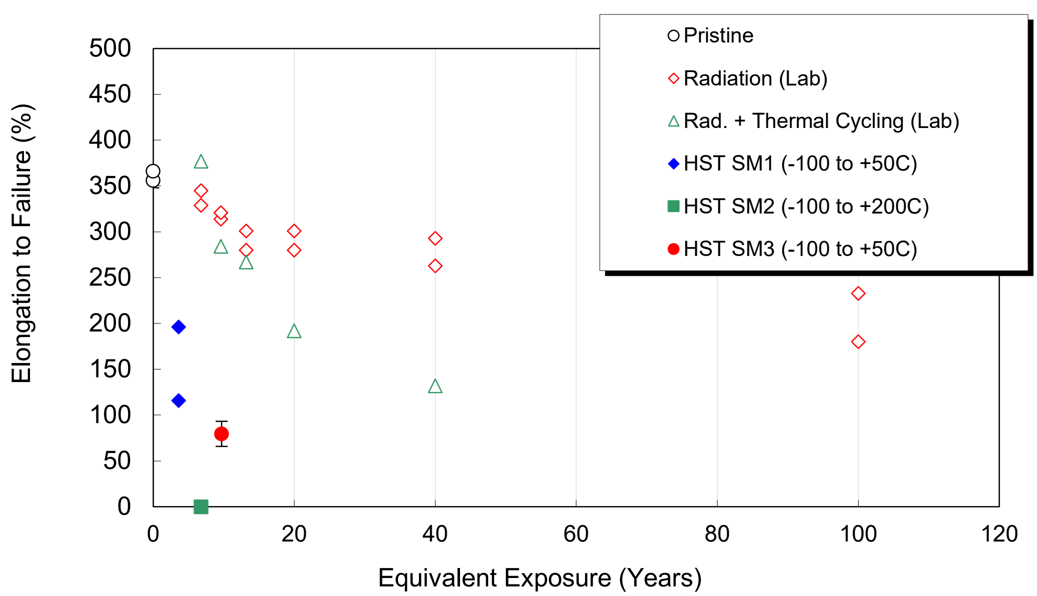


Figure 6. Ground laboratory data for radiation and thermal cycling exposure of 5 mil FEP simulating up to 100 mission years on HST.[24,29]

Flight Experiments

Because spaceflight materials exposure opportunities are rare, expensive, space-limited, and time-consuming, ground laboratory testing is often relied upon for spacecraft material environmental durability prediction. However, differences exist between AO and radiation exposure ground facilities and actual space exposures, which may result in differences in rates of oxidation and mechanical property degradation. This was described in the section above for ground laboratory radiation exposure tests, which did not simulate the degradation that occurred on the HST for similar mission equivalent exposures.[24,29]

Differences between AO ground-test data and LEO flight data have also been documented. For example, Stambler et al. compared the AO E_y values of 39 polymers in a plasma asher to LEO E_y values for the same polymers flown on Glenn's Materials International Space Station Experiment-2 (MISSE-2) Polymers Experiment.[33] The asher to in-space E_y ratios ranged from 1.0 to 37.1, indicating that some polymers have a significantly different rate of erosion in the ground-test facility as compared to in-space.[33] Therefore, actual spaceflight data is ideal for assessing the durability of a material for spacecraft mission applicability. In addition, data from actual materials spaceflight experiments can be used to determine correlations between exposures in ground test facilities and space exposure, allowing for more accurate predictions of in-space materials performance based on ground facility testing.

Materials spaceflight experiments for space environmental effects assessment have been flown on the space shuttle, LDEF, the Russian space station Mir, and other spacecraft.[34] More recently, experiments have been flown as a part of the MISSE missions flown on the exterior of the ISS. NASA Glenn Research Center has developed and flown a series of experiments as part of the MISSE 1–8 missions to further increase our understanding of spacecraft materials space environmental durability.[9,15,19,35-58]

A number of Glenn's MISSE 1-8 experiments were designed for AO erosion characterization of polymers, composites and coating spacecraft materials.[15,17,33,38,39,47,52-54,58] Glenn's ram E_y data from the MISSE 2-8 missions has been collectively reported by de Groh in NASA-TM-219982.[58] A total of 71 types of materials with 111 E_y values are provided from five MISSE missions. The majority of materials are polymers, but other materials such as various forms of carbon (i.e., pyrolytic graphite (PG) and diamond), composites, and protective coatings are also included. Glenn's MISSE experiments have also included tensile samples for radiation induced mechanical property degradation assessment,[37,41,48,51] along with materials for space environmental effects studies such as AO scattering,[35] AO undercutting,[36,45] optical and thermal durability,[19,40,50] spacesuit fabric durability,[42,55] and others. In continuing these studies, four new Glenn experiments are being flown on the ISS's external MISSE-Flight Facility (MISSE-FF). These experiments are the Polymers and Composites Experiment-1 (PCE-1) flown as part of the MISSE-9 mission, the PCE-2 flown as part of the MISSE-10 mission, the PCE-3 flown as part of the MISSE-12 mission and the PCE-4 flown as part of the MISSE-13 mission. A brief overview of Glenn's PCE 1-3 experiments was provided by de Groh in Reference 59. This paper provides a detailed overview of Glenn's PCE 1-4 experiments along with a complete list of the 365 flight samples, the PCE 1-4 sample collaborators and detailed mission information for all four experiments.

MISSE and MISSE-FF

Materials International Space Station Experiment (MISSE)

The Materials International Space Station Experiment (MISSE) program involves a series of spaceflight missions with experiments flown on the exterior of the ISS to test the performance and durability of materials and devices exposed to the LEO space environment. In the MISSE 1–8 missions, individual flight experiments were flown in suitcase-like containers called Passive Experiment Containers (PECs) that provided exposure to the space environment. The PECs were placed outside the ISS in various locations by an astronaut during an extravehicular activity (EVA), or spacewalk. The PECs were positioned in either a ram/wake or a zenith/nadir orientation, and exposed for 1-4 years between August 2001 and July 2013.[9,58] A diagram showing ram, wake, zenith, and nadir directions on the ISS under nominal flight attitudes is shown in Figure 7. The flight orientation highly affects the environmental exposure. Ram facing experiments (facing the direction of travel) receive a high flux of directed AO and sweeping (moderate) solar exposure. Zenith facing experiments (direction facing away from Earth) receive a low flux of grazing arrival AO and the highest solar exposure. Wake experiments (facing away from the direction of travel) receive essentially no AO flux and moderate solar radiation (levels similar to ram experiments). Nadir experiments (direction facing towards Earth) receive a low flux of grazing arrival AO and minimal solar radiation (albedo sunlight). All surfaces receive charged particle and cosmic radiation, which are omnidirectional. It should be noted that the actual orientation of the ISS varies because of operational requirements with a pointing variation of ±15°. After the mission exposure, the majority of PECs were retrieved during an EVA, and returned on the shuttle for post-flight analyses. The exception was MISSE-8 which was returned as part of the SpaceX-3 mission in July 2013. In the post-Shuttle Era, MISSE missions are now being flown on the MISSE-Flight Facility (MISSE-FF), ISS's new permanent external material science platform.

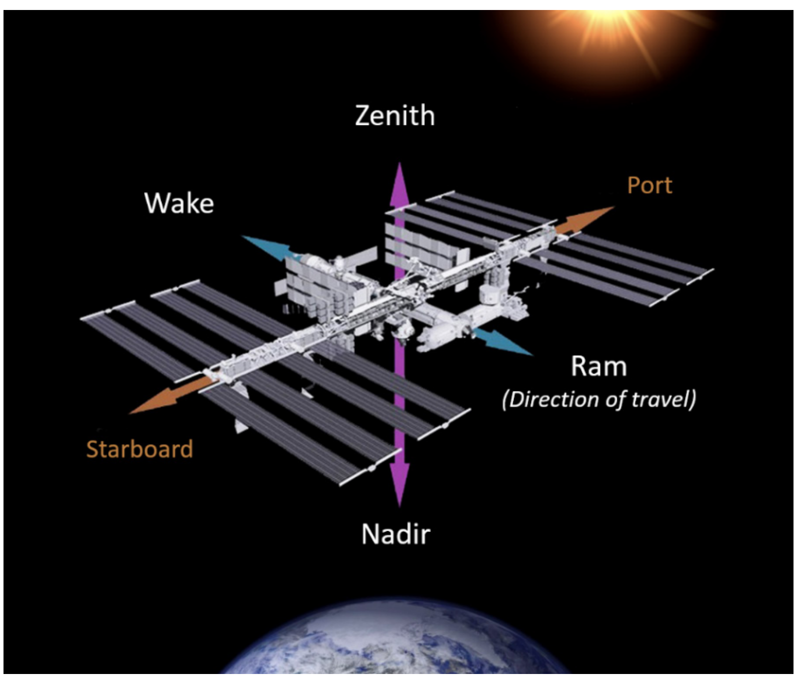


Figure 7. Diagram showing ram, wake, zenith, and nadir directions on the International Space Station.

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

The MISSE-FF is operated by Alpha Space Test & Research Alliance, LLC.[60] It is a modular and robotically serviceable external facility that is located on ISS Express Logistics Carrier-2 Site 3 (ELC-2 Site 3). It provides ram, wake, zenith, and nadir exposures. The MISSE-FF supports both passive and active experiments, with downlink of data. It is designed to include active environmental sensors that provide environmental data over time in each flight orientation, including temperature, contamination and solar exposure (ultraviolet (UV) radiation). Arrangements can be made for sensors to be flown to provide AO fluence and total ionizing dose data. On-orbit facility cameras are typically scheduled to provide monthly sample images.

MISSE Sample Carriers (MSCs), also called MISSE Science Carriers, house the material flight experiments. Each MSC has two sides, a mount-side (MS) and a swing-side (SS), with a central hinge. Materials and spacecraft components can be flown on either the MS or SS decks for direct space exposure, or they can be mounted on the underdecks. The MSCs are launched closed as pressurized cargo on either the Northrup Grumman Cygnus or SpaceX Dragon spacecraft, moved outside the ISS through the Kibo Japanese Experiment Module (JEM) Airlock on the MISSE Transfer Tray (MTT), then installed on the MISSE-FF structure via robotic arm. The SS decks are remotely opened to expose the experiments to space. The MSCs are closed during resupply ship dockings to prevent contamination and minimize AO exposure of wake surfaces. The MSCs are typically closed during local EVAs and for on-demand images.

The MSCs get initial space vacuum exposure when the JEM airlock is put under vacuum and opened to space. It can take several days to robotically move the MTT with the MSCs to ELC-2 and install the MSCs in the MISSE-FF. Each MSC is then remotely "deployed" or opened to the space environment for the first time. As mentioned above, the MSCs are typically closed and re-opened numerous times during a mission. The MSCs are then closed for a final time, robotically retrieved from the MISSE-FF and placed back into the MTT, and the MTT is robotically moved back into the JEM airlock and re-pressurized. Thus, with respect to exposure durations, the space vacuum exposure is longest, then the duration installed on the MISSE-FF, then the "deployed duration" (first time opened to final time closed), and finally the actual time directly exposed to space (accumulated open durations). These durations are discussed below for the various PCE 1-4 missions.

The MISSE-FF and the inaugural set of experiments, called MISSE-9, were launched aboard the SpaceX Commercial Resupply Services-14 (CRS-14) Dragon, also called SpaceX-14, on April 2, 2018. The MISSE-FF was robotically installed on ELC-2 Site 3 on April 8, 2018. The MISSE-9 MSCs were installed in the MISSE-FF on April 18-19, 2018. The MISSE-9 PCE-1 samples (flown in ram R2 MSC 3, wake W3 MSC 8 and zenith Z3 MSC 5) were deployed on April 19, 2018 and scheduled for a 1-year space exposure mission. Figure 8 provides an image showing the location of the MISSE-FF on ELC-2.

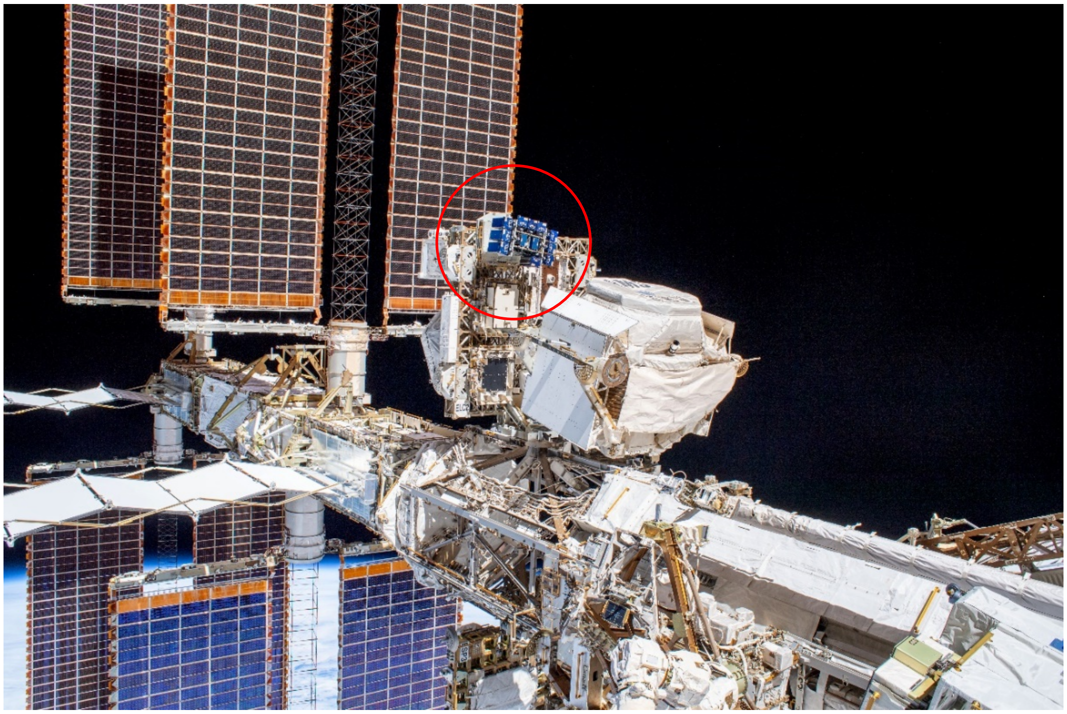


Figure 8. A view of the MISSE-FF on ELC-2 Site 3 as photographed during an EVA on November 15, 2019 (iss061e040917).

The MISSE-10 experiment MSCs were launched aboard the Northrop Grumman (NG) Cygnus cargo ship (NG-10) on November 17, 2018, and then were transferred for storage inside the ISS. The MISSE-9 MSCs were closed on December 26, 2018 in preparation for MISSE-10 installation. The MISSE-10 MSCs were robotically installed in the MISSE-FF on January 4, 2019. An on-orbit photograph of the MISSE-FF with both the MISSE-9 and MISSE-10 MSCs installed is shown in Figure 9. As seen from this top perspective, the ram MSCs are on the left, the zenith MSCs are at the top, the wake MSCs are on the right and the nadir MSCs (two) are at the bottom. The MSC numbers (i.e., R1, R2, and R3) are in numerical order going counter-clockwise (i.e., R1 is near the zenith direction (top ram MSC in Figure 9) and R3 is near the nadir direction (bottom ram MSC in Figure 9). The MISSE-9 and MISSE-10 MSCs remained closed after the MISSE-10 installation operations due to an anomaly which occurred in the communication system during the MISSE-10 installation. The MISSE-9 MSCs were not opened again on-orbit and had a final closure date of December 26, 2018, with the exception of the MISSE-9 ram MSC (R2 MSC 3) which had a final closure date of October 2, 2019, as discussed below.

A new Power and Data Box (PDB) was launched along with the MISSE-11 MSCs on April 17, 2019 as part of the NG-11 mission. The MISSE-9 PCE-1 wake and zenith MSCs (W3 MSC 8 and Z3 MSC 5, respectively) were retrieved during the MISSE-11 installation ops on April 26, 2019 and brought back inside ISS and stowed. The new MISSE-FF PDB resolved the communication issue and the MISSE-10 PCE-2 MSCs (ram R1 MSC 11, zenith Z2 MSC 10 and nadir N3 MSC 13) were deployed on April 26, 2019, exposing the samples to the space environment.

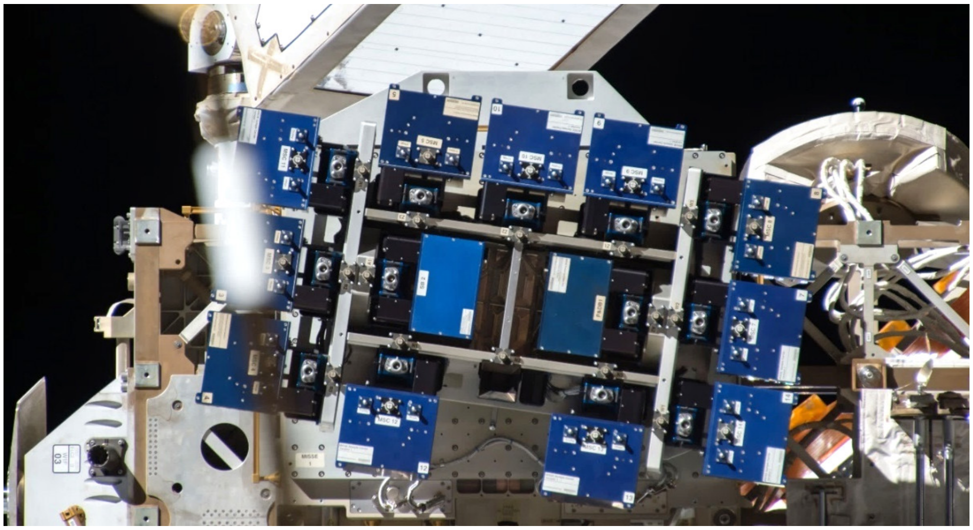


Figure 9. An on-orbit image taken on January 16, 2019 showing the top of the MISSE-FF with the MISSE-9 and MISSE-10 MSCs installed (iss058e003972).

The MISSE-9 PCE-1 wake and zenith MSCs (W3 MSC 8 and Z3 MSC 5, respectively) were returned to Earth in the SpaceX-17 Dragon capsule with splash-down on June 3, 2019. These two MSCs were installed on the MISSE-FF for 1.02 years (W3 was installed from April 18, 2018 to April 26, 2019 and Z3 was installed from April 19, 2018 to April 26, 2019) and exposed to the vacuum of space for 1.07 years (April 13, 2018 to May 9, 2019). The MSCs had an 8.3 month (0.69 year) deployed mission between the first time the MSCs were opened to space (April 19, 2018) to the last time they were closed (December 26, 2018). During this time, the MSCs were closed 21% of the time to protect against contamination from visiting vehicles, EVAs, etc. Therefore, the MISSE-9 PCE-1 zenith and wake samples were directly exposed to the space environment for a total of 6.5 months (0.54 years).

It should be noted that while MSCs are installed on the MISSE-FF and are closed, the samples on those MSCs are exposed to the vacuum of space, thermal cycling (different levels than when the MSCs are open) and energetic radiation, such as galactic cosmic rays. But, when the MSCs are closed the samples are not exposed to visible, UV and VUV radiation, x-rays, solar wind particle radiation (electrons, protons), impacts from MMOD, and atomic oxygen (AO). For these experiments, "space exposure" means the MSCs are open and the samples are directly exposed to the space environment.

The MISSE-12 experiment MSCs were launched to ISS aboard NG-12 on November 2, 2019. The MISSE-12 MSCs were robotically installed in the MISSE-FF on November 11, 2019. The PCE-3 ram MSC (R2 MSC 4) was deployed on December 3, 2019. The PCE-3 wake (W3 MSC 6) and zenith (Z1 MSC 18) carriers were installed in the wrong flight orientations (i.e., swapped) and thus were left closed until MISSE-13 installation operations in March 2020. Figures 10 and 11 provide on-orbit images of the MISSE-FF with the PCE-2 and PCE-3 MSCs installed.

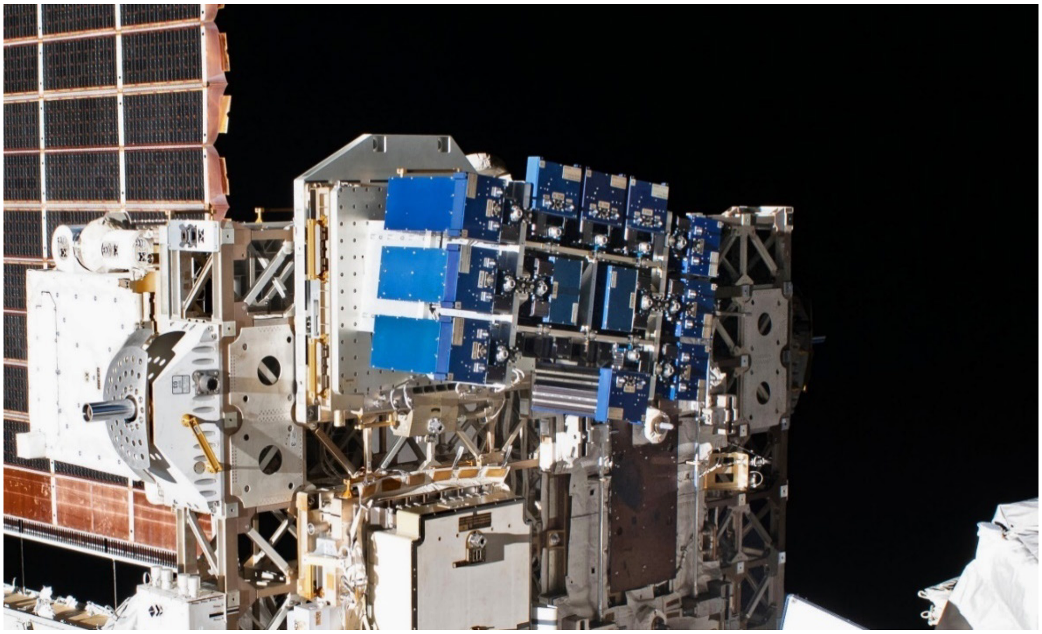


Figure 10. Close-up image of the MISSE-FF with the MISSE-10 PCE-2 and MISSE-12 PCE-3 MSCs as photographed during an EVA on January 25, 2020. The front surface of the blue ram MSCs can be seen in the closed position (iss061e142772).

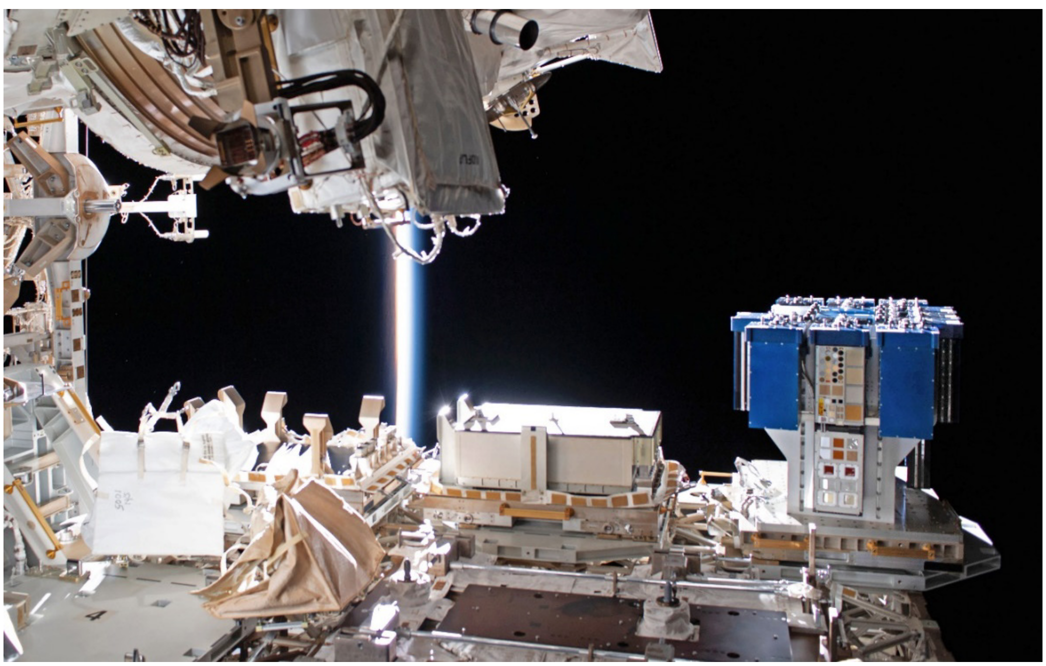


Figure 11. The wake side of the MISSE-FF with the MISSE-10 PCE-2 and MISSE-12 PCE-3 MSCs as photographed on January 25, 2020 during an EVA. The MSCs are closed, except for the central wake MSC which is open (iss061e143021).

Because the MISSE-9 MSCs were closed from December 26, 2018 until the planned retrieval in April 2019 and the LEO AO flux was low during the MISSE-9 mission due to the 11-year solar cycle period, NASA MISSE-9 principal investigators (PIs) were concerned that the ram samples would not receive the AO fluence necessary to obtain meaningful flight data. Therefore, the NASA PIs with samples on MISSE-9 R2 MSC 3 requested that the MSC be left on-orbit for additional AO exposure. Alpha Space agreed to this mission extension request. Therefore, the MISSE-9 R2 MSC 3 was re-deployed on April 26, 2019, along with the MISSE-10 PCE-2 MSCs. The MISSE-9 ram R2 MSC 3 was closed for a final time on October 2, 2019 and retrieved on November 11, 2019 during the MISSE-12 deployment ops, and brought inside ISS on November 13, 2019. The PCE-1 ram MSC 3 was exposed to the vacuum of space for 1.59 years (April 13, 2018 to November 13, 2019) and had a deployed mission duration of 1.46 years (April 19, 2018 to October 2, 2019). The MSC 3 was returned in the SpaceX-19 Dragon with splash-down on January 7, 2020 after 1.57 years on the MISSE-FF (April 18, 2018 to November 11, 2019) with a total of 9.2 months (0.77 years) of direct space exposure.

The MISSE-13 experiment MSCs were launched aboard SpaceX-20 on March 6, 2020. The MISSE-13 MSCs were robotically installed on the MISSE-FF on March 18, 2020, and were deployed on March 20, 2020 for a 6 month mission. During the MISSE-13 ops, the MISSE-12 W3 MSC 6 and Z1 MSC 18 were moved to their correct locations (switched). The MISSE-12 zenith MSC (Z1 MSC 18) was then deployed on March 20, 2020. Unfortunately, the wake carrier (W3 MSC 6) was never deployed and hence those samples were never exposed to the space environment. The 42 MISSE-12 PCE-3 wake samples will be reflown as part of the MISSE-15 mission, currently scheduled for launch on SpaceX-23 in August 2021.

The MISSE-10 MSCs were closed a significant amount of time during the MISSE-10 mission due to required safety and contamination control closures. Like for MISSE-9, NASA PIs were concerned that the MISSE-10 ram samples had not received enough atomic oxygen fluence to obtain meaningful science at the time of the planned retrieval. Therefore, NASA MISSE-10 PIs requested an on-orbit mission extension for the MISSE-10 ram MSC. Once again, the mission extension request was supported by the ISS Program Office and approved by Alpha Space. Hence, the MISSE-10 ram R1 MSC 11 remained on-orbit for additional atomic oxygen exposure until scheduled retrieval in November 2020. The MISSE-10 zenith Z2 MSC 10 and MISSE-10 nadir N3 MSC 13 were closed for the final time on March 12, 2020 and retrieved from the MISSE-FF on March 18, 2020. The MSCs were exposed to the vacuum of space for 1.25 years (December 26, 2018 to March 25, 2020) and had a deployed mission duration of 0.88 years from April 26, 2019 to March 12, 2020. The MSCs were returned in the SpaceX-20 Dragon capsule on April 7, 2020 after 1.20 years on the MISSE-FF during which time the MISSE-10 zenith Z2 MSC 10 had 8.2 months (0.69 years) of direct space exposure and the MISSE-10 nadir N3 MSC 13 had 5.7 months (0.48 years) of direct space exposure.

On April 28, 2020, Alpha Space lost communications with the MISSE-FF. Thus, the MSCs could not be remotely opened or closed, and images and active data could not be taken or downlinked. Fortunately, all the PCE 2-4 on-orbit MSCs were open at the time, with the exception of the MISSE-12 wake W3 MSC 6, which was never opened on-orbit. Thus, the PCE 2-4 on-orbit MSCs remained open receiving uninterrupted space exposure from April 28, 2020 until the final robotic closure. MISSE-12 Z1 (MSC 18) and MISSE-13 W1 (MSC 5) were robotically closed for the final time on September 2, 2020. MISSE-13 Z2 (MSC 19) was robotically closed for the final time on September 3, 2020. And, MISSE-10 R1 (MSC 11) and MISSE-12 R2 (MSC 4) were robotically closed on November 25, 2020. The MISSE-10 R1 and MISSE-12 R2 were retrieved from the MISSE-FF on November 25, 2020. MISSE-12 Z1 and MISSE-13 Z2 were retrieved on November 26, 2020. And, MISSE-12 W3 and MISSE-13 W1 were retrieved on November 27, 2020. All MSCs were brought back inside the ISS JEM Airlock on the MTT and re-pressurized on December 1, 2020. All the on-orbit PCE 2-4 MSCs were returned as part of the SpaceX-21 mission with departure from ISS on January 12, 2021, and splashdown on January 13, 2021.

The MISSE-10 PCE-2 ram MSC 11 (R1) was exposed to the vacuum of space for 1.93 years (December 26, 2018 to December 1, 2020). It was on the MISSE-FF facility for 1.90 years (January 4, 2019 to November 25, 2020) and had a deployed mission duration of 1.59 years (April 26, 2019 to November 25, 2020). During the deployed duration, the PCE-2 ram samples had a total of 1.17 years of direct space exposure.

The MISSE-12 PCE-3 ram MSC 4 (R2) was exposed to the vacuum of space for 1.07 years (November 7, 2019 to December 1, 2020). It was on the MISSE-FF facility for 1.04 years (November 11, 2019 to November 25, 2020) and had a deployed mission duration of 0.98 years (December 3, 2019 to November 25, 2020). During the deployed duration, the PCE-3 ram samples had a total of 0.89 years of direct space exposure.

MISSE-12 PCE-3 wake MSC 6 (W3) was exposed to the vacuum of space for 1.07 years (November 7, 2019 to December 1, 2020). It was on the MISSE-FF facility for 1.05 years (November 11, 2019 to November 27, 2020). As stated previously, the PCE-3 wake MSC 6 was never deployed (i.e opened). Thus, the PCE-3 wake samples had no direct space exposure.

MISSE-12 PCE-3 zenith MSC 18 (Z1) was exposed to the vacuum of space for 1.07 years (November 7, 2019 to December 1, 2020). It was on the MISSE-FF facility for 1.05 years (November 11, 2019 to November 26, 2020) and had a deployed mission duration of 0.46 years (March 20, 2020 to September 2, 2020). During the deployed duration, the PCE-3 zenith samples had a total of 0.44 years of direct space exposure.

MISSE-13 PCE-4 wake MSC 5 (W1) was exposed to the vacuum of space for 0.72 years (March 12, 2020 to December 1, 2020). It was on the MISSE-FF facility for 0.70 years (March 18, 2020 to November 27, 2020) and had a deployed mission duration of 0.46 years (March 20, 2020 to September 2, 2020). During the deployed duration, the PCE-4 wake samples had a total of 0.44 years of direct space exposure.

MISSE-13 PCE-4 zenith MSC 19 (Z2) was exposed to the vacuum of space for 0.72 years (March 12, 2020 to December 1, 2020). It was on the MISSE-FF facility for 0.70 years (March 18, 2020 to November 26, 2020) and had a deployed mission duration of 0.46 years (March 20, 2020 to September 3, 2020). During the deployed duration, the PCE-4 zenith samples had a total of 0.46 years of direct space exposure. A summary table providing the MISSE-FF exposure summary relative to Glenn’s PCE 1-4 experiments is provided in Table 1.

Table 1. Polymers and Composites Experiment 1-4 Mission Summary.

MISSE-FF Expt.	**Flight Direction**	**Number of Samples**	**MISSE Sample Carrier (MSC)**	**Launch Mission**	**Installed on MISSE-FF**	**Deployed**	**Final Time Closed**	**Retrieved from MISSE-FF**	**Return Mission**	**Time on MISSE-FF (Years)**	**Direct Space Exposure Duration (Years)**
MISSE-9 PCE-1	Ram	39	R2 (MSC 3) MS	SpaceX-14 April 2, 2018	April 18, 2018	April 19, 2018	Oct. 2, 2019	Nov. 11, 2019	SpaceX-19 Jan. 7, 2020	1.57	0.77
	Wake	52	W3 (MSC 8) MS		April 18, 2018		Dec. 26, 2018	April 26, 2019	SpaceX-17 June 3, 2019	1.02	0.54
	Zenith	47	Z3 (MSC 5) MS		April 19, 2018					1.02	0.54
MISSE-10 PCE-2	Ram	21	R1 (MSC 11) MS	NG-10 Nov. 17, 2018	Jan. 4, 2019	April 26, 2019	Nov. 25, 2020	Nov. 25, 2020	SpaceX-21 Jan. 13, 2021*	1.90	1.17
	Zenith	10	Z2 (MSC 10) MS				March 12, 2020	March 18, 2020	SpaceX-20 April 7, 2020	1.20	0.69
	Nadir	12	N3 (MSC 13) MS							1.20	0.48
MISSE-12 PCE-3	Ram	30	R2 (MSC 4) SS	NG-12 Nov. 2, 2019	Nov. 11, 2019	Dec. 3, 2019	Nov. 25, 2020	Nov. 25, 2020	SpaceX-21 Jan. 13, 2021*	1.04	0.89
	Wake	42	W3 (MSC 6) MS			N/A	N/A	Nov. 27, 2020		1.05	0
	Zenith	14	Z1 (MSC 18) MS			March 20, 2020	Sept. 2, 2020	Nov. 26, 2020		1.05	0.44
MISSE-13 PCE-4	Wake	39	W1 (MSC 5) MS	SpaceX-20 March 6, 2020	March 18, 2020	March 20, 2020	Sept. 2, 2020	Nov. 27, 2020	SpaceX-21 Jan. 13, 2021*	0.70	0.44
		26	W1 (MSC 5) SS								
	Zenith	33	Z2 (MSC 19) MS				Sept. 3, 2020	Nov. 26, 2020		0.70	0.46

MS: Mount side deck; SS: Swing side deck
*January 13, 2021 EST (January 14, 2021 UTC)

Glenn's Polymers and Composites Experiments

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

PCE-1 Overview

The Polymers and Composites Experiment-1 (PCE-1) is being flown as part of the MISSE-9 inaugural mission of MISSE-FF. The MISSE-9 PCE-1 is a passive experiment with 138 samples that were flown in ram (39 samples), wake (52 samples) and zenith (47 samples) orientations. The primary objective of the PCE-1 is to determine the LEO AO E_y of spacecraft polymers, composites, and coated samples as a function of solar irradiation and AO fluence.

Additional experiment objectives include:

- *Characterization of optical and tensile property degradation of polymers and composites in LEO*
- *Improve the understanding of AO scattering mechanisms for AO undercutting and erosion predictive models*
- *Determine the functionality and durability of LEO exposed cosmic ray shielding and shape memory composite samples*

Samples are also being flown to determine the mission AO fluence and on-orbit molecular contamination in the MISSE-9 ram, wake and zenith orientations.

PCE-1 Flight Samples

Tables 2, 3, 4, 5, and 6 provide lists of the MISSE-9 PCE-1 ram, wake 1-inch, wake tensile, zenith 1-inch and zenith tensile samples, respectively. These tables provide the MISSE-9 sample identification (ID), material, material abbreviation, thickness (for 1 layer of material), number of layers (for the ram samples), sample shape and size. The wake and zenith samples are comprised of only 1 sample layer. Approximately half of the samples are 1-inch circular or 1-inch square samples for E_y and optical property characterization, or for radiation durability assessment.

The PCE-1 includes a wide variety of samples and individual sample objectives. Polymers flown as part of Glenn's previous MISSE polymers experiments are included in the PCE-1 (and PCE 2-4) so that erosion dependence on environment exposure can be determined. For the PCE-1, these include Teflon FEP, PTFE, white Tedlar, Upilex-S, CP1, PET and PE samples flown in the ram direction. White Tedlar, Upilex-S and CP1 are examples of spacecraft polymers in which the E_y has been found to decrease with increasing LEO AO fluence.[47,58] This is due to residual ash that can build up on the surface over time as the erosion process progresses.[17] Flight data from these samples shows it is important to obtain E_y data on spacecraft polymers from multiple missions. Thus, one objective of the PCE 1-4 experiments is to obtain E_y vs. AO fluence and/or ESH data for additional spacecraft polymers. Teflon FEP and other fluoropolymers were flown in the zenith direction to see the effect of high solar exposure and low AO on E_y.

Table 2. MISSE-9 PCE-1 Ram Samples.

MISSE-9 ID	Material	Abbreviation	Thickness of One Layer (inch)	# Layers	Circular or Square	Size (inch)
M9R-C1	Polyimide (PMDA) (Kapton H)	Kapton H	0.005	2	C	1
M9R-C2	Polyimide (PMDA) (Kapton H)	Kapton H	0.005	2	C	0.8
M9R-C3	Polyimide (PMDA) (Kapton H)	Kapton H	0.005	2	C	0.65
M9R-C4	Polyimide (PMDA) (Kapton H)	Kapton H	0.005	2	C	0.5
M9R-C5	Polyimide (PMDA) (Kapton HN)	Kapton HN	0.005	2	C	1
M9R-C6	Alumina slide	Al_2O_3	0.063	1	C	1
M9R-C7	Polyoxymethylene (Delrin acetal)	POM	0.010	2	C	1
M9R-C8	Polyoxymethylene (Delrin acetal)	POM	0.010	2	C	0.8
M9R-C9	Polyoxymethylene (Delrin acetal)	POM	0.010	2	C	0.65
M9R-C10	Polyoxymethylene (Delrin acetal)	POM	0.010	2	C	0.5
M9R-C11	Epoxy (Loctite Heavy Duty)	Epoxy	0.118	1	C	1
M9R-C12	2.83% ZnO powder filled epoxy (Loctite)	ZnO-Epoxy	0.125	1	C	1
M9R-C13	5.94% ZnO powder filled epoxy (Loctite)	ZnO-Epoxy	0.125	1	C	1
M9R-C14	8.91% ZnO powder filled epoxy (Loctite)	ZnO-Epoxy	0.101	1	C	1
M9R-C15	Fluorinated ethylene propylene (Teflon FEP)	FEP	0.005	1	C	1
M9R-C16	Aluminized-Teflon (FEP/Al)*	Al-FEP	0.005	1	C	1
M9R-C17	Silver-Teflon (FEP/Ag/Inconel)*	Ag-FEP	0.005	1	C	1
M9R-C18	Carbon painted (India Ink) Teflon (FEP/C/FEP)*	FEP/C/FEP	0.014	1	C	1
M9R-C19	Polyimide (PMDA) (Kapton H)	Kapton H	0.005	2	C	1
M9R-C20	Polytetrafluoroethylene (Chemfilm DF 100)	PTFE	0.005	1	C	1
M9R-C21	Crystalline polyvinyl fluoride w/white pigment (white Tedlar)	PVF-W	0.002	1	C	1
M9R-C22	Highly Oriented Pyrolytic Graphite	HOPG	0.041	1	C	1
M9R-C23	Polyimide (BPDA) (Upilex-S)	Upilex-S	0.001	2	C	1
M9R-C24	Polyimide (CP1)	CP1	0.003	2	C	1
M9R-C25	Polyethylene terephthalate (Mylar)	PET	0.002	4	C	1
M9R-C26	Polyethylene	PE	0.002	5	C	1
M9R-C27	Magnesium Fluoride	MgF_2	0.108	1	C	1
M9R-C28	Cyanate ester graphite fiber composite	RS3-M55J 6K	0.062	1	C	1
M9R-C29	Polyimide aerogel	Polyimide Aerogel	0.064	1	C	1
M9R-C30	Polyimide aerogel	Polyimide Aerogel	0.125	1	C	1
M9R-C31	Carbon nanotube (CNT) paper	Buckypaper	0.002	3	C	1
M9R-C32	Graphene nanoplatelets (GnP) paper	GnP paper	0.010	1	C	1

Table 2. MISSE-9 PCE-1 Ram Samples, Cont.

MISSE-9 ID	Material	Abbreviation	Thickness of One Layer (inch)	# Layers	Circular or Square	Size (inch)
M9R-S1	Polyimide (PMDA) (Kapton H)	Kapton H	0.005	2	S	1
M9R-S2	Z307 (black paint)/aluminum	Z307/Al	0.035	1	S	1
M9R-S3	Ball Infrared Black (BIRB) paint/aluminum	BIRB/Al	0.100	1	S	1
M9R-S4	Carbon nanotube (CNT) coated SiC w/ 0.5 mil Kapton cover	Kapton H/CNT/SiC	0.130	1	S	1
M9R-S5	Indium tin oxide coated Kapton HN/aluminum	ITO/Kapton HN/Al	0.002	1	S	1
M9R-S6	Indium tin oxide coated silver-Teflon	ITO/FEP/Ag/Inconel	0.005	1	S	1
M9R-S7	Atomic Oxygen Scattering Chamber with salt-sprayed Kapton H lid (30° angle)	AO S.C. (30°)	0.275	1	S	1

*Teflon FEP is space facing

Table 3. MISSE-9 PCE-1 Wake 1-Inch Samples.

MISSE-9 ID	Material	Abbreviation	Thickness (inch)	Circular or Square
M9W-C1	Polyimide (PMDA) (Kapton H)	Kapton H	0.005	C
M9W-C2	Polyimide (PMDA) (Kapton HN)	Kapton HN	0.005	C
M9W-C3	Alumina slide	Al_2O_3	0.063	C
M9W-C4	Fluorinated ethylene propylene (Teflon FEP)	FEP	0.005	C
M9W-C5	Aluminized-Teflon (FEP/Al)*	Al-FEP	0.005	C
M9W-C6	Silver-Teflon (FEP/Ag/Inconel)*	Ag-FEP	0.005	C
M9W-C7	Carbon painted (India Ink) Teflon (FEP/C/FEP)*	FEP/C/FEP	0.015	C
M9W-C8	Polyvinyl chloride	PVC	0.005	C
M9W-C9	Cosmic ray shielding (CRS) sample	CRS	0.039	C
M9W-C10	Shape memory composite (SMC) sample	SMC	0.236	C
M9W-S1	Indium tin oxide coated Kapton HN/aluminum	ITO/Kapton HN/Al	0.002	S
M9W-S2	Indium tin oxide coated silver-Teflon	ITO/FEP/Ag/Inconel	0.005	S
M9W-S3	Indium tin oxide coated silver-Teflon	ITO/FEP/Ag/Inconel	0.005	S
M9W-S4	Carbon nanotube (CNT) coated SiC	CNT/SiC	0.13	S

*Teflon FEP is space facing

Table 4. MISSE-9 PCE-1 Wake Tensile Samples.

MISSE-9 ID	Material	Abbreviation	Thickness (inch)
M9W-T1	Aluminized-Teflon (FEP/Al)* - Cut Parallel to Roll Lines	Al-FEP	0.002
M9W-T2	Aluminized-Teflon (FEP/Al)* - Cut Parallel to Roll Lines	Al-FEP	0.002
M9W-T3	Aluminized-Teflon (FEP/Al)* - Cut Parallel to Roll Lines	Al-FEP	0.002
M9W-T4	Aluminized-Teflon (FEP/Al)* - Cut Parallel to Roll Lines	Al-FEP	0.002
M9W-T5	Aluminized-Teflon (FEP/Al)* - Cut Parallel to Roll Lines	Al-FEP	0.002
M9W-T6	Aluminized-Teflon (FEP/Al)* - Cut Normal to Roll Lines	Al-FEP	0.002
M9W-T7	Aluminized-Teflon (FEP/Al)* - Cut Normal to Roll Lines	Al-FEP	0.002
M9W-T8	Aluminized-Teflon (FEP/Al)* - Cut Normal to Roll Lines	Al-FEP	0.002
M9W-T9	Aluminized-Teflon (FEP/Al)* - Cut Normal to Roll Lines	Al-FEP	0.002
M9W-T10	Aluminized-Teflon (FEP/Al)* - Cut Normal to Roll Lines	Al-FEP	0.002
M9W-T11	Aluminized-Teflon (FEP/Al)* - Cut Parallel to Roll Lines	Al-FEP	0.005
M9W-T12	Aluminized-Teflon (FEP/Al)* - Cut Parallel to Roll Lines	Al-FEP	0.005
M9W-T13	Aluminized-Teflon (FEP/Al)* - Cut Parallel to Roll Lines	Al-FEP	0.005
M9W-T14	Aluminized-Teflon (FEP/Al)* - Cut Parallel to Roll Lines	Al-FEP	0.005
M9W-T15	Aluminized-Teflon (FEP/Al)* - Cut Parallel to Roll Lines	Al-FEP	0.005
M9W-T16	Aluminized-Teflon (FEP/Al)* - Cut Normal to Roll Lines	Al-FEP	0.005
M9W-T17	Aluminized-Teflon (FEP/Al)* - Cut Normal to Roll Lines	Al-FEP	0.005
M9W-T18	Aluminized-Teflon (FEP/Al)* - Cut Normal to Roll Lines	Al-FEP	0.005
M9W-T19	Aluminized-Teflon (FEP/Al)* - Cut Normal to Roll Lines	Al-FEP	0.005
M9W-T20	Aluminized-Teflon (FEP/Al)* - Cut Normal to Roll Lines	Al-FEP	0.005
M9W-T21	Silver-Teflon (FEP/Ag/Inconel)* - Cut Parallel to Roll Lines	Ag-FEP	0.005
M9W-T22	Silver-Teflon (FEP/Ag/Inconel)* - Cut Parallel to Roll Lines	Ag-FEP	0.005
M9W-T23	Silver-Teflon (FEP/Ag/Inconel)* - Cut Parallel to Roll Lines	Ag-FEP	0.005
M9W-T24	Silver-Teflon (FEP/Ag/Inconel)* - Cut Parallel to Roll Lines	Ag-FEP	0.005
M9W-T25	Carbon painted (India Ink) Teflon (FEP/C)* - Cut Parallel to Roll Lines	C-FEP	0.002
M9W-T26	Carbon painted (India Ink) Teflon (FEP/C)* - Cut Parallel to Roll Lines	C-FEP	0.002
M9W-T27	Carbon painted (India Ink) Teflon (FEP/C)* - Cut Parallel to Roll Lines	C-FEP	0.002
M9W-T28	Carbon painted (India Ink) Teflon (FEP/C)* - Cut Parallel to Roll Lines	C-FEP	0.002
M9W-T29	Carbon painted (India Ink) Teflon (FEP/C)* - Cut Parallel to Roll Lines	C-FEP	0.002
M9W-T30	Carbon painted (India Ink) Teflon (FEP/C)* - Cut Parallel to Roll Lines	C-FEP	0.005
M9W-T31	Carbon painted (India Ink) Teflon (FEP/C)* - Cut Parallel to Roll Lines	C-FEP	0.005
M9W-T32	Carbon painted (India Ink) Teflon (FEP/C)* - Cut Parallel to Roll Lines	C-FEP	0.005
M9W-T33	Carbon painted (India Ink) Teflon (FEP/C)* - Cut Parallel to Roll Lines	C-FEP	0.005
M9W-T34	Carbon painted (India Ink) Teflon (FEP/C)* - Cut Parallel to Roll Lines	C-FEP	0.005
M9W-T35	Aluminized-Teflon (Al/FEP) - Cut Parallel to Roll Lines (Al space facing)	Al/FEP	0.002
M9W-T36	Aluminized-Teflon (Al/FEP) - Cut Parallel to Roll Lines (Al space facing)	Al/FEP	0.002
M9W-T37	Aluminized-Teflon (Al/FEP) - Cut Parallel to Roll Lines (Al space facing)	Al/FEP	0.002
M9W-T38	Aluminized-Teflon (Al/FEP) - Cut Parallel to Roll Lines (Al space facing)	Al/FEP	0.002

*FEP layer is space facing for all samples except Al/FEP (T35-T38)

Table 5. MISSE-9 PCE-1 Zenith 1-Inch Samples.

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

*Teflon FEP is space facing

Table 6. MISSE-9 PCE-1 Zenith Tensile Samples.

MISSE-9 ID	Material	Abbreviation	Thickness (inch)
M9Z-T1	Aluminized-Teflon (FEP/Al)* - Cut Parallel to Roll Lines	Al-FEP	0.002
M9Z-T2	Aluminized-Teflon (FEP/Al)* - Cut Parallel to Roll Lines	Al-FEP	0.002
M9Z-T3	Aluminized-Teflon (FEP/Al)* - Cut Parallel to Roll Lines	Al-FEP	0.002
M9Z-T4	Aluminized-Teflon (FEP/Al)* - Cut Parallel to Roll Lines	Al-FEP	0.002
M9Z-T5	Aluminized-Teflon (FEP/Al)* - Cut Normal to Roll Lines	Al-FEP	0.002
M9Z-T6	Aluminized-Teflon (FEP/Al)* - Cut Normal to Roll Lines	Al-FEP	0.002
M9Z-T7	Aluminized-Teflon (FEP/Al)* - Cut Normal to Roll Lines	Al-FEP	0.002
M9Z-T8	Aluminized-Teflon (FEP/Al)* - Cut Normal to Roll Lines	Al-FEP	0.002
M9Z-T9	Aluminized-Teflon (FEP/Al)* - Cut Parallel to Roll Lines	Al-FEP	0.005
M9Z-T10	Aluminized-Teflon (FEP/Al)* - Cut Parallel to Roll Lines	Al-FEP	0.005
M9Z-T11	Aluminized-Teflon (FEP/Al)* - Cut Parallel to Roll Lines	Al-FEP	0.005
M9Z-T12	Aluminized-Teflon (FEP/Al)* - Cut Parallel to Roll Lines	Al-FEP	0.005
M9Z-T13	Aluminized-Teflon (FEP/Al)* - Cut Normal to Roll Lines	Al-FEP	0.005
M9Z-T14	Aluminized-Teflon (FEP/Al)* - Cut Normal to Roll Lines	Al-FEP	0.005
M9Z-T15	Aluminized-Teflon (FEP/Al)* - Cut Normal to Roll Lines	Al-FEP	0.005
M9Z-T16	Aluminized-Teflon (FEP/Al)* - Cut Normal to Roll Lines	Al-FEP	0.005
M9Z-T17	Carbon painted (India Ink) Teflon (FEP/C)* - Cut Parallel to Roll Lines	C-FEP	0.002
M9Z-T18	Carbon painted (India Ink) Teflon (FEP/C)* - Cut Parallel to Roll Lines	C-FEP	0.002
M9Z-T19	Carbon painted (India Ink) Teflon (FEP/C)* - Cut Parallel to Roll Lines	C-FEP	0.002
M9Z-T20	Carbon painted (India Ink) Teflon (FEP/C)* - Cut Parallel to Roll Lines	C-FEP	0.002
M9Z-T21	Aluminum/Teflon FEP (Al/FEP) - Cut Parallel to Roll Lines	Al/FEP	0.002
M9Z-T22	Aluminum/Teflon FEP (Al/FEP) - Cut Parallel to Roll Lines	Al/FEP	0.002
M9Z-T23	Aluminum/Teflon FEP (Al/FEP) - Cut Parallel to Roll Lines	Al/FEP	0.002
M9Z-T24	Aluminum/Teflon FEP (Al/FEP) - Cut Parallel to Roll Lines	Al/FEP	0.002

*FEP layer is space facing for all samples except Al/FEP (T21-T24)

Because inorganic filler can impact the E_y, four samples have been included in the PCE-1 to evaluate the impact of specific quantities of inorganic filler on the E_y of composite samples. The samples are epoxy with varying levels of ZnO filler (0%, 2.83%, 5.94%, and 8.91%). This is intended to provide data for quantitative modeling of the effect of inorganic filler materials on E_y.

Atomic oxygen has a certain probability of reaction with an impacted surface, which is material dependent. For example, the probability of reaction with an anodized surface is negligible, but the probability of the AO recombining is 33%.[61] Thus, AO can scatter off an impacted spacecraft surface in LEO. This can result is AO erosion problems, such as AO undercutting or AO scattering within a telescope body. Typically, MISSE sample holders have 45° chamfered edges. Because AO can scatter off the impacted surface (typically anodized Al), this can cause focused AO near the exposed edge of the flight sample. Examples of focused AO erosion of MISSE 2 flight samples is provided by Banks et. al. in Reference 62. The PCE-1 includes eight samples to characterize MISSE flight hardware AO focusing effects on the AO E_y value. The PCE-1 samples include four different size samples (0.5-inch, 0.65-inch, 0.8-inch, and 1-inch diameter samples) of both Kapton® H and polyoxymethylene (POM). By including multiple sized samples, the effect of the chamfered sample holder focusing of the ram AO is reduced with increasing sample diameter. This allows one to more accurately extrapolate the LEO E_y which would occur on large area spacecraft surfaces from small test samples.

Another unique PCE-1 sample is the Atomic Oxygen Scattering Chamber. The 1-inch square PCE-1 AO Scattering Chamber has a 30° angled Al base and a salt-sprayed Kapton H inner lid (i.e., scatter surface). The objective of the PCE-1 Scattering Chamber is to measure the distribution of AO scattered off a 30° angled surface. The data will be compared to the scattered distribution from a similar MISSE AO Scattering Chamber with a normal incident (i.e., 90°) base and is relevant to AO undercutting and scattering modeling.[35] If there is sufficient fluence to enable measurable erosion around the salt particles, then the effective E_y as a function of scattering angle off the inclined aluminum base can be measured and compared to the results from a prior non-inclined surface. Figure 12 provides a pre-flight photograph of the PCE-1 AO Scattering Chamber (M9R-S7) components along with a schematic drawing of assembled chamber.

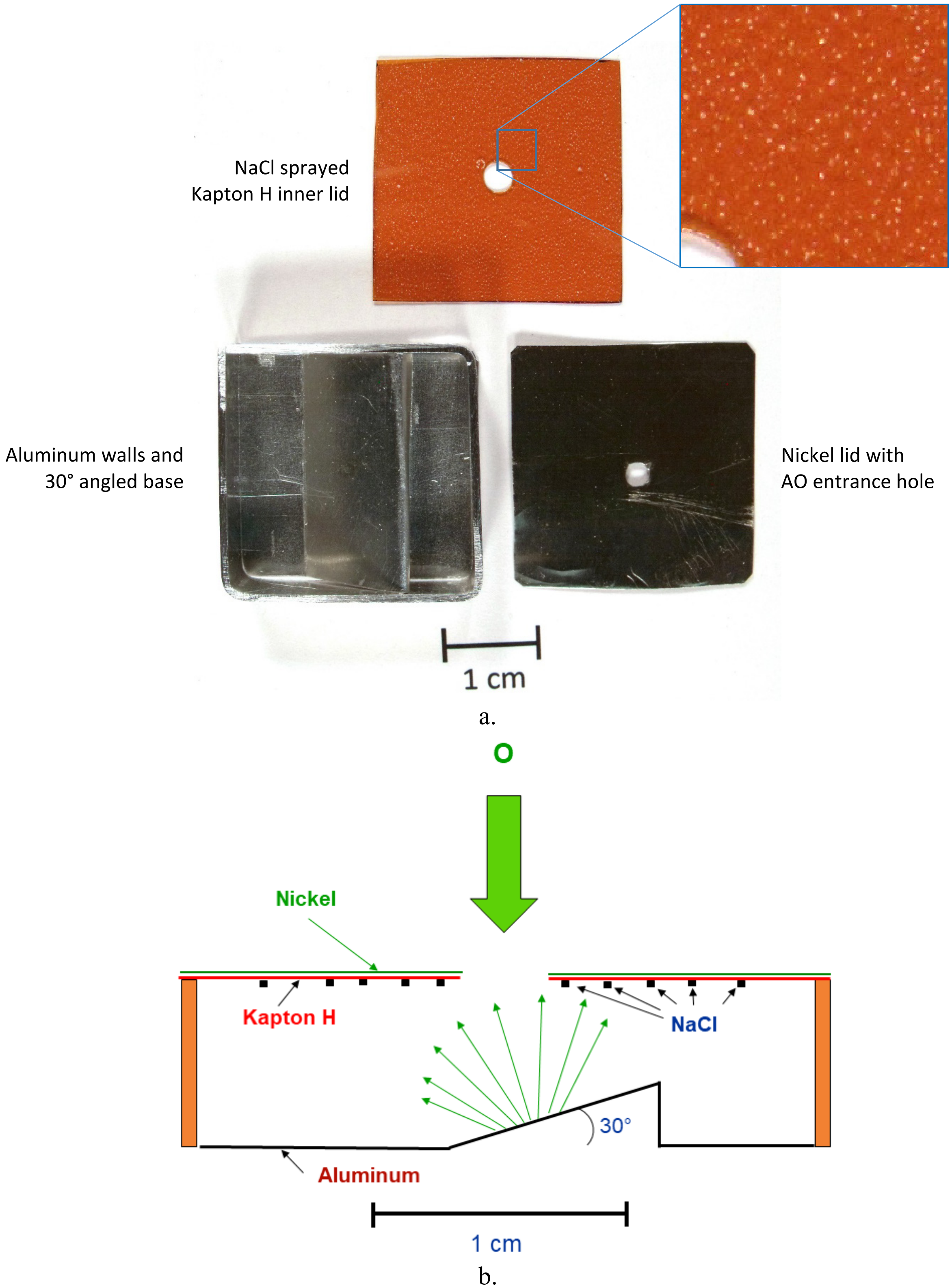


Figure 12. PCE-1 AO Scattering Chamber (M9R-S7): a). Pre-fight photograph of the individual components including a close-up image of the salt-sprayed Kapton inner lid, and b). Schematic diagram of the assembled AO Scattering Chamber.

The PCE-1 also includes the following:

- Samples to validate the effect of passive heating on the E_y of Teflon FEP.
- Samples to assess the optical and electrical performance and durability of indium tin oxide (ITO) conductive coatings.
- Specialty coatings, such as Z307 black paint and Ball Infrared Black (BIRB) paint are included for performance and durability assessment with both ram (AO) and zenith (solar radiation) exposures.
- A cosmic ray shielding (CRS) sample for radiation durability assessment of new shielding material for spacesuits and spacecraft. The CRS sample is comprised of two functionalized low density polyethylene (LDPE) sheets: one with BN on half the sheet, and one with Sm-Co powder on half the sheet. These sheets were combined to make a four quartered sample. Figure 13 is a pre-flight photograph of the CRS sample which was flown in the wake direction.
- Two shape memory composite (SMC) samples (also called shape memory polymer composite (SMPC) samples) were flown to assess the functionality of space radiation exposed SMCs for space structures. These are two-laminate SMPC materials with co-cured SMP interlayer from powder. These samples were launched with an "open window" configuration (non-equilibrium shape). The windows will close on-orbit if a characteristic temperature is reached. The closure permits the evaluation of on-orbit sample shape recovery due to solar heating, or heat transfer from the platform. One SMC sample was flown in the wake direction (M9W-C10) and one was flown in the zenith direction (M9Z-C17). Figure 14 provides pre-flight photographs of the zenith SMC sample. Figure 14a shows the sample prior to integration in the flight deck. Figure 14b shows the unique open window shape, which allows on-orbit shape changes to be seen in the on-orbit images.

In addition, there are a variety of Teflon fluorinated ethylene propylene (FEP) tensile samples that were flown in both the wake (38 samples) and zenith (24 samples) directions for radiation embrittlement studies. The tensile samples were fabricated using an ASTM D638-08 punch. The tensile samples are either aluminized-Teflon FEP (FEP/Al), silver-Teflon FEP (FEP/Ag/Inconel) or carbon back-surface painted Teflon FEP (FEP/C). The FEP/C samples heat passively to a higher temperature on-orbit than the FEP/Al or the FEP/Ag/Inconel.

Figure 13. Pre-flight photograph of the wake CRS sample (M9W-C9).

a.

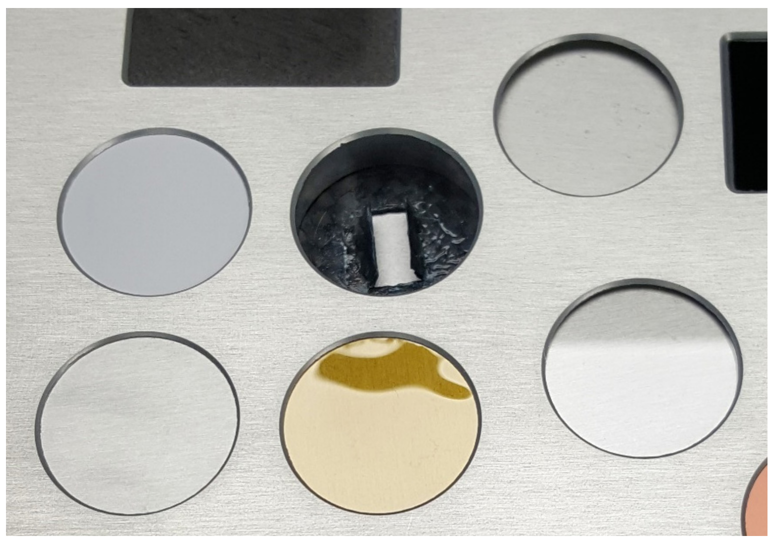
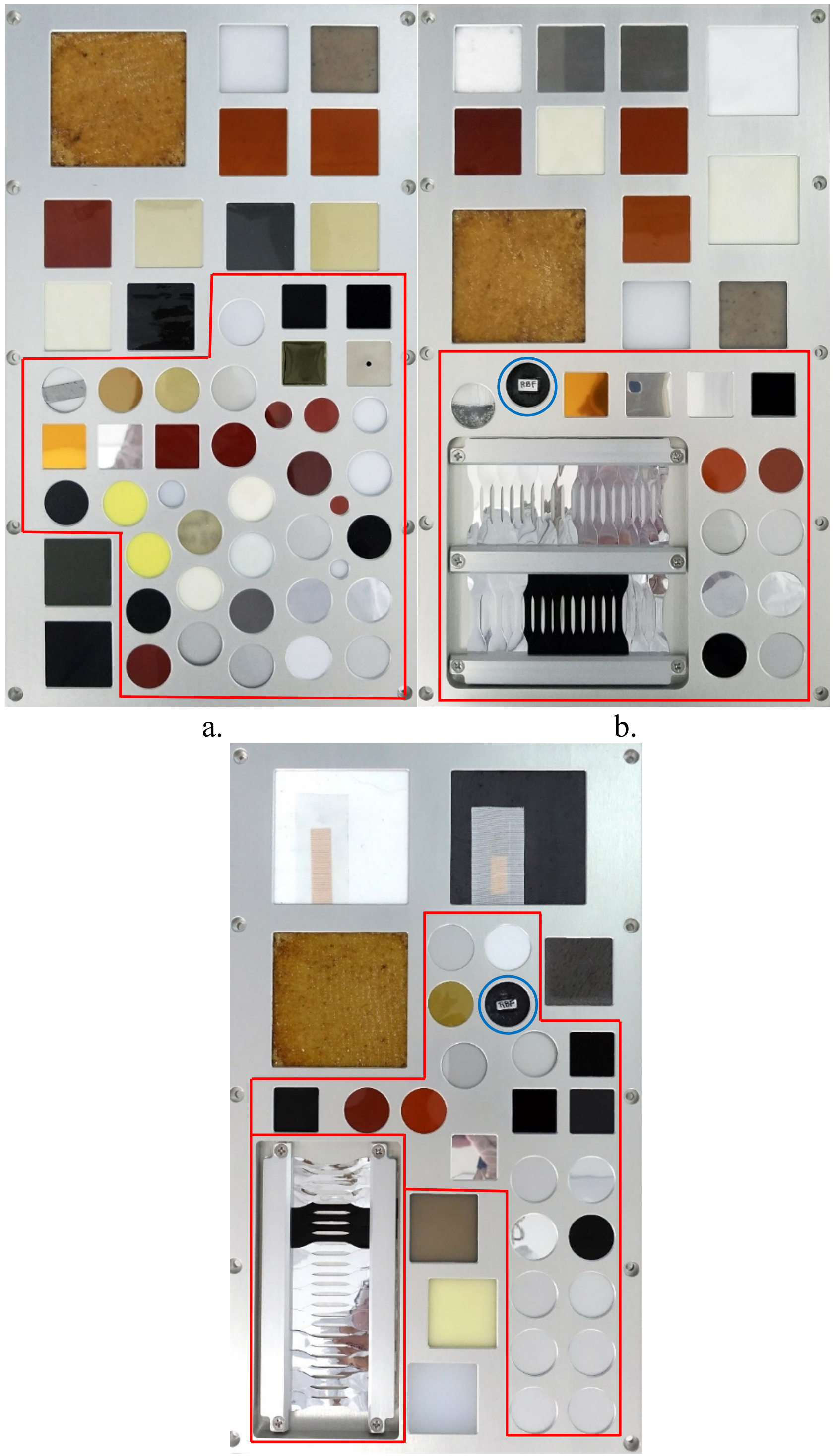

b.

Figure 14. Pre-flight photographs of the zenith SMC sample (M9Z-C17): a). Prior to integration, and b). Integrated in the Z3 MSC 5 MS deck (Photo credit: Alpha Space).

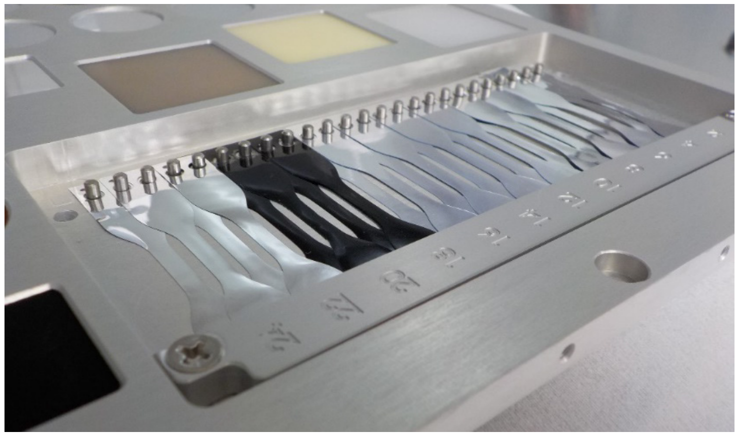
Figure 15 shows a pre-flight photograph of the MISSE-9 PCE-1 samples loaded into the ram, wake and zenith flight mount-side (MS) decks. Each deck includes samples (50% of the space) from two experiments, the PCE-1 and NASA Langley Research Center's Polymeric Materials Experiment. Figure 16 shows pre-flight photographs of the MISSE-9 decks with the PCE-1 samples outlined in red. It should be noted that aluminum blocks with "RBF" on them, for remove before flight, are in the shape memory composite samples (SMC) in Figures 16b and 16c pre-flight photos. These blocks were removed before flight. The Tensile holder "bars" that hold the tensile samples in place were replaced with bars that include sample numbers after these photographs were taken, and prior to flight, so that the tensile sample ID could be seen in the on-orbit images. Figure 17 shows photographs of the zenith (Figures 17a and 17b) and wake (Figure 17c) tensile samples mounted on the decks with the tensile ID bars. Figure 17a shows how the tensile samples are mounted on pegs.

Figure 15. Pre-flight photograph of the MISSE-9 PCE-1 samples loaded into the MSC MS flight decks, from left to right: R2 MSC 3 (ram), W3 MSC 8 (wake), and Z3 MSC 5 (zenith).

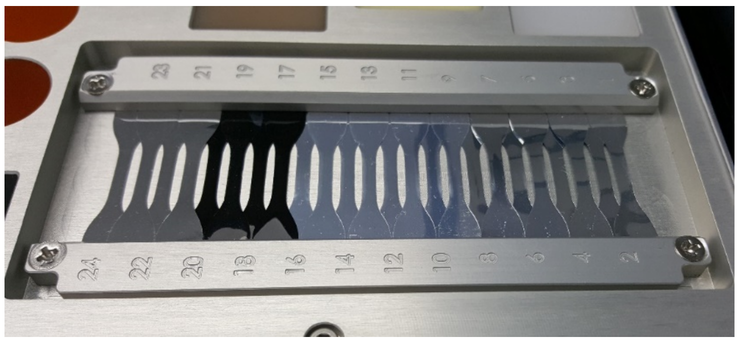


a. b. c.

Figure 16. Pre-flight photographs of the MISSE-9 MSC decks with the PCE-1 samples outlined in red: a). Ram samples in the R2 MSC 3 MS deck, b). Wake samples in the W3MSC 8 MS deck (the sample with the "RBF" block is circled in blue), and c). Zenith samples in the Z3 MSC 5 MS deck (the sample with the "RBF" block is circled in blue).



a.



b.

c.

Figure 17. Pre-flight photographs of the MISSE-9 tensile samples mounted with the ID bars: a). Zenith samples showing how samples are mounted on pegs, b). Zenith samples with ID#s 1-24, and c). Wake samples with ID#s 1-38.(Photo credit: Alpha Space)

Fabrication and Pre-flight Characterization

When fabricating the PCE-1 flight Samples (and also the PCE 2-4 flight samples), typically an identical back-up sample was fabricated and pre-flight characterized along with the flight sample. The flight sample ID includes the designation "F" (i.e., M9R-C1 (F)) and the back-up sample ID includes the designation of "B" (i.e., M9R-C1 (B)). The back-up samples will be used as a control sample for post-flight comparisons with the flight samples, such as for changes in optical and thermal properties. For the PCE-1, only one back-up sample was flown. That was the ram Z307 coated aluminum sample (M9R-S2 (B)). The flight sample was found to be too big for the flight sample holder upon integration.

One of the critical issues with using mass loss for obtaining accurate E_y data is that dehydrated mass measurements are needed. Many polymer materials, such as Kapton, are very hygroscopic (absorbing up to 2% of their weight in moisture) and can fluctuate in mass with humidity and temperature. Therefore, for accurate mass loss measurements to be obtained, it is necessary that the samples be fully dehydrated (i.e., in a vacuum desiccator) immediately prior to measuring the mass both pre-flight and post-flight. Thus, dehydrated mass of the PCE 1 (and PCE 2-4) flight samples was obtained pre-flight for all samples to be characterized for LEO E_y.

To obtain the pre-flight mass, the PCE 1-4 flight and back-up samples were dehydrated in a vacuum desiccator maintained at a pressure of 8.0 to 13.3 Pa (60 to 100 mtorr) with a mechanical roughing pump. Typically, five flight samples and their corresponding control samples were placed in a vacuum desiccator, in a particular order, and left under vacuum for a minimum of 72 hours. Once a sample was removed for weighing, the vacuum desiccator was immediately put back under vacuum to keep the other samples under vacuum. Previous tests showed that the mass of a dehydrated sample was not adversely affected if the desiccator was opened and quickly closed again and pumped back down to approximately 20 Pa (150 mtorr) prior to that sample being weighed. This process allows multiple samples to be dehydrated together. The time at which the sample was first exposed to air was recorded along with the times at which it was weighed. A total of three mass readings were obtained and averaged. The total time it took to obtain the three readings, starting from the time air was let into the desiccator, was typically 5 minutes. The samples were weighed pre-flight using a Sartorius ME 5 Microbalance (0.000001 g sensitivity). Heavier samples were measured using a Sartorius Balance R160P (0.00001 g sensitivity). Records of the following were kept: the sequence of sample weighing, the number of samples in each set, the time under vacuum prior to weighing, the temperature and humidity in the room, the time air was let into the desiccator, and the time a sample was taken out of the desiccator, the time of each weighing and the mass. The same procedure and sequence will be repeated with the samples post-flight.

In addition, pre-flight photographs of the individual flight samples were obtained along with photos of the samples integrated into the MISSE-FF decks.

PCE-1 Mission Overview

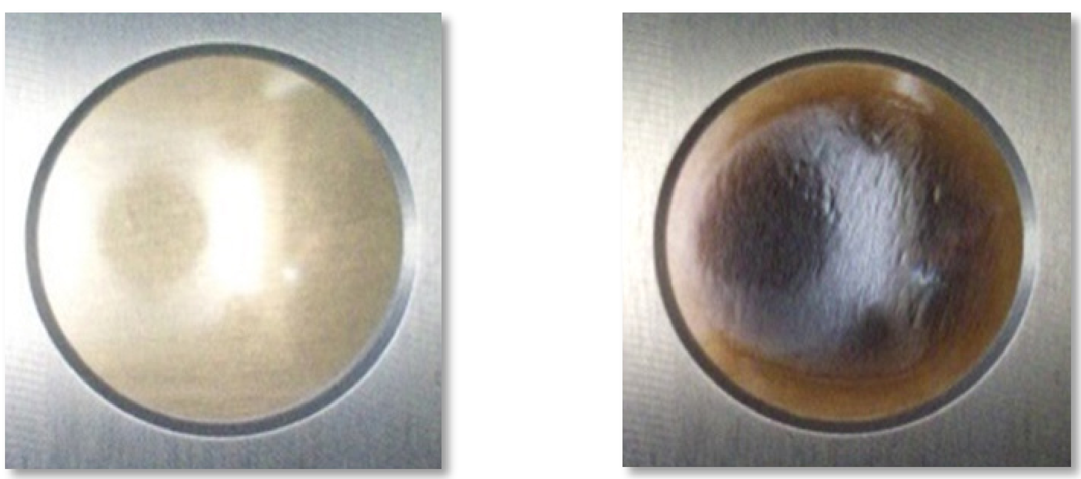
The MISSE-9 PCE-1 experiment was launched aboard SpaceX-14 along with the MISSE-FF and the PCE-1 MSCs (ram R2 MSC 3, zenith Z3 MSC 5 and wake W3 MSC 8) were deployed on April 19, 2018. The MISSE-9 PCE-1 MSCs (except ram R2 MSC 3) were closed

December 26, 2018 for the final time on-orbit and retrieved from the MISSE-FF on April 26, 2019. The MSCs were returned to Earth in the SpaceX-17 Dragon on June 3, 2019 after 1.02 years on the MISSE-FF with an 8.3 month deployed mission and 6.5 months (0.54 years) of direct space exposure. The MSCs were exposed to the vacuum of space for 1.07 years (April 13, 2018 to May 9, 2019). The PCE-1 zenith and wake samples were de-integrated from the MSC decks in July 2019 and are currently undergoing post-flight analyses.

Because the MISSE-9 ram samples had only received 6.5 months of ram AO exposure at the time of the original scheduled retrieval, the PCE-1 ram samples remained on-orbit for additional AO exposure when the PCE-1 wake and zenith MSCs were retrieved. The MISSE-9 ram R2 MSC 3 was closed for a final time on-orbit on October 2, 2019. The MSC was exposed to the vacuum of space for 1.59 years (April 13, 2018 to November 13, 2019) and had a deployed mission duration of 1.46 years (April 19, 2018 to October 2, 2019). It was retrieved on November 11, 2019 and returned in the SpaceX-19 Dragon on January 7, 2020 after 1.57 years on the MISSE-FF with 9.2 months (0.77 years) of direct space exposure. The MISSE-9 PCE-1 ram samples were de-integrated from the MSC deck in February 2020 and are currently undergoing post-flight analyses.

<u>*PCE-1 On-Orbit Images*</u>

The Alpha Space provided monthly on-orbit photographs show a number of sample changes over time. Some samples became visually darkened, such as the wake polyvinyl chloride (PVC) sample (M9W-C8) sown in Figure 18. Figure 18a is an on-orbit image taken on April 23, 2018 shortly after deployment. Figure 18b shows an on-orbit image of the same sample taken on December 26, 2018 after 8 months on-orbit. During the 8 month exposure, the MSCs were closed 21% of the time for contamination avoidance. Therefore, the samples were exposed to space for 6.5 months. As can be seen, the sample has become extremely darkened during the 6.5 months of LEO wake exposure. It is expected to be very brittle also.

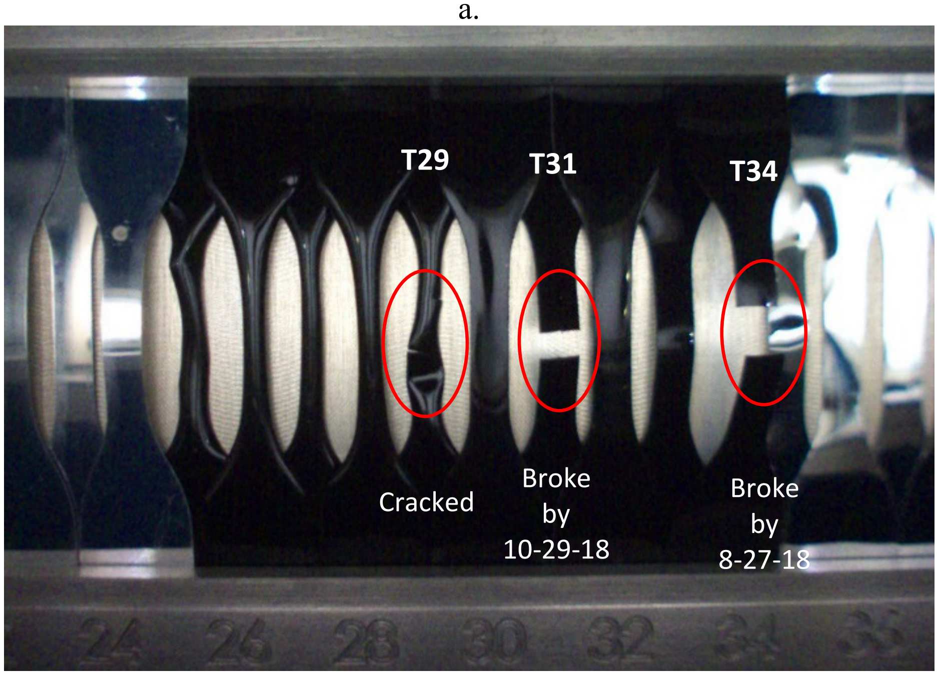


a. b.

Figure 18. On-orbit images of the PCE wake PVC sample (M9W-C8): (a). Image taken on April 23, 2018 shortly after deployment, and (b). Image taken on December 26, 2018 after 6.4 months of space exposure. (Photo credit: Alpha Space)

Another sample change that has been observed in the on-orbit images is cracking and breaking of some of the tensile samples, as shown in Figure 19. Figure 19 shows on-orbit images of the wake FEP/C tensile samples taken on July 25, 2018 with the samples not broken (Figure 19a) and on December 26, 2018 with broken and cracked samples (Figure 19b). As can be seen in Figure 19b, there is one cracked (T29) and two broken (T31 and T34) FEP/C samples. The T34 sample,

a.



b.

Figure 19. On-orbit images of the PCE-1 wake FEP/C tensile samples: a). July 25, 2018 image with no broken samples, and b). December 26, 2018 image showing two broken (T31 and T34) and one cracked (T29) tensile samples. (Photo credit: Alpha Space)

which is 5 mil thick FEP/C, was observed to have broken by August 27, 2018 after only 3.2 months of space exposure (MSC open duration). Sample T31, which is also 5 mil thick FEP/C, was observed to have broken by October 28, 2018 after 5 months of space exposure. The T29 sample, which is 2 mil thick FEP/C appears to be cracked in two places, as observed in the December 26, 2018 image. None of the wake FEP/Al samples (2 mil and 5 mil thick) or the wake FEP/Ag/Inconel samples (5 mil thick) appear to be cracked, or broken, indicating that the higher on-orbit temperature of the C/FEP has a synergistic effect that significantly exacerbates the radiation-induced embrittlement of FEP in space. These preliminary results are consistent with similar findings reported by de Groh on Teflon FEP tensile samples (2 mil thick FEP/Al and FEP/C) flown on MISSE 7.[51]

PCE-1 Sample Collaboration

The MISSE-9 PCE-1 is a collaborative effort with a number of researchers from various organizations. The PCE-1 sample collaborators are listed in Table 7 along with the collaborative flight sample materials and number of flight samples.

Table 7. MISSE-9 PCE-1 Sample Collaborators.

Collaborator(s)	Organization	Material	Abbreviation	Number of Samples
Loredana Santo Fabrizio Quadrini	University of Rome Tor Vergata	Cosmic ray shielding sample (CRS)	CRS	1
		Shape memory composite sample (SMC)	SMC	2
Genevieve Devaud	Ball Aerospace	Z307 (black paint)/aluminum	Z307/Al	2
		Ball Infrared Black (BIRB) paint/aluminum	BIRB/Al	2
		Epocnt (carbon nanotube in epoxy matrix)	Epocnt	1
John Fleming	Ball Aerospace	Carbon nanotube (CNT) coated SiC (Kapton cover on ram sample)	CNT/SiC	3
Lawrence Drzal	Michigan State University	Graphene nanoplatelets (GnP) paper	GnP paper	1
Nathan Baier	Multek-Sheldahl	Indium tin oxide (ITO) coated Kapton HN/aluminum	ITO/Kapton HN/Al	1
		ITO coated silver Teflon	ITO/FEP/Ag/Inconel	4
Jessica Cashman Mary Ann Meador*	NASA Glenn (LMN)	Polyimide aerogel (DMBZ-BPDA)	Polyimide Aerogel	2
Henry de Groh	NASA Glenn (LMA)	Carbon nanotube (CNT) paper	Buckypaper (CNT paper)	1

*Retired

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

PCE-2 Overview

The MISSE-10 PCE-2 is a passive experiment with 43 samples being flown in ram (21 samples), zenith (10 samples), and nadir (12 samples) directions. The objectives of the PCE-2 are similar to the PCE-1. The primary objective is to determine the LEO AO E_y of polymers, composites, and coated samples as a function of solar irradiation and AO fluence.

Additional experiment objectives include:

- *Characterization of optical property degradation of spacecraft polymers and composites in LEO*
- *Improve the understanding of AO scattering mechanisms for AO undercutting and erosion predictive models*
- *Determine the functionality and durability of LEO exposed cosmic ray shielding and shape memory composite samples*

Also like the PCE-1, samples are being flown to determine the AO fluence for the mission, and characterize any molecular contamination, in each flight direction.

PCE-2 Flight Samples

Tables 8, 9, and 10 provide lists of the MISSE-10 PCE-2 ram, zenith and nadir samples, respectively. These tables provide the MISSE-10 sample ID, material, material abbreviation, thickness (for 1 layer of material), number of layers (for the ram samples), total thickness, sample shape and size. The zenith and nadir samples are comprised of only 1 sample layer. The PCE-2 samples are either 1-inch circular or 1-inch square, with the exception of a 2-inch x 1-inch Photographic AO Monitor (M10R-R1).

The PCE-2 includes a wide variety of samples and individual sample objectives. One of the unique samples being flown as part of the PCE-2 is the Photographic AO Monitor (M10R-R1). This sample has nine stepped layers of 0.3 mil thick Kapton over a white Tedlar substrate (crystalline polyvinyl fluoride w/TiO_2 pigments) that is half coated with a very thin layer of carbon. Thus, the thickness of the Kapton H varies from 0.3 mil to 2.7 mil thick. Using on-orbit imagery, this sample should provide the AO fluence over the mission duration, in a step-wise manner. A pre-flight photograph of the PCE-2 Photographic AO Monitor is shown in Figure 20. A similar but smaller (1-inch square) AO fluence Monitor (M19N-S1) with 3 layers of 0.3 mil Kapton is flying in the nadir direction (M10N-S1).

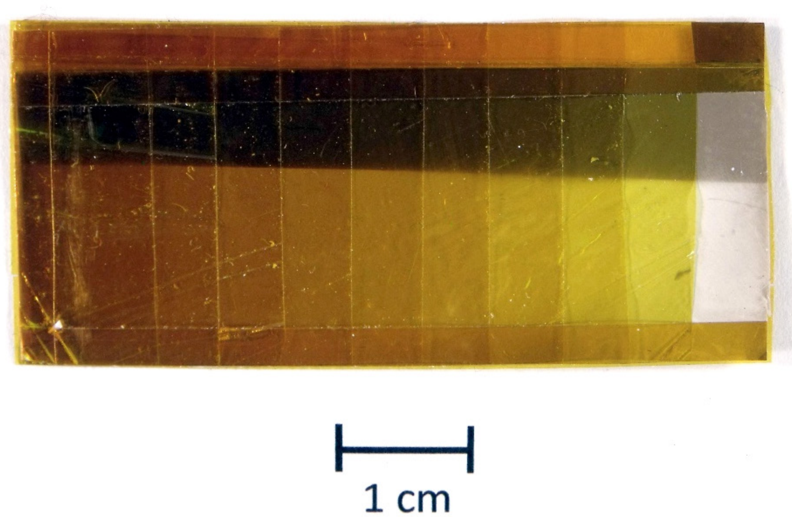


Figure 20. Pre-flight photograph of the PCE-2 Photographic AO Monitor (M10R-R1).

Table 8. MISSE-10 PCE-2 Ram Samples.

MISSE-10 ID	Material	Abbreviation	Thickness (mils)	# Layers	C or S	Size (Inch)
M10R-C1	Polyimide (PMDA) (Kapton H) - 45° chamfer (Std)	Kapton H	5	2	C	1
M10R-C2	Polyimide (PMDA) (Kapton H) - 30° chamfer edge	Kapton H	5	2	C	1
M10R-C3	Polyimide (PMDA) (Kapton H) - 60° chamfer edge	Kapton H	5	2	C	1
M10R-C4	Alumina slide	Al_2O_3	63	1	C	1
M10R-C5	Au/Polyoxymethylene (Delrin acetal) - Scratched	Au/POM	10	1	C	1
M10R-C6	Al/Kapton H - Scratched vertically & horizontally	Al/Kapton H	5	1	C	1
M10R-C7	Polyimide (PMDA) (Kapton HN)	Kapton HN	5	2	C	1
M10R-C8	Fluorinated ethylene propylene (Teflon FEP)	FEP	5	1	C	1
M10R-C9	Aluminized-Teflon (FEP/Al)*	FEP/Al	5	1	C	1
M10R-C10	Teflon FEP clad carbon paint (India Ink) (FEP/C/FEP)*	FEP/C/FEP	14	1	C	1
M10R-C11	Polyethylene naphthalate (PEN)	PEN	2.95	2	C	1
M10R-C12	Metallized Polyethylene naphthalate (PEN) film (Al (100 nm)/PEN (2 micron)/black Cr (15 nm)) with Kapton ring	Al/PEN/Bk Cr (M-PEN)	0.083	2	C	1
M10R-C13	Crystalline polyvinyl fluoride w/white pigment (white Tedlar)	PVF-W	2	1	C	1
M10R-C14	Polyimide (BPDA) (Upilex-S)	Upilex-S	1	2	C	1
M10R-C15	AO Scattering Chamber with salt-sprayed POM lid	AO S.C.	275	1	C	1
M10R-C16	AO Scattering Chamber with salt-sprayed POM lid (30° angle)	AO S.C. (30°)	275	1	C	1
M10R-C17	Shape memory composite sample (SMC)	SMC	275	1	C	1
M10R-C18	Shape memory composite sample (SMC)	SMC	275	1	C	1
M10R-C19	Cyanate ester graphite fiber composite	CEGFC	72.5	1	C	1
M10R-C20	LaRC SI (soluble imide) based polyimide/inorganic nanoparticle composite (radiation resistant polyimide (RPI))	LaRC RPI-2	1	3	C	1
M10R-R1	Photographic AO Fluence Monitor	Photo AO Monitor	5.7	1	R	2.2 x 1.0

*Teflon FEP is space facing

Table 9. MISSE-10 PCE-2 Zenith Samples.

MISSE-10 ID	Material	Abbreviation	Thickness (mils)	# Layers	C or S	Size (inch)
M10Z-C1	Polyimide (PMDA) (Kapton H)	Kapton H	5	1	C	1
M10Z-C2	Carbon (≤700Å) coated Crystalline polyvinyl fluoride w/white pigment (white Tedlar)	C/PVF-W	2	1	C	1
M10Z-C3	Polyimide (PMDA) (Kapton HN)	Kapton HN	5	1	C	1
M10Z-C4	Au-Kapton H - mounted 90° to nadir (1/2 Au coated, 1/2 NaCl sprayed), Ni base	Au-Kapton H/Ni	275	1	C	1
M10Z-C5	Alumina slide	Al_2O_3	63	1	C	1
M10Z-C6	Fluorinated ethylene propylene (Teflon FEP)	FEP	5	1	C	1
M10Z-C7	Aluminized-Teflon (FEP/Al)*	FEP/Al	5	1	C	1
M10Z-C8	Teflon FEP clad carbon paint (India Ink) (FEP/C/FEP)*	FEP/C/FEP	14	1	C	1
M10Z-C9	Metallized Polyethylene naphthalate (PEN) film (aluminum (100 nm)/PEN (2 micron)/black chromium (15 nm)) with Kapton ring	Al/PEN/Bk Cr	0.083	2	C	1
M10Z-C10	LaRC SI (soluble imide) based polyimide/inorganic nanoparticle composite (radiation resistant polyimide (RPI))	LaRC RPI-2	0.9	3	C	1

*Teflon FEP is space facing

Table 10. MISSE-10 PCE-2 Nadir Samples.

MISSE-10 ID	Material	Abbreviation	Thickness (mils)	C or S	Size (inch)
M10N-C1	Polyimide (PMDA) (Kapton H) - 45° chamfer (Standard)	Kapton H	5	C	1
M10N-C2	Polyimide (PMDA) (Kapton H) - 30° chamfer edge	Kapton H	5	C	1
M10N-C3	Polyimide (PMDA) (Kapton H) - 60° chamfer edge	Kapton H	5	C	1
M10N-C4	Au-Kapton H - mounted 90° to nadir (1/2 Au coated, 1/2 NaCl sprayed), Ni base	Au-Kapton H/Ni	275	C	1
M10N-C5	Alumina slide	Al_2O_3	63	C	1
M10N-C6	Fluorinated ethylene propylene (Teflon FEP)	FEP	5	C	1
M10N-C7	Aluminized-Teflon (FEP/Al)*	FEP/Al	5	C	1
M10N-C8	Teflon FEP clad carbon paint (India Ink) (FEP/C/FEP)*	FEP/C/FEP	14	C	1
M10N-C9	Shape memory composite sample (SMC)	SMC	275	C	1
M10N-C10	Low density polyethylene for cosmic ray shielding (CRS)	CRS (LD)	22	C	1
M10N-C11	Polyimide (PMDA) (Kapton HN)	Kapton HN	5	C	1
M10N-S1	Photographic AO Fluence Monitor	Photo AO Monitor	7.9	S	1x1

*Teflon FEP is space facing

Like the PCE-1, polymers flown as part of Glenn's previous MISSE polymers experiments are included in the PCE-2 so that erosion dependence on environment exposure can be determined. For the PCE-2, these include Teflon FEP, white Tedlar and Upilex-S flown in ram direction. Teflon FEP is also flown in the zenith and nadir directions.

The PCE-2 includes the following samples to assess various AO scattering effects:

- Three Kapton H samples are included to determine the effect of the sample holder chamfer angle on the AO Ey. Kapton H samples are flown in MISSE sample trays (decks) with 30°, 45°, and 60° chamber angles. It should be noted that the standard MISSE holder has a 45° chamfer and a 0.030 inch thick lip.
- Aluminum coated Kapton H and Au coated POM samples with scratches in the protective coatings are being flown in the ram direction to evaluate the AO undercutting profile at the defect site. This information will be used to improve Glenn's Monte Carlo AO undercutting models.
- Two AO Scattering Chambers with salt-sprayed POM lids are included in the PCE-2 ram direction. One AO Scattering Chamber has a normal (90°) Al base and one has a 30° angled Al base.
- Two samples are included to characterize the AO fluence at 90° to the ram direction. One is flown in the zenith direction (M10Z-C4) and the other is flown in the nadir direction (M10N-C4). The samples are comprised of Kapton H films, 1/2 coated with Au and 1/2 salt-sprayed, mounted perpendicular (90°) to the sample plane. And the samples are mounted in the zenith and nadir flight decks such that the Au/NaCl sprayed Kapton surface is facing the ram direction. Figure 21 shows pre-flight photographs of the zenith sample (M10Z-C4).

a. b.

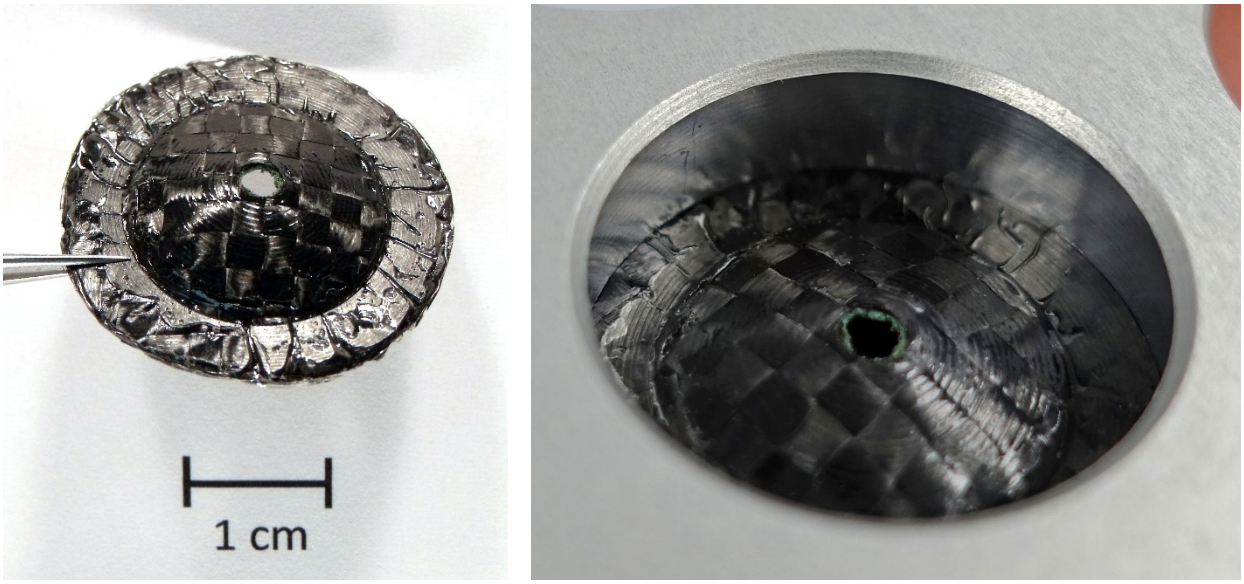
Figure 21. Pre-flight photographs of the PCE-2 sample Au-Kapton H/Ni (M10Z-C4): a). As fabricated, and b). As mounted in the M10 Z2 MSC 10 MS deck.

The PCE-2 also includes the following:

- Samples to validate the effect of passive heating on the E_y of Teflon FEP.
- Potential solar sail materials (Polyethylene naphthalate (PEN) and metallized PEN) and space deployable structure materials (LaRC SI (soluble imide) based polyimide/inorganic nanoparticle composite (LaRC RPI-2)) are included for LEO environmental durability assessment. These materials are being flown in both the ram and zenith directions.
- A cyanate ester graphite fiber composite sample for AO erosion characterization
- A low density cosmic ray shielding (CRS (LD)) sample for radiation durability assessment of new shielding material for spacesuits and spacecraft. This CRS sample incorporates modified FeO instead of Sm-Co powder in LDPE. And, the shielded substance in this sample is human DNA. This CRS (LD) sample was flown in the nadir direction. Figure 22 provides a pre-flight photograph of the nadir CRS (LD) sample (M10N-C10).
- Three SMC samples (also called shape memory polymer composites (SMPC) samples) to assess the functionality of space radiation exposed SMPC materials for space structures. These SMC samples are comprised of pre-cured SMP foam in a dome configuration (non-equilibrium shape). Two dome SMC samples were flown in the ram direction (M10R-C17 and M10R-C18) and one dome SMC sample was flown in the nadir direction (M10N-C9). Figure 23 provides pre-flight photographs of the nadir SMC sample (M10N-C9).

A pre-flight photograph of the PCE-2 samples loaded into the ram (R1 MSC 11), zenith (Z2 MSC 10), and nadir (N3 MSC 13) MS decks is shown in Figure 24. Figure 25 shows close-up pre-flight photographs of the PCE-2 samples in the ram, zenith and nadir decks. For the PCE-2, only one back-up sample was flown instead of the flight sample, the ram Au coated polyoxymethylene scratched sample (M10R-C5 (B)) for undercutting studies.

Figure 22. Pre-flight photograph of the nadir CRS (LD) sample (M10N-C10).



a. b.

Figure 23. Pre-flight photographs of the nadir SMC sample (M10N-C9): a). Prior to integration showing the dome shape, and b). Integrated in the N3 MSC 13 MS deck with an aluminum spacer at the outer circumference.

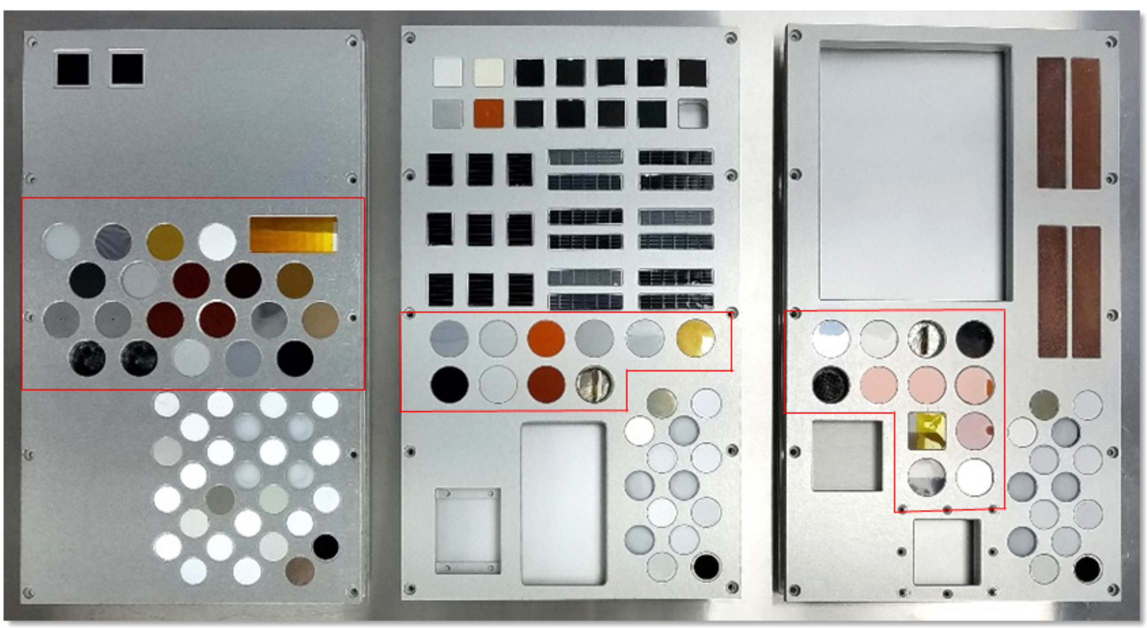
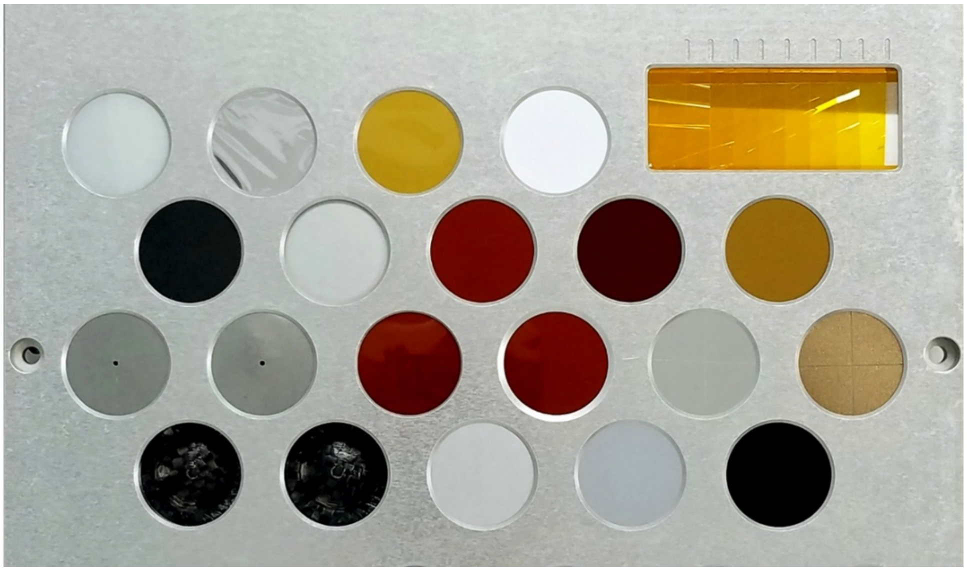
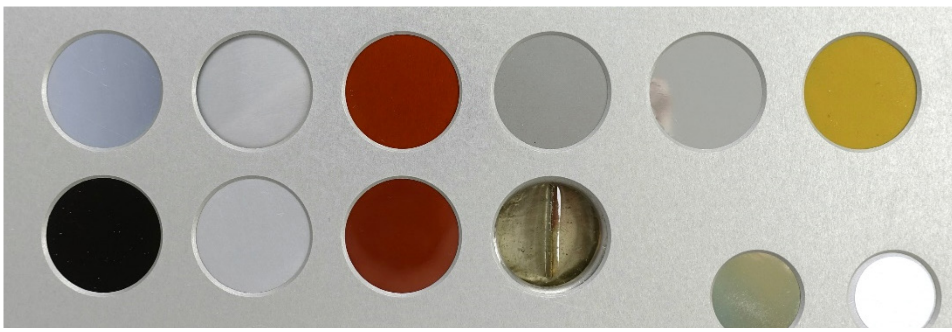


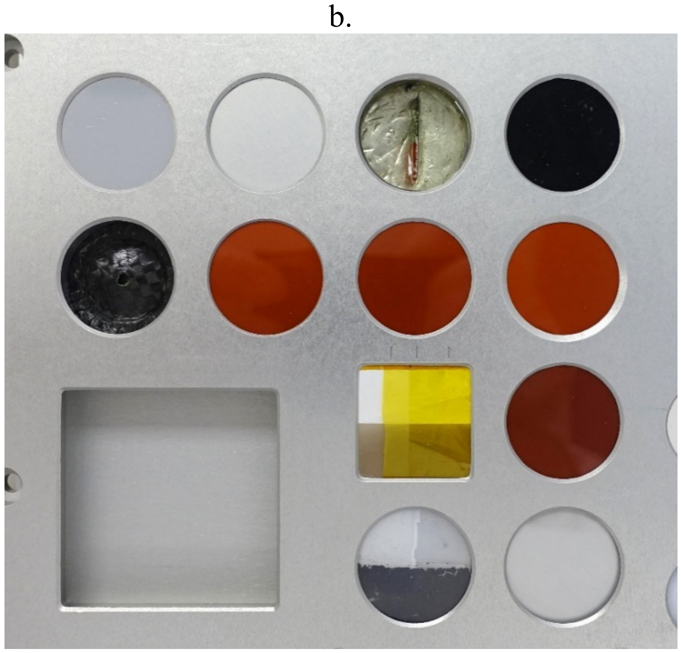
Figure 24. Pre-flight photograph of the MISSE-10 PCE-2 samples loaded into the MSC MS flight decks, from left to right: R1 MSC 11 (ram), Z2 MSC 10 (zenith), and N3 MSC 13 (wake). The PCE-2 samples are shown outlined in red.



a.



b.



c.

Figure 25. Pre-flight close-up photographs of the MISSE-10 PCE-2 samples: a). ram samples, b). zenith samples, and c). nadir samples.

PCE-2 Mission Overview

The MISSE-10 PCE-2 experiment was launched aboard NG-10 on November 17, 2018, and was transferred to storage inside the ISS. The PCE-2 MSCs (ram R1 MSC 11, zenith Z2 MSC 10 and nadir N3 MSC 13) were robotically installed in the MISSE-FF on January 4, 2019. The PCE-2 MSCs were deployed on April 26, 2019, after a new Power and Data Box (PDB) was installed.

The PCE-2 zenith and nadir MSCs were closed for a final time on-orbit on March 12, 2020 and retrieved from the MISSE-FF on March 18, 2020. The MSCs were exposed to the vacuum of space for 1.25 years (December 26, 2018 to March 25, 2020) and had a deployed mission duration of 0.88 years (April 26, 2019 to March 12, 2020). The MSCs were returned to Earth in the SpaceX-20 Dragon on April 7, 2020 after 1.20 years on the MISSE-FF during which time the MISSE-10 zenith Z2 MSC 10 had 8.2 months (0.69 years) of direct space exposure and the MISSE-10 nadir N3 MSC 13 had 5.7 months (0.48 years) of direct space exposure. The PCE-2 zenith and nadir samples are currently waiting to be de-integrated from the MSC decks.

The MISSE-10 PCE-2 ram R1 MSC 11, which remained on-orbit for additional AO exposure, was robotically closed and retrieved on November 25, 2020, and brought back inside the ISS JEM Airlock on December 1, 2020. It was returned as part of the SpaceX-21 mission on January 13, 2021. The MISSE-10 ram MSC was exposed to the vacuum of space for 1.93 years (December 26, 2018 to December 1, 2020). It was on the MISSE-FF facility for 1.90 years (January 4, 2019 to November 25, 2020) and had a deployed mission duration of 1.59 years (April 26, 2019 to November 25, 2020). During the deployed duration, the PCE-2 ram samples had a total of 1.17 years of direct space exposure.

PCE-2 Sample Collaboration

The MISSE-10 PCE-2 is a collaborative effort with a number of researchers from various organizations. The sample collaborators are listed in Table 11 along with the flight materials and number of flight samples.

Table 11. MISSE-10 PCE-2 Sample Collaborators.

Collaborator(s)	Organization	Material	Abbreviation	Number of Samples
Loredana Santo Fabrizio Quadrini	University of Rome Tor Vergata	Low density cosmic ray shielding sample (CRS)	CRS	1
		Shape memory composite sample (SMC)	SMC	3
Genevieve Devaud	Ball Aerospace	Cyanate ester graphite fiber composite	CEGFC	1
Jin Ho Kang	NASA LaRC	Polyethylene naphthalate (PEN)	PEN	1
		Metallized PEN film (Al (100 nm)/PEN (2 micron)/black Cr (15 nm)) with Kapton ring	Al/PEN/Bk Cr (M-PEN)	2
		LaRC SI (soluble imide) based polyimide/inorganic nanoparticle composite (radiation resistant polyimide (RPI))	LaRC RPI-2	2

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

PCE-3 Overview

The MISSE-12 PCE-3 is a passive experiment with 86 samples being flown in ram (30 samples), wake (42 samples) and zenith (14 samples) directions. The primary objective is to determine the LEO AO E_y of polymers, composites, and coated samples as a function of solar irradiation and AO fluence. Like, the PCE 1-2, samples are included to determine the AO fluence for the mission, and characterize any molecular contamination, in each flight direction. The objectives of the PCE-3 are similar to the PCE-1 and PCE-2.

Additional experiment objectives include:

- *Characterization of optical and tensile property degradation of spacecraft polymers and composites in LEO*
- *Understanding of AO undercutting mechanisms for improved AO erosion modeling*
- *Determining the functionality and durability of shape memory alloys, shape memory composites, melanin based composites and new solar cell cover slides after space radiation exposure*.

PCE-3 Flight Samples

Tables 12, 13, and 14 provide lists of the MISSE-12 PCE-3 ram, wake and zenith samples, respectively. These tables provide the MISSE-12 sample ID, material, material abbreviation, thickness (for 1 layer of material), total thickness, sample shape and size. The zenith and nadir samples are comprised of only 1 sample layer. The only sample that has multiple sample layers is the ram sample M12R-C1 Kapton H which has two 5 mil layers for a total thickness of 10 mils (0.010 inches).

Like the PCE-1 and PCE-2, polymers flown as part of Glenn's previous MISSE polymers experiments are included in the PCE-3 so that erosion dependence on environment exposure can be determined. For the PCE-3, these include Teflon FEP, white Tedlar and PVOH flown in ram direction. Teflon FEP is also flown in the wake direction.

Photographic AO Monitors are also being flown as part of the PCE-3 so that the AO fluence can be determined in a step-wise manner over the mission duration using the on-orbit images. For the PCE-3, four Photographic AO Monitors are being flown. Two in the ram direction (M12R-S1 and M12R-S2), one in the wake direction (M12W-S11) and one in the zenith direction (M12Z-S1). Each of these Photographic AO monitors are 1-inch square. All monitors have three stepped layers of gossamer thin Kapton over a white Tedlar substrate that is half coated with a very thin layer of carbon. One of the ram monitors (M12R-S1) and the wake and zenith monitors each have 0.3 mil thick Kapton H layers. Thus, the thickness of the Kapton H varies from 0.3 mil to 0.9 mil thick. The second ram monitor (M12R-S2) has three stepped layers of 0.5 mil Kapton H. Thus, the thickness of the Kapton H varies from 0.5 mil to 1.5 mil thick. Pre-flight photographs of two PCE-3 Photographic AO Monitors are shown in Figure 26.

Table 12. MISSE-12 PCE-3 Ram Samples.

MISSE-12 ID	Material	Abbreviation	Thickness (inch)	C or S
M12R-C1	Polyimide (PMDA) (Kapton H)	Kapton H	0.01 (2 x 0.005")	C
M12R-C2	Early mission AO F photographic detector (drops of PMMA/carbon soot/white vinyl siding (polyvinyl chloride (PVC) resin))	PMMA/C/PVC	0.042	C
M12R-C3	Alumina slide	Al_2O_3	0.063	C
M12R-C4	Fluorinated ethylene propylene (Teflon FEP)	FEP	0.005	C
M12R-C5	Aluminized-Teflon (FEP/Al)*	FEP/Al	0.005	C
M12R-C6	Teflon FEP back-surface spray painted with BBQ black (carbon) paint*	FEP/C	0.014	C
M12R-C7	Crystalline polyvinyl fluoride w/white pigment (white Tedlar)	PVF-W	0.002	C
M12R-C8	Polyvinyl alcohol	PVOH	0.005	C
M12R-C9	Polyimide aerogel (High density)	Aerogel HD	0.118	C
M12R-C10	Polyimide aerogel (Low density)	Aerogel LD	0.118	C
M12R-C11	Magic Black (Acktar Ltd.) coated aluminum	Magic Black/Al	0.135	C
M12R-C12	StaMet coated Kapton XC	StaMet/Kapton XC	0.001	C
M12R-C13	Demron (black polyester/polymer+metal blend/clear embossed polyethylene)/PVC	Demron/PVC	0.028	C
M12R-C14	Ge coated Kapton XC	Ge/Kapton XC	0.003	C
M12R-C15	Silver filled epoxy (ECCOBOND 56C) coated aluminum	Ag Epoxy/Al	0.135	C
M12R-C16	ISS Array Coated Kapton (SiO_2/Kapton)	ISS ACK	0.001	C
M12R-C17	CV1144-0 coated Kapton	CV1144-0/Kapton	0.003	C
M12R-C18	S383-70 silicone (1/2 uncoated and 1/2 coated with Braycote) flown with an Al separator	S383-70 & B/S383-70	0.090	C
M12R-C19	S383-70 silicone (1/2 coated with sunscreen and 1/2 coated with ZnO in Braycote) flown with an Al separator	SS/S383-70 & ZnO-B/S383-70	0.090	C
M12R-C20	Polyimide aerogel (High density, AO skin removed)	Aerogel HD-AO	0.118	C
M12R-C21	Polyimide aerogel (Low density, AO skin removed)	Aerogel LD-AO	0.118	C
M12R-C22	ISS Array Coated Kapton (SiO_2/Kapton), Directed beam	ISS ACK-DB	0.001	C
M12R-C23	ISS Array Coated Kapton (SiO_2/Kapton), Hyperthermal	ISS ACK-HT	0.001	C
M12R-C24	ITO/Teflon/VD Aluminum	ITO-FEP	0.005	C
M12R-C25	Vantablack CX2/aluminum (6061-T651)	Vantablack CX2/Al	0.135	C
M12R-C26	Vantablack (S-IR)/aluminum (6061-T651)	Vantablack (S-IR)/Al	0.135	C
M12R-C27	Shape memory composite sample (SMC)	SMC-1	0.275	C
M12R-C28	Shape memory composite sample (SMC)	SMC-2	0.275	C
M12R-S1	Photographic AO Fluence Monitor #1 (0.3 mil layers)	AO Photo Monitor 1	0.010	S
M12R-S2	Photographic AO Fluence Monitor #2 (0.5 mil layers)	AO Photo Monitor 2	0.010	S

*Teflon FEP is space facing

Table 13. MISSE-12 PCE-3 Wake Samples.

MISSE-12 ID	Material	Abbreviation	Thickness (inch)	C or S
M12W-C1	Polyimide (PMDA) (Kapton H)	Kapton H	0.005	C
M12W-C2	Early mission AO F photographic detector (white vinyl siding (polyvinyl chloride (PVC) resin) - carbon soot - drops of PMMA)	PMMA/C/PVC	0.056	C
M12W-C3	Alumina slide	Al_2O_3	0.063	C
M12W-C4	Fluorinated ethylene propylene (Teflon FEP)	FEP	0.005	C
M12W-C5	Aluminized-Teflon (FEP/Al)*	FEP/Al	0.005	C
M12W-C6	Teflon FEP back-surface spray painted with BBQ black (carbon) paint*	FEP/C	0.014	C
M12W-C7	S383-70 silicone (1/2 uncoated and 1/2 coated with Braycote) flown with an Al separator	S383-70 & B/S383-70	0.090	C
M12W-C8	S383-70 silicone (1/2 coated with sunscreen and 1/2 coated with ZnO in Braycote) flown with an Al separator	SS/S383-70 & ZnO-B/S383-70	0.090	C
M12W-C9	Polyimide aerogel (High density)	Aerogel HD	0.118	C
M12W-C10	Polyimide aerogel (Low density)	Aerogel LD	0.118	C
M12W-C11	Magic Black (Acktar Ltd.) coated aluminum	Magic Black/Al	0.135	C
M12W-C12	StaMet coated Kapton XC	StaMet/Kapton XC	0.001	C
M12W-C13	Demron (black polyester/polymer+metal blend/clear embossed polyethylene)/PVC	Demron/PVC	0.028	C
M12W-C14	Solar Array Black Kapton	SA BK	0.38	C
M12W-C15	Solar Array Black Kapton (tension)	SA BK-T	0.38	C
M12W-C16	Solar Array Kapton	SA K	0.38	C
M12W-C17	Solar Array Kapton (tension)	SA K-T	0.38	C
M12W-C18	Solar Array FEP	SA FEP	0.38	C
M12W-C19	Solar Array FEP (tension)	SA FEP-T	0.38	C
M12W-C20	Shape memory composite sample (SMC)	SMC-1	0.275	C
M12W-C21	Shape memory composite sample (SMC)	SMC-2	0.275	C
M12W-C22	Cosmic ray shielding (CRS) sample (High weight shielding layer)	CRS-HW	0.039	C
M12W-C23	Cosmic ray shielding (CRS) sample (Low weight shielding layer)	CRS-LW	0.039	C
M12W-C24	Vantablack CX2/aluminum (6061-T651)	Vantablack CX2/Al	0.135	C
M12W-C25	Vantablack (S-IR)/aluminum (6061-T651)	Vantablack (S-IR)/Al	0.135	C
M12W-C26	Polyvinyl chloride	PVC	0.005	C
M12W-C27	Silver filled epoxy (ECCOBOND 56C) coated aluminum	Ag-Epoxy/Al	0.135	C
M12W-C28	CMG (ceria doped borosilicate glass) Pseudomorphic Glass with UVR (UV rejection coating)	CMG-PMG-UVR	0.0075	C
M12W-C29	Flexible Optical Solar Reflector (OSR)	FLOSR	0.0075	C
M12W-C30	Fractal Black (Acktar Ltd.) coated aluminum	Fractal Black/Al	0.135	C
M12W-S1	Shape Memory Alloy (Binary NiTi-FWM)	SMA NiTi	0.020	S**
M12W-S2	Shape Memory Alloy (NiTiHf-FS5)	SMA NiTiHf	0.078	S**
M12W-S3	Shape Memory Alloy (NiTiAu-Ext198)	SMA NiTiAu	0.078	S**

Table 13. MISSE-12 PCE-3 Wake Samples, Cont.

MISSE-12 ID	Material	Abbreviation	Thickness (inch)	C or S
M12W-S4	Shape Memory Alloy (NiTiPt-Ext99)	SMA NiTiPt	0.078	S**
M12W-S5	Shape Memory Alloy (NiTiPd-Ext119)	SMA NiTiPd	0.078	S**
M12W-S6	Shape Memory Alloy (Binary NiTi-FWM)	SMA NiTi	0.020	S**
M12W-S7	Shape Memory Alloy (NiTiHf-FS5)	SMA NiTiHf	0.078	S**
M12W-S8	Shape Memory Alloy (NiTiAu-Ext198)	SMA NiTiAu	0.078	S**
M12W-S9	Shape Memory Alloy (NiTiPt-Ext99)	SMA NiTiPt	0.078	S**
M12W-S10	Shape Memory Alloy (NiTiPd-Ext119)	SMA NiTiPd	0.078	S**
M12W-S11	Photographic AO Fluence Monitor #1 (0.3 mil layers)	AO Photo Monitor	0.010	S
M12W-S12	Indium tin oxide (ITO) coated aluminized-Kapton HN	ITO/Kapton HN/Al	0.002	S

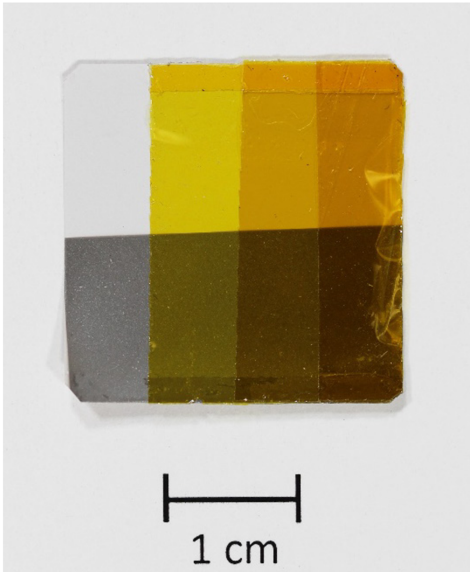
*FEP layer is space facing

**SMA samples are comprised of 4 - 0.25" x 1" pieces; except NiTi is 2 - 0.5" x 1" pieces

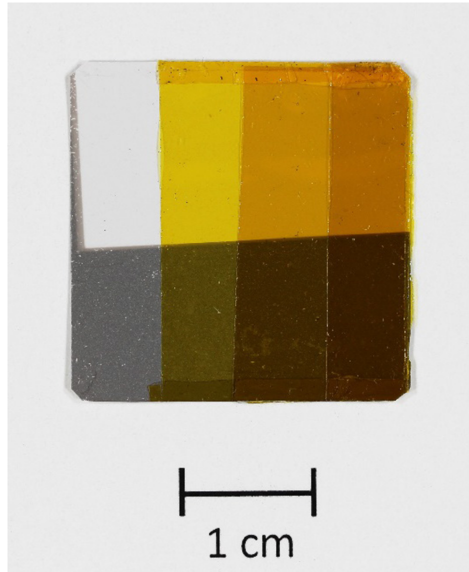
Table 14. MISSE-12 PCE-3 Zenith Samples.

MISSE-12 ID	Material	Abbreviation	Thickness (inch)	C or S
M12Z-C1	Crew Vehicle modified thermal control paint (S13NT: 6N/LO-1)	CV TCP	0.0625	C
M12Z-C2	Crew Vehicle RTV (low outgassing) (RTV577-LV)	CV RTV	0.0625	C
M12Z-C3	Solar Array Black Kapton (tension)	SA BK2-T	0.275	C
M12Z-C4	Cosmic ray shielding (CRS) sample (high weight shielding layer)	CRS-HW	0.039	C
M12Z-C5	Fused Silica Pseudomorphic Glass with UVR	FS-PMG-UVR	0.007	C
M12Z-C6	Fused Silica Pseudomorphic Glass	FS-PMG	0.009	C
M12Z-C7	Compressed mycelium with thin polylactic acid (PLA) coating on the space exposure side with a polyvinyl chloride backing layer	PLA/CMy/PVC	0.25	C
M12Z-C8	PLA with PVC backing layer	PLA/PVC	0.012	C
M12Z-C9	Fungal melanin powders infused into PLA with polyvinyl chloride (PVC) backing layer	PLA-FunMel/PVC	0.38	C
M12Z-C10	Synthetic melanin powders infused into PLA with polyvinyl chloride (PVC) backing layer	PLA-SynMel/PVC	0.38	C
M12Z-S1	Photographic AO Fluence Monitor (0.3 mil layers)	AO Photo Monitor	0.01	S
M12Z-S2	Shape Memory Alloy (Binary NiTi-FWM)	SMA NiTi	0.02	S*
M12Z-S3	Shape Memory Alloy (NiTiHf-FS5)	SMA NiTiHf	0.078	S*
M12Z-S4	Shape Memory Alloy (NiTiAu-Ext198)	SMA NiTiAu	0.078	S*

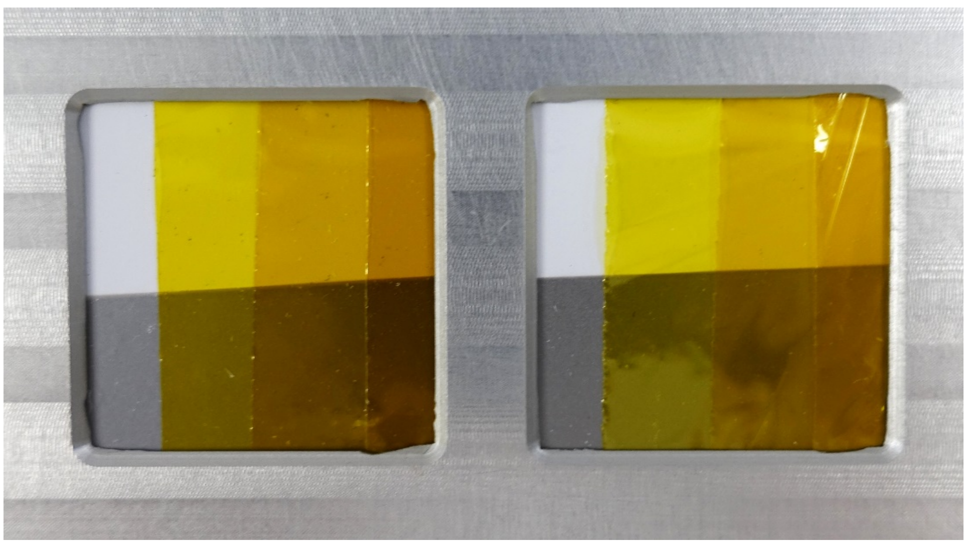
*NiTi is comprised of 2 - 0.5" x 1" pieces, NiTiHf and NiTiAu is comprised of 4 - 0.25" x 1" pieces



a.



b.



c.

Figure 26. Pre-flight photographs of the PCE-3 Photographic AO Monitors: a). M12R-S1 with 0.3 mil Kapton H layers, b). M12R-S2 with 0.5 mil Kapton H layers, and c). M12R-S1 (right) and M12R-S2 (left) mounted in the M12 R2 SS deck.

The PCE-3 includes five types of Shape Memory Alloy (SMA) materials (NiTi, NiTiHf, NiTiAu, NiTiPt and NiTiPd) to assess the radiation durability for space-based solid-state actuation and structural components (i.e., rovers, bearing alloys). A total of 13 samples are flown in either the zenith (3) or wake (10) direction. The binary samples (NiTi) are each comprised of 2 - 0.5” x 1” pieces in a 1-inch square sample holder. One piece is polished and the other is not polished. The other SMA samples are comprised of 4 - 0.25” x 1” pieces in a 1-inch square samples holder. Two pieces are polished and two are not. A close-up pre-flight photograph of the wake SMA samples is provided in Figure 27. The individual sample pieces can be seen (M12W-S1 to M12W-S10). Also included in the photo are the wake Photographic AO Monitor (M12W-S11) and an ITO coated Kapton HN/Al sample (M12W-S12).

One unique set of samples being flown as part of the PCE-3 is a set of melanin samples. A total of four samples are being flown in the zenith direction, as shown in Figure 28. These samples are: 1). Compressed mycelium with thin polylactic acid (PLA) surface coating and a polyvinyl chloride (PVC) backing layer (M12Z-C7), 2). Fungal melanin powders infused into PLA with PVC backing layer (M12Z-C9), 3). Synthetic melanin powders infused into PLA with PVC backing layer (M12Z-C10), and 4). PLA with PVC backing layer (control, M12Z-C8). The objective for these samples is radiation shielding assessment of melanin composites for spacesuit and space structure applications.

Uncoated and coated docking seal (S383-70 silicone) samples are being flown in the ram and wake direction. Two 1-inch diameter samples that are 1/2 uncoated and 1/2 coated with Braycote (flown with an Al separator) are being flown in the ram (M12R-C18) and wake (M12W-C7) directions to determine the effects of AO and UV on the elastomer and a grease commonly used on seals of this type. And, two 1-inch diameter samples that are 1/2 coated with sunscreen and 1/2 coated with ZnO in Braycote (flown with an Al separator) are being flown in the ram (M12R-C19) and wake (M12W-C8) directions to determine the effectiveness of coatings to protect seal elastomers from AO and UV, and to further flight qualify a new elastomer seal grease and protective coating. A pre-flight photograph of the ram samples is provided in Figure 29.

Figure 27. Close-up pre-flight photograph of the MISSE-12 wake SMA samples.

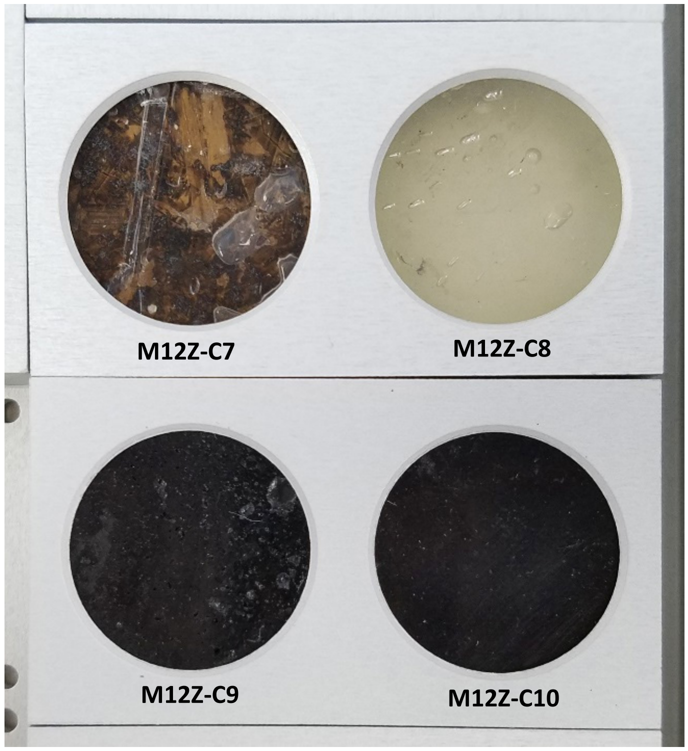


Figure 28. Pre-flight photograph of the melanin-based samples in the MISSE-12 Z1 MSC MS deck.

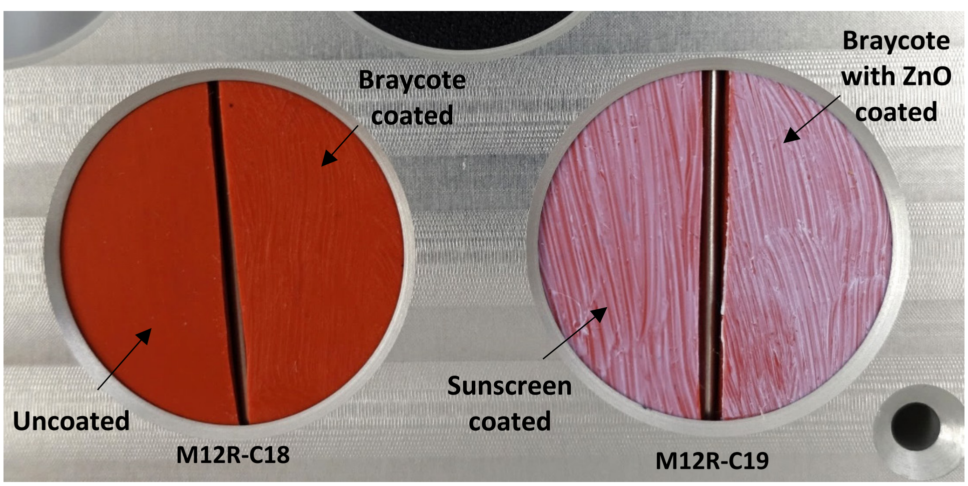


Figure 29. Pre-flight photograph of the MISSE-12 ram coated and uncoated docking seal material samples M12R-C18 (left) and M12R-C19 (right).

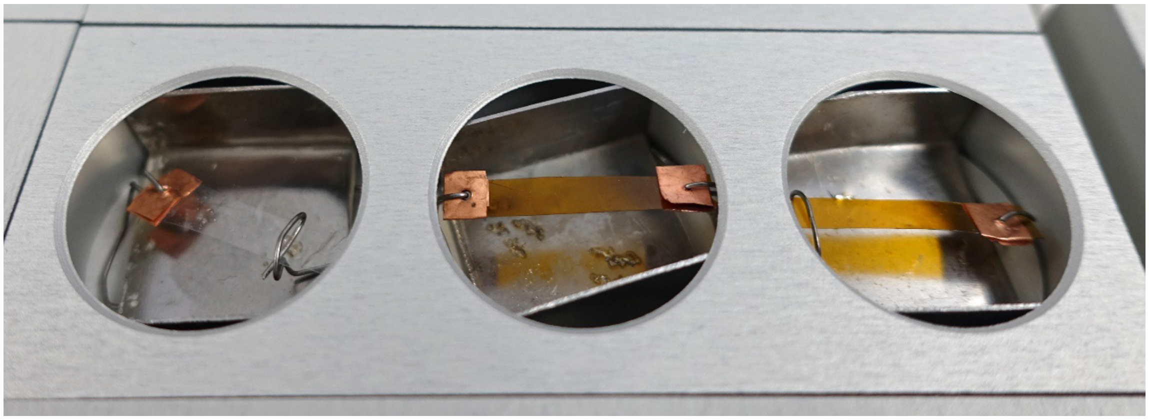


Figure 30. Close-up photograph of 3 tensile loaded MISSE-12 samples in the W3 MSC 6 MS deck (M12W-C18 (left), M12W-C17 (center), M12W-C16 (right).

A variety of ISS solar array materials including samples mounted with, and without, tensile loading are being flown in the wake or zenith directions to determine if space exposure while under tension affects their mechanical properties. Figure 30 provides a pre-flight photo of three of the tensile loaded samples in the M12 W3 (MSC 6) MS deck. Also, included in the PCE-3 are ISS array coated Kapton samples to calibrate ground vs. space erosion for coated Kapton.

The MISSE-12 PCE-3 also includes:

- Samples to validate the effect of passive heating on the E_y of Teflon FEP.
- Low and high density polyimide aerogels for AO and radiation durability assessment
- Samples to assess the optical and electrical performance and durability of indium tin oxide (ITO) conductive coatings.
- Specialty coatings including Magic Black, Fractal Black, Vantablack CX2, Vantablack (S-IR), StaMet coated Kapton XC and Ge coated Kapton XC for AO erosion and/or optical property characterization and modeling data.
- Pseudomorphic glass and flexible Optical Solar Reflector (OSR) samples for optical and thermal property performance for photovoltaic applications.
- Demron radiation resistant fabric for AO durability and optical properties assessment.
- Shape memory polymer composite (SMC or SMPC) samples to assess the AO durability, and the functionality of space radiation exposed SMCs for space structures. These SMC samples use pre-cured SMP film and have a "trigger configuration" (non-equilibrium shape). Samples with two different thicknesses of the SMP film are flown. Two samples are being flown in the ram direction (M12R-C27 and M12R-C28) and two samples are being flown in the wake direction (M12W-C20 and M12W-C21). Figure 31 provides a pre-flight photograph of the PCE-3 ram SMC samples loaded in the MISSE-12 R2 MSC 4 SS flight deck. Like the PCE-1 SMC samples, these SMC samples are designed so on-orbit shape changes can be observed in the on-orbit images.
- Cosmic ray shielding (CRS) samples with high weight (HW) and low weight (LW) shielding for radiation durability assessment of new shielding materials for spacesuits and spacecraft. These multi-layer sheet CRS samples were fabricated by co-molding three single functionalized layers (full size) of LDPE: one with Sm-Co, one with FeO, and one with BN. Two CRS samples are being flown in the wake direction (M12W-C22 (HW) and

M12W-C23 (LW)) and one CRS samples is being flown in the zenith direction (M12Z-C4 (HW)). Figure 32 provides a pre-flight photograph of the zenith CRS-HW sample (M12W-C4).

- Silver filled epoxy for AO E_y measurements and optical degradation characterization of epoxy materials for material properties and modeling. The oxidized silver is supposed to enhance recombination of the AO which should manifest itself as a reduction in E_y.

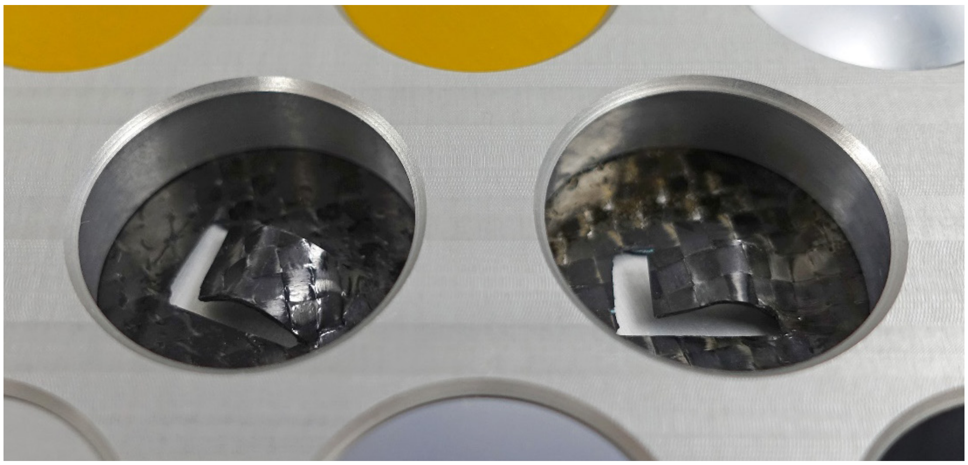


Figure 31. Pre-flight photograph of the MISSE-12 ram SMC samples in the R2 MSC 4 SS deck (M12R-C27 (left) and M12R-C28 (right)).

Figure 32. Pre-flight photograph of the zenith CRS-HW sample (M12Z-C4).

A pre-flight photograph of the PCE-3 samples loaded into the ram (R2 MSC 4 SS), zenith (Z1 MSC 18 MS), and wake (W3 MSC 6 MS) decks is shown in Figure 33. Figure 34 provides close-up photographs of the PCE-3 samples in the MSC decks. It should be noted that 6 wake samples and 4 zenith samples were moved to different MSC locations after the photographs in Figure 33 and Figure 34 were taken during sample integration. These 10 samples have two red boxes around them in Figure 33. The final flight positions are provided in the zenith and wake decks photos in Figure 35, with two red boxes around the samples in their new positions. The large yellow sample in Z1 MSC 18 MS shown in Figures 33 to 35 is not part of the PCE-3. For the PCE-3, four wake "back-up" samples were flown instead of the "flight" samples. This was because the flight samples were too big for the flight hardware or the flight sample got a small mark on it. Thus, the following back-up samples were flown: Low density polyimide aerogel (M12W-C10 (B)), StaMet coated Kapton XC (M12W-C12 (B)), Vantablack CX2 coated aluminum (M12W-C24 (B)) and Flexible Optical Solar Reflector (M12W-C-29 (B)).

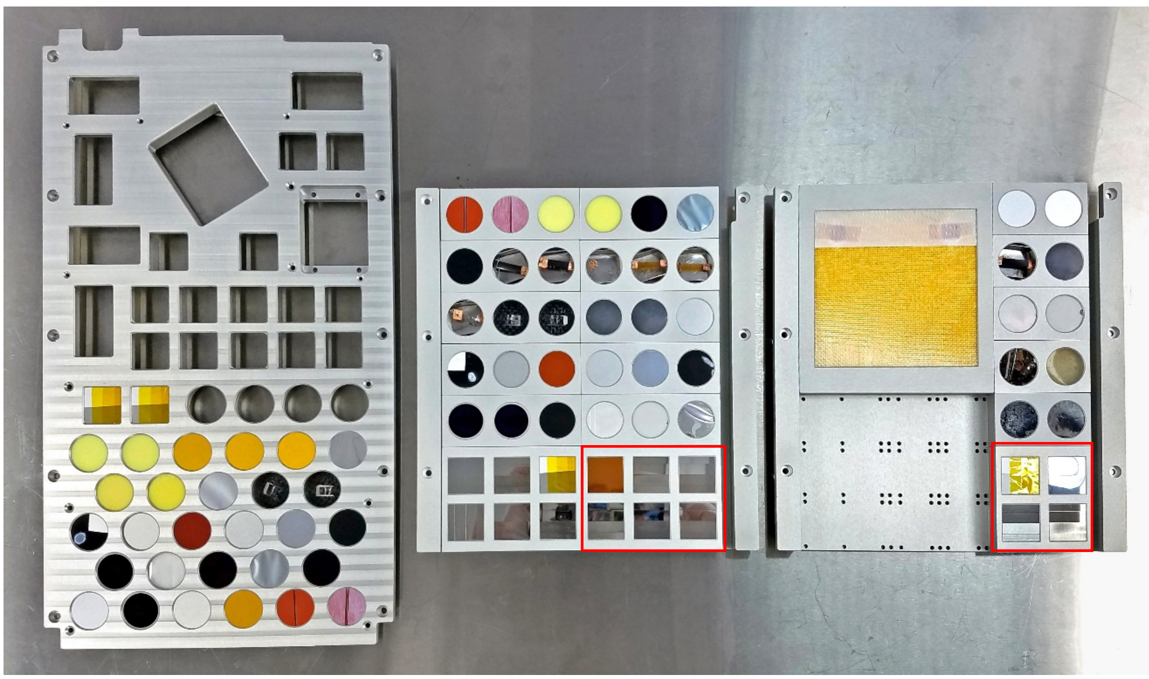


Figure 33. Pre-flight photograph of the MISSE-12 PCE-3 samples loaded into the MSC flight decks, from left to right: R2 MSC 4 SS (ram), W3 MSC 6 MS (wake) and Z1 MSC 18 MS (zenith). The large yellow sample in Z1 MSC 18 MS is not part of the PCE-3. Samples in red boxes were moved to a different location on the deck prior to flight.

Figure 34. Close-up photographs of the MISSE-12 PCE-3 samples loaded into the MSC flight decks, a). R2 MSC 4 SS (ram), b). W3 MSC 6 MS (wake), and c). Z1 MSC 18 MS (zenith). The large yellow sample in Z1 MSC 18 MS is not part of the PCE-3.

a. b.

Figure 35. Final deck configuration of the MISSE-12 wake and zenith MSC flight decks: a). W3 MSC 6 MS (wake), and b). Z1 MSC 18 MS (zenith). The moved samples are in the red-box areas. (Photo credit: Alpha Space)

<u>*PCE-3 Mission Overview*</u>

The MISSE-12 PCE-3 experiment was launched aboard Cygnus NG-12 on November 2, 2019 and the MSCs were installed in the MISSE-FF on November 11, 2019. The MISSE-12 ram carrier was deployed on December 3, 2019. The wake and zenith carriers, originally installed in the wrong flight orientation, were moved to the correct locations (switched) on March 16 and March 17, 2020, respectively. The MISSE-12 zenith MSC (Z1 MSC 18) was deployed on March 20, 2020. As stated previously, the wake carrier (W3 MSC 6) was never deployed and hence those samples have never been directly exposed to the space environment. The MISSE-12 PCE-3 wake samples will be re-flown on the MISSE-15 mission. MISSE-12 Z1 (MSC 18) was closed for the final time on September 2, 2020 and MISSE-12 R2 (MSC 4) was closed on November 25, 2020. MISSE-12 R2 was retrieved on November 25, 2020, MISSE-12 Z1 was retrieved on November 26, 2020, and MISSE-12 W3 was retrieved on November 27, 2020. The MSC s were re-pressurized on December 1, 2020 and returned as part of the SpaceX-21 mission on January 13, 2021.

The MISSE-12 PCE-3 ram MSC 4 (R2) was exposed to the vacuum of space for 1.07 years (November 7, 2019 to December 1, 2020). It was on the MISSE-FF facility for 1.04 years (November 11, 2019 to November 25, 2020) and had a deployed mission duration of 0.98 years (December 3, 2019 to November 25, 2020). During the deployed duration, the PCE-3 ram samples had a total of 0.89 years of direct space exposure.

MISSE-12 PCE-3 wake MSC 6 (W3) was exposed to the vacuum of space for 1.07 years (November 7, 2019 to December 1, 2020). It was on the MISSE-FF facility for 1.05 years (November 11, 2019 to November 27, 2020), but it was never deployed (i.e., opened). Thus, the PCE-3 wake samples had no direct space exposure.

MISSE-12 PCE-3 zenith MSC 18 (Z1) was exposed to the vacuum of space for 1.07 years (November 7, 2019 to December 1, 2020). It was on the MISSE-FF facility for 1.05 years (November 11, 2019 to November 26, 2020) and had a deployed mission duration of 0.46 years (March 20, 2020 to September 2, 2020). During the deployed duration, the PCE-3 zenith samples had a total of 0.44 years of direct space exposure.

PCE-3 Sample Collaboration

The MISSE-12 PCE-3 is a collaborative effort with a number of researchers from various organizations. The sample collaborators are listed in Table 15 along with the collaborative flight materials and number of flight samples. Materials were also provided by MAXAR Space Solutions (StaMet coated Kapton XC) and RST Radiation Shield Technologies, Inc. (Demron).

Table 15. MISSE-12 PCE-3 Sample Collaborators.

Collaborator(s)	Organization	Material	Abbreviation	Number of Samples
Loredana Santo Fabrizio Quadrini	University of Rome Tor Vergata	Cosmic ray shielding (CRS) sample (High weight shielding layer)	CRS-HW	2
		Cosmic ray shielding (CRS) sample (Low weight shielding layer)	CRS-LW	1
		Shape memory composite sample (SMC)	SMC	4
Genevieve Devaud[1] Samir Singh[1] Dina Katsir[2]	[1]Ball Aerospace [2]Acktar Ltd.	Magic Black (Acktar Ltd.) coated aluminum	Magic Black/Al	2
		Silver filled epoxy (ECCOBOND 56C) coated aluminum	Ag Epoxy/Al	2
		Fractal Black (Acktar Ltd.) coated aluminum	Fractal Black/Al	1
Ben Jensen[1] John Fleming[2]	[1]Surrey Nanosystems [2]Ball Aerospace	Vantablack CX2/aluminum (6061-T651)	Vantablack CX2/Al	2
		Vantablack (S-IR)/aluminum (6061-T651)	Vantablack (S-IR)/Al	2
David Wilt	Air Force Research Lab (AFRL)	Fused Silica Pseudomorphic Glass with UVR (ultraviolet rejection coating)	FS-PMG-UVR	1
		Fused Silica Pseudomorphic Glass	FS-PMG	1
		CMG (ceria doped borosilicate glass) Pseudomorphic Glass with UVR	CMG-PMG-UVR	1
		Flexible Optical Solar Reflector (OSR)	FLOSR	1
Kathleen Spaner Ronald DeMeo	RST Radiation Shield Technologies, Inc.	Demron (black polyester/polymer+metal blend/clear embossed polyethylene)/PVC	Demron/PVC	2
Jessica Cashman Mary Ann Meador (retired)	GRC LMN	Polyimide aerogel (High density)	Aerogel HD	2
		Polyimide aerogel (Low density)	Aerogel LD	2
		Polyimide aerogel (High density, AO skin removed)	Aerogel HD-AO	1
		Polyimide aerogel (Low density, AO skin removed)	Aerogel LD-AO	1

Table 15. MISSE-12 PCE-3 Sample Collaborators, Cont.

Collaborator(s)	Organization	Material	Abbreviation	Number of Samples
Sharon Miller	GRC LME	ISS Array Coated Kapton (SiO_2/Kapton)	ISS ACK	1
		ISS Array Coated Kapton (SiO_2/Kapton), Directed beam	ISS ACK-DB	1
		ISS Array Coated Kapton (SiO_2/Kapton), Hyperthermal	ISS ACK-HT	1
		ITO/Teflon/VD Aluminum	ITO-FEP	1
		Crew Vehicle modified thermal control paint (S13NT: 6N/LO-1)/Al	CV TCP	1
		Crew Vehicle RTV (low outgassing) (RTV577-LV)/Aluminum	CV RTV	1
		Solar Array Black Kapton (tension)	SA BK2-T	2
		Solar Array Black Kapton	SA BK	1
		Solar Array Kapton	SA K	1
		Solar Array Kapton (tension)	SA K-T	1
		Solar Array FEP	SA FEP	1
		Solar Array FEP (tension)	SA FEP-T	1
Santo Padula II Othmane Benafan	GRC LMA	Shape Memory Alloy (Binary NiTi)	SMA NiTi	3
		Shape Memory Alloy (NiTiHf)	SMA NiTiHf	3
		Shape Memory Alloy (NiTiAu)	SMA NiTiAu	3
		Shape Memory Alloy (NiTiPt)	SMA NiTiPt	2
		Shape Memory Alloy (NiTiPd)	SMA NiTiPd	2
Theresa Benyo[1] Andrew Trunek[2] Radamés Cordero[3] Arturo Casadevall[3] Quigly Dragotakes[3] Ali Dhinojwala[4] Saranshu Singla[4] Chris Maurer[5]	[1]GRC LMN [2] GRC LCS [3]Johns Hopkins Univ. [4]Univ. of Akron [5]redhouse studio	Compressed mycelium with thin polylactic acid (PLA) surface coating and a polyvinyl chloride (PVC) backing layer	PLA/CMy/PVC	1
		PLA with PVC backing layer	PLA/PVC	1
		Fungal melanin powders infused into PLA with PVC backing layer	PLA-FunMel/PVC	1
		Synthetic melanin powders infused into PLA with PVC backing layer	PLA-SynMel/PVC	1
Henry de Groh	GRC LMA	S383-70 silicone (1/2 uncoated and 1/2 coated with Braycote) flown with an Al separator	S383-70 & B/S383-70	2
		S383-70 silicone (1/2 coated with sunscreen and 1/2 coated with ZnO in Braycote) flown with an Al separator	SS/S383-70 & ZnO-B/S383-70	2

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

<u>*PCE-4 Overview*</u>

The MISSE-13 PCE-4 is a passive experiment with 98 samples being flown in the wake (65 samples) and zenith (33 samples) directions. The primary objectives of the PCE-4 are to determine optical and mechanical property degradation of spacecraft materials, and to assess the functionality of shape memory alloys, shape memory polymer composites, melanin based composites and elastomer seal samples after radiation exposure in LEO. Like, the PCE 1-3, samples are included to determine the AO fluence in each mission orientation. Teflon FEP samples will be used for contamination studies. Specific materials and sample objectives are discussed in the PCE-4 Flight Sample section below.

PCE-4 Flight Samples

Tables 16, 18, 19, and 20 provide lists of the MISSE-13 PCE-4 wake MS, wake SS tensile, wake SS stressed and zenith samples, respectively. These tables provide the MISSE-13 sample ID, material, material abbreviation, thickness, sample shape and size. All samples are comprised of only 1 sample layer. Tables 17 and 21 provide the individual SMA sample details for wake rectangular sample M13W-R1 (Table 17) and zenith rectangular sample M13Z-R1 and zenith square sample M13Z-S3 (Table 21).

In addition to 1-inch samples for E_y, optical property characterization, and/or radiation durability assessment (see Tables 16 and 19), there are 24 Teflon fluorinated ethylene propylene (FEP) and vapor deposited aluminum clear polyimide 1 (VDA/CP1) tensile samples being flown in the wake direction for radiation embrittlement studies (see Table 17). The tensile samples were fabricated using an ASTM D638-08 punch. Figure 36 shows the tensile samples in the tensile holder with the sample IDs on the tensile holder bars. Three of the samples (M13W-T1 – M13W-T3) are 2 mil thick Teflon FEP and thus are clear. Therefore, it is difficult to see the samples on the holder (IDs 1-3). This is the same tensile sample holder that flew on MISSE-9 with the PCE-1 zenith tensile samples.

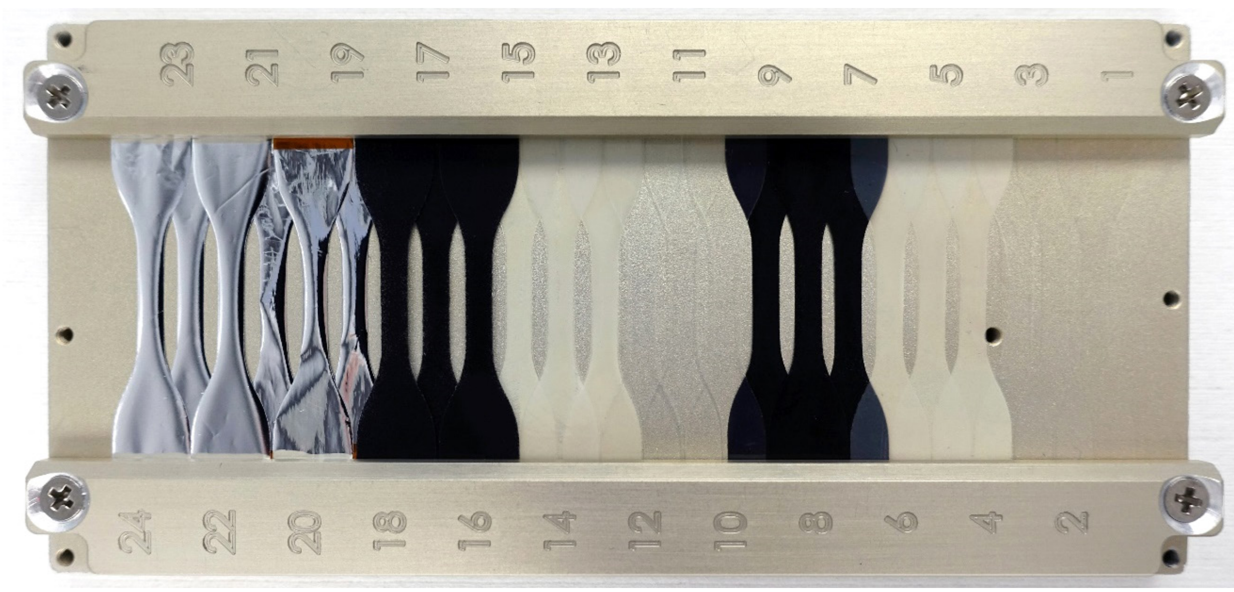


Figure 36. Pre-flight photograph of the MISSE-13 wake tensile samples mounted in the MISSE-13 W1 MSC 19 SS tensile flight holder with sample ID bars.

Table 16. MISSE-13 PCE-4 Wake (Mount-Side) Samples.

MISSE-13 ID	Material	Abbreviation	Thickness (mils)	C, S or R
M13W-C1	Polyimide (PMDA) (Kapton H)	Kapton H	5	C
M13W-C2	James Webb Space Telescope (JWST) Sun shield (Si/2 mil Kapton E/VDA)	JWST	2	C
M13W-C3	JWST Sun shield material under folding stress	JWST FS	2	C
M13W-C4	Aluminized-Teflon FEP*	FEP/Al	5	C
M13W-C5	Aluminized-Teflon FEP under folding stress*	FEP/Al FS	5	C
M13W-C6	VDA/CP1-PTFE composite solar sail material (with Kapton HN frame/966 acrylic adhesive on back surface)	VDA/CP1-PTFE	0.3	C
M13W-C7	VDA/CP1-PTFE composite solar sail material under folding stress	VDA/CP1-PTFE FS	0.3	C
M13W-C8	VDA/CP1 solar sail material (with Kapton HN frame adhered with 3M 966 acrylic adhesive on front surface)	VDA/CP1	0.2	C
M13W-C9	S0383-70 silicone (1"dia. seal)	S0383-70	210	C
M13W-C10	S0383-70 silicone with 1.5% titanium dioxide additive (1"dia. seal)	TiO_2-S0383-70	210	C
M13W-C11	S0383-70 silicone coated with Braycote 601EF grease (1"dia. seal)	B/S0383-70	210	C
M13W-C12	S0383-70 silicone coated with Braycote 601EF grease plus ZnO (BZ) sunscreen (1"dia. seal)	BZ/S0383-70	210	C
M13W-C13	S0383-70 silicone coated Dow Corning 7 + ZnO (DCZ) sunscreen (1"dia. seal)	DCZ/S0383-70	210	C
M13W-C14	Shape memory composite sample (SMC)	SMC (1b)	47	C
M13W-C15	Shape memory composite sample (SMC)	SMC (2b)	47	C
M13W-C16	Cosmic ray shielding (CRS) sample	CRS (1b)	12	C
M13W-C17	Cosmic ray shielding (CRS) sample	CRS (2b)	12	C
M13W-C18	BR-127 NC ESD/Al (Solvay BR-127 non-chromated (NC) electric static dissipative (ESD) Modified Phenolic Primer Black on an Al substrate)	BR-127 NC ESD/Al	136	C
M13W-C19	Compressed mycelium with thin polylactic acid (PLA) coating on the space exposure side with a polyvinyl chloride backing layer	PLA/CMy/PVC	250	C
M13W-C20	Fungal melanin powders infused into PLA with polyvinyl chloride (PVC) backing layer	PLA-FunMel/PVC	380	C
M13W-C21	Synthetic melanin powders infused into PLA with polyvinyl chloride (PVC) backing layer	PLA-SynMel/PVC	380	C
M13W-C22	PLA with PVC backing layer	PLA/PVC	12	C
M13W-C23	Polyphenylsulfone (PPSU), Radel 5500	PPSU	12.5	C
M13W-C24	Polyphenylsulfone (PPSU), Radel 5500, with boron nitride (BN) platelets	PPSU-BN	8.5	C
M13W-S1	Photographic AO Fluence Monitor (0.3 mil Kapton H on C coated white Tedlar)	AO Photo Monitor	10	S
M13W-S2	VDA/CP1 NEAScout solar sail material (with Kapton HN frame/966 acrylic adhesive on front surface)	VDA/CP1	0.1	S
M13W-R1	Shape Memory Alloys (13 samples: 2 - 0.5" x 1" + 11 - 0.25" x 1" pieces (Binary NiTi, etc.))	SMA	20	R 1" x 4"

*FEP is space facing

Table 17. MISSE-13 PCE-4 Wake (Mount-Side) SMA Samples.

MISSE-13 ID	Sample ID	Abbreviation	Composition	Condition	Dimensions (inch)
M13W-R1	M13W-R1-1	H18-003 aged	NiTi-1Hf	Polished	1/2" x 1" x 0.08"
	M13W-R1-2	H18-003 aged	NiTi-1Hf	Unpolished	1/2" x 1" x 0.08"
	M13W-R1-3	Ext. 99	NiTiPt	Polished	1/4" x 1" x 0.08"
	M13W-R1-4	Ext. 99	NiTiPt	Unpolished	1/4" x 1" x 0.08"
	M13W-R1-5	Ext. 119	NiTiPd	Polished	1/4" x 1" x 0.08"
	M13W-R1-6	Ext. 119	NiTiPd	Unpolished	1/4" x 1" x 0.08"
	M13W-R1-7	Ext. 198	NiTiAu	Polished	1/4" x 1" x 0.08"
	M13W-R1-8	Ext. 198	NiTiAu	Unpolished	1/4" x 1" x 0.08"
	M13W-R1-9	Ext. 201	NiTiAu	Polished	1/4" x 1" x 0.08"
	M13W-R1-10	Ext. 201	NiTiAu	Unpolished	1/4" x 1" x 0.08"
	M13W-R1-11	FS#1Z	NiTi-20Zr	Polished	1/4" x 1" x 0.08"
	M13W-R1-13	FS#5	NiTi-20Hf	Polished	1/4" x 1" x 0.08"
	M13W-R1-14	FS#5	NiTi-20Hf	unpolished	1/4" x 1" x 0.08"

Note: M13W-R1-12 was flown in the zenith direction with M13Z-S3

Table 18. MISSE-13 PCE-4 Wake (Swing-Side) Tensile Samples.

MISSE-13 ID	Material	Abbreviation	Thickness (mils)
M13W-T1	Teflon (FEP)	FEP	2
M13W-T2	Teflon (FEP)	FEP	2
M13W-T3	Teflon (FEP)	FEP	2
M13W-T4	Teflon (FEP) - AO textured on back surface	FEP-AO	2
M13W-T5	Teflon (FEP) - AO textured on back surface	FEP-AO	2
M13W-T6	Teflon (FEP) - AO textured on back surface	FEP-AO	2
M13W-T7	Teflon (FEP) - AO textured and C coated on the back surface	FEP/C	2
M13W-T8	Teflon (FEP) - AO textured and C coated on the back surface	FEP/C	2
M13W-T9	Teflon (FEP) - AO textured and C coated on the back surface	FEP/C	2
M13W-T10	Teflon (FEP)	FEP	5
M13W-T11	Teflon (FEP)	FEP	5
M13W-T12	Teflon (FEP)	FEP	5
M13W-T13	Teflon (FEP) - AO textured on back surface	FEP-AO	5
M13W-T14	Teflon (FEP) - AO textured on back surface	FEP-AO	5
M13W-T15	Teflon (FEP) - AO textured on back surface	FEP-AO	5
M13W-T16	Teflon (FEP) - AO textured and C coated on the back surface	FEP/C	5
M13W-T17	Teflon (FEP) - AO textured and C coated on the back surface	FEP/C	5
M13W-T18	Teflon (FEP) - AO textured and C coated on the back surface	FEP/C	5
M13W-T19	VDA/CP1 solar sail material (Kapton grip support on front)	VDA/CP1	0.2
M13W-T20	VDA/CP1 solar sail material (Kapton grip support on front)	VDA/CP1	0.2
M13W-T21	VDA/CP1 solar sail material (Kapton grip support on front)	VDA/CP1	0.2

Table 18. MISSE-13 PCE-4 Wake (Swing-Side) Tensile Samples, Cont.

MISSE-13 ID	Material	Abbreviation	Thickness (mils)
M13W-T22	VDA/CP1-PTFE composite solar sail material*	VDA/CP1-PTFE	0.3
M13W-T23	VDA/CP1-PTFE composite solar sail material*	VDA/CP1-PTFE	0.3
M13W-T24	VDA/CP1-PTFE composite solar sail material*	VDA/CP1-PTFE	0.3

*Kapton grip support on back
All tensile samples are cut parallel to roll lines
All FEP samples were heated at 60 °C for 24 hours under vacuum

Table 19. MISSE-13 PCE-4 Wake (Swing-Side) Stressed Samples.

MISSE-13 ID	Material	Abbreviation	Thickness (mils)
M13W-SR1	VDA/CP1 solar sail material	VDA/CP1	0.2
M13W-SR2	VDA/CP1-PTFE composite solar sail material	VDA/CP1-PTFE	0.3

Table 20. MISSE-13 PCE-4 Zenith (Mount-Side) Samples.

MISSE-13 ID	Material	Abbreviation	Thickness (mils)	C, S or R
M13Z-C1	Polyimide (PMDA) (Kapton H)	Kapton H	5	C
M13Z-C2	James Webb Space Telescope (JWST) Sun shield (Si/2 mil Kapton E/VDA)	JWST	2	C
M13Z-C3	JWST Sun shield material under folding stress	JWST FS	2	C
M13Z-C4	Aluminized-Teflon FEP	FEP/Al	5	C
M13Z-C5	Aluminized-Teflon FEP under folding stress	FEP/Al FS	5	C
M13Z-C6	VDA/CP1-PTFE composite solar sail material under folding stress	VDA/CP1-PTFE FS	0.3	C
M13Z-C7	S0383-70 silicone (1"dia. seal)	S0383-70	210	C
M13Z-C8	S0383-70 silicone with 1.5% titanium dioxide additive (1" dia. seal)	TiO_2/S0383-70	210	C
M13Z-C9	S0383-70 silicone coated with Braycote 601EF grease plus ZnO (BZ) sunscreen (1" dia. seal)	BZ/S0383-70	210	C
M13Z-C10	S0383-70 silicone coated Dow Corning 7 + ZnO (DCZ) sunscreen (1"dia. seal)	DCZ/S0383-70	210	C
M13Z-C11	Shape memory composite sample (SMC)	SMC (1a)	47	C
M13Z-C12	Shape memory composite sample (SMC)	SMC (2a)	47	C
M13Z-C13	Cosmic ray shielding (CRS) sample	CRS (1a)	12	C
M13Z-C14	Cosmic ray shielding (CRS) sample	CRS (2a)	12	C
M13Z-C15	BR-127 NC ESD/Al (Solvay BR-127 non-chromated (NC) electric static dissipative (ESD) Modified Phenolic Primer Black on an Al substrate)	BR-127 NC ESD/Al	137	C
M13Z-C16	S0383-70 silicone coated with Braycote 601EF grease (1"dia. seal)	B/S0383-70	210	C

Table 20. MISSE-13 PCE-4 Zenith (Mount-Side) Samples, Cont.

MISSE-13 ID	Material	Abbreviation	Thickness (mils)	C, S or R
M13Z-S1	Photographic AO Fluence Monitor (0.3 mil Kapton H on C coated white Tedlar)	AO Photo Monitor	10	S
M13Z-S2	VDA/CP1-PTFE composite solar sail material (with Kapton HN frame/966 acrylic adhesive on back surface)	VDA/CP1-PTFE	0.3	S
M13Z-S3	Shape Memory Alloys: W12, Z13, Z14 (0.25" x 1" pieces)	SMA	20	S
M13Z-R1	Shape Memory Alloys (12 samples (Z1-Z12): 2 - 0.5" x 1" + 10 - 0.25" x 1" pieces (Binary NiTi, etc.))	SMA	20	R 1" x 4"

Table 21. MISSE-13 PCE-4 Zenith (Mount-Side) SMA Samples.

MISSE-13 ID	Sample ID	Abbreviation	Composition	Condition	Dimensions (inch)
M13Z-R1	M13Z-R1-1	H18-003 aged	NiTi-1Hf	Polished	1/2" x 1" x 0.08"
	M13Z-R1-2	H18-003 aged	NiTi-1Hf	Uunpolished	1/2" x 1" x 0.08"
	M13Z-R1-3	Ext. 99	NiTiPt	Polished	1/4" x 1" x 0.08"
	M13Z-R1-4	Ext. 99	NiTiPt	Unpolished	1/4" x 1" x 0.08"
	M13Z-R1-5	Ext. 119	NiTiPd	Polished	1/4" x 1" x 0.08"
	M13Z-R1-6	Ext. 119	NiTiPd	Unpolished	1/4" x 1" x 0.08"
	M13Z-R1-7	Ext. 198	NiTiAu	Polished	1/4" x 1" x 0.08"
	M13Z-R1-8	Ext. 198	NiTiAu	Unpolished	1/4" x 1" x 0.08"
	M13Z-R1-9	Ext. 201	NiTiAu	Polished	1/4" x 1" x 0.08"
	M13Z-R1-10	Ext. 201	NiTiAu	Unpolished	1/4" x 1" x 0.08"
	M13Z-R1-11	FS#1Z	NiTi-20Zr	Polished	1/4" x 1" x 0.08"
	M13Z-R1-12	FS#1Z	NiTi-20Zr	Unpolished	1/4" x 1" x 0.08"
M13Z-S3	M13Z-R1-13	FS#5	NiTi-20Hf	Polished	1/4" x 1" x 0.08"
	M13Z-R1-14	FS#5	NiTi-20Hf	Unpolished	1/4" x 1" x 0.08"
	M13W-R1-12	FS#1Z	NiTi-20Zr	Unpolished	1/4" x 1" x 0.08"

The PCE-4 also includes two stretched solar sail samples being flown in the wake direction (see Table 18) to assess on-orbit tensile stress on radiation induced degradation of gossamer solar sail materials. The samples are VDA coated 0.2 mil thick CP1 (M13W-SR1) for the Near-Earth Asteroid (NEA) Scout mission and VPA coated 0.3 mil thick CP1-PTFE composite solar sail material being considered for the Solar Cruiser project (M13W-SR2). Figure 37 is a pre-flight photograph of the stretched solar sail samples mounted under tensile loading.

Another set of unique samples flying as part of the PCE-4 is a spacecraft polymer being flown in unstressed and under folding stress configurations. These include sample sets of James Webb Space Telescope (JWST) Sun shield material and aluminized-Teflon FEP being flown in both the wake and zenith directions, and VPA/CP1-PFTE composite material being flown in the wake direction. Figure 38 provides a pre-flight photograph of the aluminized-Teflon FEP sample (M13W-C5) under folding stress with a close-up image showing the bend.

Photographic AO Monitors are being flown as part of the PCE-4 in the wake and zenith directions. Because very little AO is expected in these directions, a modified design was used for the PCE-4 experiment. These samples include a thin vapor deposited layer of carbon and one layer of 0.3 mil thick Kapton H on white Tedlar. Pre-flight photographs of the wake (M13W-S1) and zenith (M13W-S2) flight samples are provided in Figure 39.

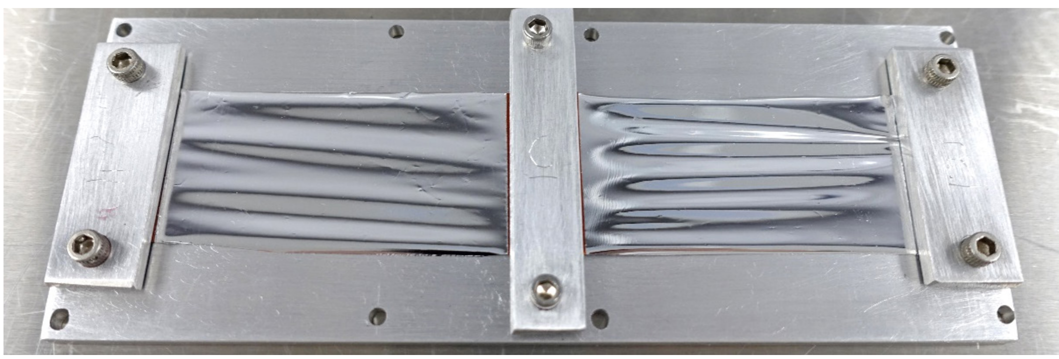


Figure 37. Pre-flight photograph of the stretched soil sail samples mounted on the MISSE-13 W1 MSC 19 SS flight deck. Sample 13W-SR1 is on the right and sample M13W-SR2 is on the left.

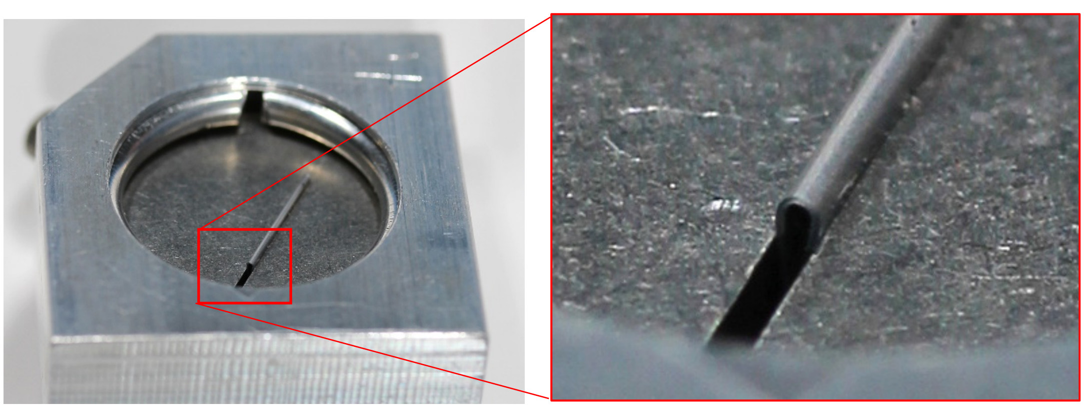
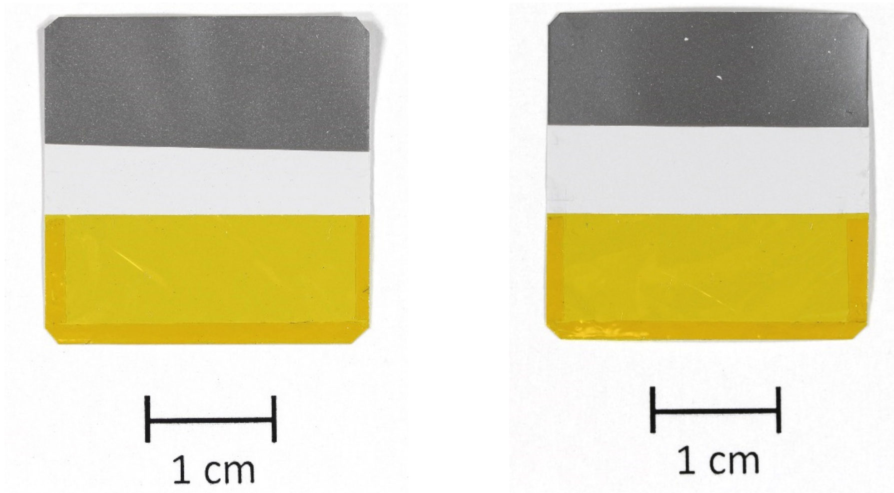
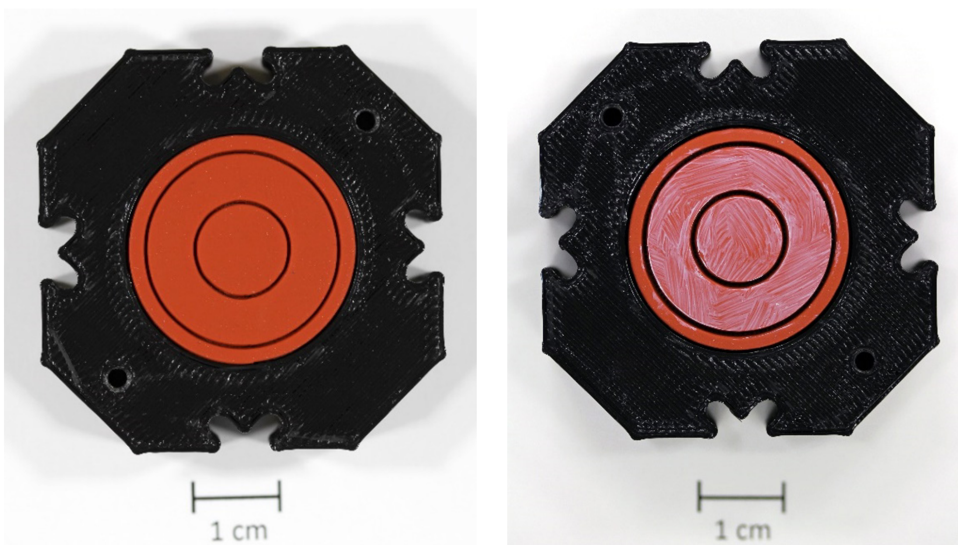


Figure 38. Pre-flight photograph of aluminized-Teflon FEP under folding stress (M13W-C5).



a. b.

Figure 39. Pre-flight photographs of the PCE-4 AO Photographic Monitor flight samples: a). Wake monitor (M13W-S1), and b). Zenith monitor (M13Z-S1).



a. b.

Figure 40. Pre-flight photographs of two of the PCE-4 zenith seal flight samples: a). Uncoated S0383-70 silicone seal (M13Z-C7), and b). S0383-70 silicone coated with Dow Corning 7 + ZnO (DCZ) sunscreen (M13Z-C10).

The PCE-4 also includes baseline, reformulated and protected elastomer material (S0383-70) seal samples for space-rated vacuum seals. Five samples are being flown in the wake direction (M13W-C9 through M13W-C13) and five similar samples are being flown in the zenith direction (MM13Z-C7 through M13Z-C10, plus M13Z-C16). Figure 40 provides pre-flight photographs of the uncoated zenith flight sample (M13Z-C7) and the zenith flight sample with the Dow Corning 7 + ZnO (DCZ) sunscreen coating (M13Z-C10).

Other samples being flown as part of the PCE-4 for space radiation durability assessment include:

- Shape memory alloys for solid-state actuation and structural components (i.e., rovers, bearing alloys). Twelve SMA samples are being flown in the zenith direction in the M13Z-R1 holder and 13 SMA samples are being flown in the wake direction in the M13W-R1 holder.
- Melanin based composites for spacesuit and space structure applications. These melanin samples are the same materials as the MISSE-12 PCE-3 samples being flown in the zenith direction. But, the PCE-4 samples are being flown in the wake direction on MISSE-13. The PCE-4 samples are: 1). Compressed mycelium with thin PLA surface coating and a PVC backing layer (M13W-C19), 2). Fungal melanin powders infused into PLA with PVC backing layer (M13W-C20), 3). Synthetic melanin powders infused into PLA with PVC backing layer (M13W-C21), and 4). PLA with PVC backing layer (control, M13W-C22).
- Shape memory polymer composite (SMC) samples to assess the AO durability, and the functionality of space radiation exposed SMCs for space structures. These SMC samples are in a flat configuration (equilibrium shape). Two SMC samples are being flown in the wake direction (M13W-C14 and M13W-C15) and two SMC samples are being flown in the zenith direction (M13Z-C11 and M13Z-C12).
- Cosmic ray shielding (CRS) samples for radiation durability assessment of new shielding materials for spacesuits and spacecraft. These samples are comprised of a single-layer sheet of LDPE functionalized with a mixture of FeO and BN powder. Two CRS samples are being flown in the wake direction (M13W-C16 and M13W-C17) and two CRS samples are being flown in the zenith direction (M13Z-C13 and M13Z-C14).
- Protective and optical coatings, such as Solvay BR 127 NC ESD static dissipative black primer used for a wide range of space applications. Solvay BR 127 NC ESD samples are being flown in the wake (M13W-C18) and zenith (M13Z-C15) directions.
- Polyphenylsulfone (PPSU) with BN additives (M13W-C24), and without BN additives (M13W-C23) to assess the effect of BN for increased radiation durability in PPSU for 3D-printable composites. These PPSU samples are being flown in the wake direction.

A pre-flight photograph of the PCE-4 samples loaded into the zenith (Z2 MSC 5 MS), wake mount side (W1 MSC 19 MS) and wake swing side (W1 MSC 19 SS) decks is shown in Figure 41. The PCE-4 samples in the wake MS deck are outlined in red. The larger white and metallized square samples in MSC 19 MS is not part of the PCE-4. Figure 42 provides close-up photographs of the PCE-4 samples. For the PCE-4 all “flight” samples were flown, no “back-up” samples were integrated in the flight hardware.

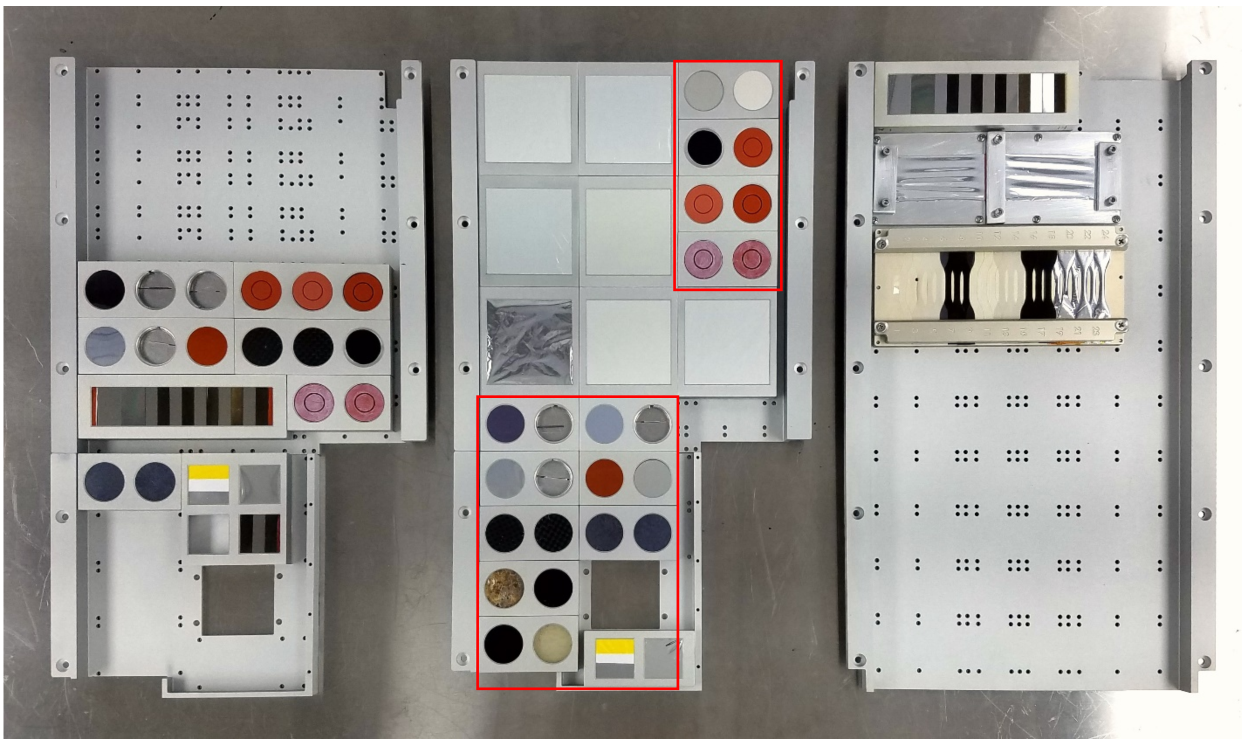


Figure 41. Pre-flight photograph of the MISSE-13 PCE-4 samples loaded into the MSC flight decks, from left to right: Z2 MSC 19 MS (zenith), W1 MSC 19 MS (wake) and W1 MSC 19 SS (wake). The PCE-4 samples in the wake MS deck are outlined in red.

a. b.

c. d.

Figure 42. Close-up photographs of the MISSE-13 PCE-4 samples loaded into the MSC flight decks: a). Lower section of samples in W1 MSC 19 MS (wake), b). Upper section of samples in W1 MSC 19 MS (wake), c). Samples in W1 MSC 19 SS (wake), and c). Samples in Z2 MSC 5 MS (zenith).

PCE-4 Mission Overview

The MISSE-13 PCE-4 experiment was launched aboard SpaceX-20 on March 6, 2020 and the MSCs were installed in the MISSE-FF on March 18, 2020. The MISSE-13 wake (W1 MSC 5) and zenith (Z2 MSC 19) carriers were deployed on March 20, 2020. The wake MSC 5 was robotically closed for the final time on September 2, 2020 and the zenith MSC 19 was closed for the final time on September 3, 2020. These MSCs had constant space exposure from April 28, 2020 until September 2-3, 2020. MISSE-13 Z2 was retrieved on November 26, 2020 and MISSE-13 W1 was retrieved on November 27, 2020. The MSCs were re-pressurized on December 1, 2020 and returned as part of the SpaceX-21 mission on January 13, 2021.

MISSE-13 PCE-4 wake MSC 5 (W1) was exposed to the vacuum of space for 0.72 years (March 12, 2020 to December 1, 2020). It was on the MISSE-FF facility for 0.70 years (March 18, 2020 to November 27, 2020) and had a deployed mission duration of 0.46 years (March 20, 2020 to September 2, 2020). During the deployed duration, the PCE-4 wake samples had a total of 0.44 years of direct space exposure.

MISSE-13 PCE-4 zenith MSC 19 (Z2) was exposed to the vacuum of space for 0.72 years (March 12, 2020 to December 1, 2020). It was on the MISSE-FF facility for 0.70 years (March 18, 2020 to November 26, 2020) and had a deployed mission duration of 0.46 years (March 20, 2020 to September 3, 2020). During the deployed duration, the PCE-4 zenith samples had a total of 0.46 years of direct space exposure.

PCE-4 Sample Collaboration

The MISSE-13 PCE-4 is a collaborative effort with a number of researchers from various organizations. The sample collaborators are listed in Table 22 along with the flight materials and number of flight samples.

Table 22. MISSE-13 PCE-4 Sample Collaborators.

Collaborator(s)	Organization	Material	Abbreviation	Number of Samples
Loredana Santo Fabrizio Quadrini	University of Rome Tor Vergata	Cosmic ray shielding (CRS) sample (multilayer composite made with low density polyethylene (LDPE) film)	CRS	4
		Shape memory composite sample (SMC) (carbon fiber epoxy composite layers and epoxy resin (3M Scotchkote 206 N))	SMC	4
John Fleming Ryan Cheng	Ball Aerospace	BR-127 NC ESD/Al (Solvay BR-127 NC ESD Modified Phenolic Primer BLACK SDS on an Al substrate)	BR-127 NC ESD/Al	2
Othmane Benafan Santo Padula II	GRC LMA	Shape Memory Alloys (NiTi-1Hf, NiTiPt, NiTiPd, NiTiAu, NiTi-20Zr, NiTi-20Hf)	SMA	13
		Shape Memory Alloys (NiTi-1Hf, NiTiPt, NiTiPd, NiTiAu, NiTi-20Zr)	SMA	12
		Shape Memory Alloys (NiTi-20Zr, NiTi-20Hf)	SMA	3

Table 22. MISSE-13 PCE-4 Sample Collaborators, Cont.

Collaborator(s)	Organization	Material	Abbreviation	Number of Samples
Joe Matas and Les Johnson (GSFC) Brandon Framer (NeXolve) Sharon Miller (LME)	NASA GSFC NeXolve GRC LME	VDA/CP1-PTFE composite solar sail material (with Kapton HN frame adhered with 3M 966 acrylic adhesive on back surface)	VDA/CP1-PTFE	2
		VDA/CP1-PTFE composite solar sail material under folding stress	VDA/CP1-PTFE FS	2
		VDA/CP1 solar sail material (0.2 mil with Kapton HN frame on front surface)	VDA/CP1	1
		VDA/CP1 NEAScout solar sail material (0.1 mil with Kapton HN frame on front surface)	VDA/CP1	1
		VDA/CP1 solar sail material under tensile loading	VDA/CP1 (TL)	1
		VDA/CP1-PTFE composite solar sail material under tensile loading	VDA/CP1-PTFE (TL)	1
		VDA/CP1 solar sail material (Kapton grip support on front) - tensile sample	VDA/CP1 (TS)	3
		VDA/CP1-PTFE composite solar sail material (Kapton grip support on back) - tensile sample	VDA/CP1-PTFE (TS)	3
Theresa Benyo[1] Andrew Trunek[2] Radamés Cordero[3] Arturo Casadevall[3] Quigly Dragotakes[3] Ali Dhinojwala[4] Saranshu Singla[4] Chris Maurer[5]	[1]GRC LMN [2] GRC LCS [3]Johns Hopkins University [4]Univ. of Akron [5]redhouse studio	Compressed mycelium with thin polylactic acid (PLA) surface coating and a polyvinyl chloride (PVC) backing layer	PLA/CMy/PVC	1
		Fungal melanin powders infused into PLA with PVC backing layer	PLA-FunMel/PVC	1
		Synthetic melanin powders infused into PLA with PVC backing layer	PLA-SynMel/PVC	1
		PLA with PVC backing layer	PLA/PVC	1
Tiffany Williams	GRC LMN	Polyphenylsulfone (PPSU), Radel 5500	PPSU	1
		Polyphenylsulfone (PPSU), Radel 5500, with boron nitride (BN) platelets	PPSU-BN	1
Pat Dunlap (LMT) Janice Mather (UA)	GRC LMT GRC Univ. Akron/LMT	S0383-70 silicone	S0383-70	2
		S0383-70 silicone with 1.5% titanium dioxide additive	TiO_2-S0383-70	2
		S0383-70 silicone coated with Braycote 601EF grease	B/S0383-70	2
Henry de Groh	GRC LMA	S0383-70 silicone coated with Braycote 601EF grease plus ZnO (BZ) sunscreen	BZ/S0383-70	2
		S0383-70 silicone coated Dow Corning 7 + ZnO (DCZ) sunscreen	DCZ/S0383-70	2

Summary

This paper provides a detailed overview of Glenn's PCE 1-4 experiments along with a complete list of the 365 flight samples, the PCE 1-4 sample collaborators and detailed mission exposure information. The results from these NASA Glenn flight experiments will provide spacecraft designers with LEO AO and radiation performance and durability data, which can be used to develop durable spacecraft components.

NASA Glenn Research Center's Polymers and Composites Experiment 1-4 (PCE 1-4) have been exposed to the space environment on the ISS's external MISSE-Flight Facility (MISSE-FF). The PCE-1 was flown as part of the MISSE-9 mission, the PCE-2 was flown as part of the MISSE-10 mission, the PCE-3 was flown as part of the MISSE-12 mission and the PCE-4 was flown as part of the MISSE-13 mission. The primary objective of these experiments is to determine the AO and radiation durability of spacecraft polymers and composites. In addition, each experiment has a wide variety of spacecraft materials and hence they each have numerous additional sample objectives.

Each of the PCE 1-4 are designed to examine the consequences of AO interactions. The AO E_y of susceptible materials can vary by orders of magnitude causing large variations in spacecraft component structural durability. In addition, changes in surface morphology caused by directed or sweeping ram AO erosion can result in increased solar heating due to increases in solar absorptance. Thermal emittance can also decrease due to AO thickness loss, thus can contribute to increases in solar heating. Therefore, numerous samples are being flown for AO E_y and optical and thermal property characterization. In each experiment, several materials are flown in both ram and zenith flight orientations to determine the effect of varying solar to AO ratios on E_y. Certain common spacecraft materials, such as Teflon FEP, white Tedlar, Upilex-S, CP1 and PET, are included on multiple MISSE missions so erosion dependence on environment exposure (i.e., mission AO fluence, solar exposure, and temperature) can be determined. The PCE-1 includes epoxy composite samples with varying ZnO levels to determine the effect of inorganic filler level on AO durability. And, a variety of samples, such as AO Scattering Chambers, samples of varying exposure diameters, and coated samples with scratched coatings, are being flown to characterize AO scattering and AO undercutting processes.

All four PCE experiments include samples to provide better insight into radiation durability of polymers and composites. The MISSE-9 PCE-1 includes 38 Teflon FEP tensile samples flown in the wake direction and 24 Teflon FEP samples flown in the zenith direction. Teflon samples with the same film thickness and back-surface coatings are being flown in both the wake and zenith directions, so variations in radiation exposure from the different flight directions can provide insight into radiation induced embrittlement of Teflon, a commonly used spacecraft insulation material. Different back-surface coatings are also included. In addition, 24 Teflon FEP tensile samples are being flown in the wake direction as part of the MISSE-13 PCE-4 to provide additional LEO radiation exposure levels. In addition, shape memory alloys, shape memory composites, melanin based composites, stressed and unstressed gossamer sun shield materials, coated and uncoated docking seal samples, and new solar cell cover slides are being flown for space radiation durability and/or shielding assessment.

References

1. Dickerson, R. E., Gray, H. B. and Haight, G. P., *Chemical Principles 3rd Edition*. Menlo Park, CA: Benjamin Cummings Publishing Co. Inc. p. 457, 1979.
2. de Groh, K. K., Banks, B. A. and McCarthy, C. E., *Spacecraft Polymers Atomic Oxygen Durability Handbook*. NASA–HDBK–6024, 2017.
3. National Aeronautics and Space Administration: U.S. Standard Atmosphere, 1976. NASA TM–X–74335, 1976.
4. Gregory, J. C., "Interaction of Hyperthermal Atoms on Surfaces in Orbit: The University of Alabama Experiment," David E. Brinza, Ed., *Proceedings of the NASA Workshop on Atomic Oxygen Effects*, *Nov. 10–11*, *1986*. JPL 87-14, pp. 29–30.
5. Dever, J. A., "Low Earth Orbital Atomic Oxygen and Ultraviolet Radiation Effects on Polymers," NASA TM 103711, February 1991.
6. de Groh, K. K., Banks, B. A., Miller, S. K. R., and Dever, J. A., Degradation of Spacecraft Materials (Chapter 28), Handbook of Environmental Degradation of Materials, Myer Kutz (editor), William Andrew Publishing, pp. 601–645, 2018.
7. O'Neal, R. L., Levine, A. S. and Kiser, C. C., *Photographic Survey of the LDEF Mission*. NASA SP-531. NASA LaRC: Hampton, VA (1996).
8. de Groh, K. K. and Banks, B. A., "Atomic Oxygen Undercutting of Long Duration Exposure Facility Aluminized-Kapton Multilayer Insulation," *Journal of Spacecraft and Rockets*. Vol. 31, No. 4, pp. 656-664 (July-August 1994).
9. de Groh, K. K., Banks, B. A., Dever, J. A., Jaworske, K. J., Miller, S. K., Sechkar, E. A. and Panko, S. R., "NASA Glenn Research Center's Materials International Space Station Experiments (MISSE 1-7)," Proceedings of the International Symposium on "SM/MPAC&SEED Experiment," JAXA-SP-08-015E, March 2009, pp. 91–119; also NASA TM-2008-215482, December 2008.
10. Banks, B. A., de Groh, K. K., and Miller, S. K., "Low Earth Orbital Atomic Oxygen Interactions with Spacecraft Materials," Materials Research Society Symposium Proceedings 2004, NN8.1; also NASA/TM-2004-213400, November 2004.
11. Banks, B. A., Mirtich, M. J., Rutledge, S. K. and Swec, D. M., "Sputtered Coatings for Protection of Spacecraft Polymers," *Thin Solid Films. Vol. 127, pp. 107–114 (1985).*
12. Visentine, J. T., Leger, L. J., Kuminecz, J. F., and Spiker, I. K., "STS-8 Atomic Oxygen Effects Experiment," Paper AIAA-85-0415, AIAA 23rd Aerospace Sciences Meeting. Reno, NV (1985).
13. Koontz, S. L., Leger, L. J., Visentine, J. T., Hunton, D. E., Cross, J. B., and Hakes, C. L., "EOIM-III Mass Spectrometry and Polymer Chemistry: STS 46, July-August 1992." *Journal of Spacecraft and Rockets, Vol. 32*, *No. 3 (1995) 483–495*.
14. Silverman, E. M., *Space Environmental Effects on Spacecraft: LEO Materials Selection Guide.* NASA CR-4661, Part 1, August 1995.
15. de Groh, K. K., Banks, B. A., McCarthy, C. E., Rucker, R. N., Roberts L. M., and Berger, L. A., "MISSE 2 PEACE Polymers Atomic Oxygen Erosion Experiment on the International Space Station," *High Performance Polymers* 20 (2008) 388–409.
16. de Groh, K. K., Banks, B. A., Clark, G. W., Hammerstrom, A. M., Youngstrom, E. E. Kaminski, C., Fine E. S., and Marx, L. M., "A Sensitive Technique Using Atomic Force Microscopy to Measure the Low Earth Orbit Atomic Oxygen Erosion of Polymers," NASA TM-2001-211346, December 2001.

17. Banks, B. A., Simmons, J. C., de Groh, K. K., Miller, S. K., "The Effect of Ash and Inorganic Pigment Fill on the Atomic Oxygen Erosion of Polymers and Paints," Proceedings of the '12th International Symposium on Materials in the Space Environment (ISMSE 12)', Noordwijk, The Netherlands (ESA SP-705, February 2013).
18. American Society for Testing and Materials: 2000 ASTM Standard Extraterrestrial Spectrum Reference E–490–00, 2000 (http://rrede.nrel.gov/solar/sectra/AMO).
19. Waters, D. L., de Groh, K. K., Banks, B. A., and Cameron, K. C., "Changes in Optical and Thermal Properties of the MISSE 2 PEACE Polymers and Spacecraft Silicones," Proceedings of the International Symposium on Materials in a Space Environment (ISMSE-11), September 15–18, 2009, Aix-en-Provence, France, 2009.
20. Hansen, P. A., Townsend, J. A., Yoshikawa, Y., Castro, D. J., Triolo, J. J., and Peters, W. C., SAMPE International Symposium, 43, (1998) 570.
21. Townsend, J. A., Hansen, P. A., Dever, J. A., de Groh, K. K., Banks, B. A., Wang, L., and He, C. C., "Hubble Space Telescope Metallized Teflon FEP Thermal Control Materials: On-Orbit Degradation and Post-Retrieval Analysis," *High Performance Polymers 11 (1999) 81–99.*
22. de Groh, K. K, Perry, B. A., Mohammed, J. A., and Banks, B.A., "Analyses of Hubble Space Telescope Aluminized-Teflon Multilayer Insulation Blankets Retrieved After 19 Years of Space Exposure," NASA TM-2015-218476, February 2015.
23. Banks, B. A., de Groh, K. K., Stueber, T. J., Sechkar, E. A., and Hall, R. L., "Ground Laboratory Soft X-Ray Durability Evaluation of Aluminized FEP Teflon Thermal Control Insulation," Proceedings of the 43rd International SAMPE Symposium and Exhibition, Volume 43, 1998, pp. 1523–1533; also NASA TM-1988-207914/REV, July 1998.
24. Townsend, J., Powers, C., Viens, M., Ayres-Treusdell, M. and Munoz, B., "Degradation of Teflon FEP following Charged Particle Radiation and Rapid Thermal Cycling," Proc. Space Simulation Conf., NASA CR-1998-208598, pp. 201–209.
25. de Groh, K. K., Gaier, J. R., Hall, R. L., Espe, M. P., Cato, D. R. Sutter J. K. and Scheiman, D. A., "Insights into the Damage Mechanism of Teflon FEP from the Hubble Space Telescope," *High Performance Polymers 12 (2000) 83–104.*
26. de Groh, K. K., Dever, J. A., Sutter, J. K., Gaier, J. R., Gummow, J. D., Scheiman D. A. and He, C., "Thermal Contributions to the Degradation of Teflon FEP on the Hubble Space Telescope," *High Performance Polymers 13 (2001) S401-S420.*
27. Dever, J. A., de Groh, K. K., Banks, B. A., Townsend, J. A., Barth, J. L., Thomson, S., Gregory, T., and Savage, W., "Environmental Exposure Conditions for Teflon Fluorinated Ethylene Propylene on the Hubble Space Telescope," *High Performance Polymers 12 (2000) 125–139.*
28. Dever, J. A., de Groh, K. K., Messer, R. K., McClendon, M. W., Viens, M., Wang L. L., and Gummow, J. D., "Mechanical Properties of Teflon FEP Retrieved from the Hubble Space Telescope," *High Performance Polymers 13 (2001) S373-S390.*
29. Dever, J. A., de Groh, K. K., Banks B. A. and Townsend, J. A., "Effects of Radiation and Thermal Cycling on Teflon FEP," *High Performance Polymers 11 (1999) 123–140.*
30. Blackwood, J. R., Townsend, J. A., Hansen, P. A., McClendon, M. W., Dever, J. A., de Groh, K. K., Reed, B. B., He, C. C., and Peters, W. C., "Hubble Space Telescope Third Servicing Mission Retrieved Metallized Teflon FEP Analysis," Proceedings of the SAMPE 2001 Conference, Long Beach, CA, May 6–10, 2001, pp. 1797–1810.
31. de Groh, K. K. and Martin, M., "The Effect of Heating on the Degradation of Ground Laboratory and Space Irradiated Teflon FEP," NASA TM-2002-211704, July 2002.

32. de Groh, K. K., Snyder A., and Finlay, K. A., "Degradation of Hubble Space Telescope Aluminized-Teflon Bi-Stem Thermal Shields," *High Performance Polymers 20 (2008) 410–428*.
33. Stambler, A. H., Inoshita, K. E., Roberts, L. M., Barbagallo, C. E., de Groh, K. K., and Banks, B. A., "Ground-Laboratory to In-Space Atomic Oxygen Correlation for the PEACE Polymers," in Protection of Materials and Structures from Space Environment, Ed. J.I. Kleiman, AIP Conference Proceedings 1087, pp. 51–66, 2009; also NASA/TM—2011-126904, 2011.
34. de Groh, K. K., "Materials Spaceflight Experiments," Encyclopedia of Aerospace Engineering, R. Blockley and W. Shyy (eds). John Wiley & Sons Ltd, Chichester, UK, pp. 2535–2552 (2010).
35. B. A. Banks, K. K. de Groh, and S. K. Miller, "MISSE Scattered Atomic Oxygen Characterization Experiment," Proceedings of the 2006 National Space & Missile Materials Symposium in conjunction with the 2006 MISSE Post-Retrieval Conference, Orlando, Florida, June 26–30, 2006; also NASA/TM—2006-214355.
36. Snyder, A., Banks, B. A., and Waters, D. L., "Undercutting Studies of Protected Kapton H Exposed to In-Space and Ground-Based Atomic Oxygen," Proceedings of the 10th International Symposium on Materials in a Space Environment & 8th International Conference on Protection of Materials and Structures in a Space Environment, Collioure, France, June 19–23, 2006; also NASA/TM—2006-214387, August 2006.
37. Dever, J. A., Miller, S. K., Sechkar, E. A., and Wittberg, T. N., "Space Environment Exposure of Polymer Films on the Materials International Space Station Experiment: Results from MISSE 1 and MISSE 2," *High Performance Polymers, 20 (2008) 371–387*.
38. de Groh, K. K., Banks, B. A., "MISSE 2 PEACE Polymers Erosion Morphology Studies," Proceedings of the International Symposium on Materials in a Space Environment (ISMSE-11), September 15–18, 2009, Aix-en-Provence, France, 2009.
39. Banks, B. A., Backus, J. A., Manno, M. V., Waters, D. L., Cameron, K. C. and de Groh, K. K., "Prediction of Atomic Oxygen Erosion Yield for Spacecraft Polymers," *Journal of Spacecraft and Rockets*, *Vol. 48*, *No. 1 (2011) 14–22*.
40. Jaworske, D. A., "Space Durable Solar Selective Cermet Coatings," *Journal of Thermophysics and Heat Transfer, Vol. 25*, *No. 3 (2011) 462–463*.
41. Miller, S. K. R and Dever, J. A., "Materials International Space Station Experiment 5 (MISSE 5) Polymer Film Thermal Control Experiment," *Journal of Spacecraft and Rockets, Vol. 48*, *No. 2 (2011) 240–245*.
42. Gaier, J. R., Folz, A., Baldwin, S. M., Waters, D. L., McCue, T. R., Jaworske, D. A., Clark, G. W., Batman, B. and Bruce, J., "Post-Flight Characterization of Samples for the MISSE-7 Spacesuit Fabric Exposure Experiment of EVA Fabric Samples for MISSE-7," NASA/TM—2012-217651.
43. Guo, A., Yi, G. T., Ashmead, C. C., Mitchell, G. G., de Groh, K. K., and Banks, B.A., "Embrittlement of MISSE 5 Polymers After 13 Months of Space Exposure," Protection of Materials and Structures from the Space Environment (Proceedings of ICPMSE-10J 2011 Okinawa, Japan), Eds. J. Kleiman, M. Tagawa, Y. Kimoto, Astrophysics and Space Science Proceedings 32, Springer, 2012, pp. 389–398; also NASA/TM—2012-217645, September 2012.
44. Hung C-C., de Groh, K. K., and Banks, B. A., "Optical and Scanning Electron Microscopy of the Materials International Space Station Experiment (MISSE) Spacecraft Silicone

Experiment," Protection of Materials and Structures from the Space Environment (Proceedings of ICPMSE-10J 2011 Okinawa, Japan), Eds. J. Kleiman, M. Tagawa, Y. Kimoto, Astrophysics and Space Science Proceedings 32, Springer, 2012, pp. 93–103; also NASA/TM—2012-217678, August 2012.
45. Miller, S. K. R., Banks, B. A., and Tollis, G., "MISSE Results Used for RF Plasma Ground Testing-To-Space-exposure Correlation for Coated Kapton," Proceedings of the 9th International Conference on Protection of Materials and Structures from Space Environment (ICPMSE-9), Toronto, Canada May 20–23, 2008; NASA/TM—2012-217687, August 2012.
46. Waters, D. L., de Groh, K. K., Banks, B. A. and Sechkar, E. A., "Polymer Strain Experiment on MISSE 6," Protection of Materials and Structures from the Space Environment, Protection of Materials and Structures from the Space Environment (Proceedings of ICPMSE-10J 2011 Okinawa, Japan), Eds. J. Kleiman, M. Tagawa, Y. Kimoto, Astrophysics and Space Science Proceedings 32, Springer, 2012, pp. 57–71.
47. de Groh, K. K., Banks, B. B., Mitchell, G. G., Yi, G. T., Guo, A., Ashmead, C. C., Roberts, L. M., McCarthy, C. E., and Sechkar, E. A., "MISSE 6 Stressed Polymers Experiment Atomic Oxygen Erosion Data," Proceedings of the '12th International Symposium on Materials in the Space Environment (ISMSE 12)', Noordwijk, The Netherlands, ESA SP-705, February 2013; also NASA/TM—2013-217847. Prior 19
48. Miller, S. K. R and Sechkar, E. A., "An Examination of Radiation Induced Tensile Failure of Stressed and Unstressed Polymer Films Flown on MISSE 6," Proceedings of the '12th International Symposium on Materials in the Space Environment (ISMSE 12), Noordwijk, The Netherlands, ESA SP-705, February 2013.
49. Imka, E. C., Asmar, O. C., de Groh III, H. C. and Banks, B. A., "Effects of Low Earth Orbit on Docking Seal Materials," NASA/TM—2014-218435, December 2014.
50. Jaworske, D. A. "Low Earth Orbit Environmental Durability of Recently Developed Thermal Control Coatings," NASA/TM—2015-218712, May 2015.
51. de Groh, K. K, Perry, B. A., and Banks, B. A., "Effect of 1.5 Years of Space Exposure on Tensile Properties of Teflon," *Journal of Spacecraft and Rockets*, *Vol. 53*, *No. 6*, *November-December 2016*, *1002–1011.*
52. de Groh, K. K., Banks, B. A., Yi, G. T., Haloua, A., Imka, E. C., Mitchell, G. G., Asmar, O. C., Leneghan, H. A., and Sechkar, E. A., "Erosion Results of the MISSE 7 Polymers Experiment and Zenith Polymers Experiment After 1.5 Years of Space Exposure," NASA/TM—2016-219167, December 2016 (Corrected Copy March 2017).
53. de Groh, K. K., Banks, B. A., Asmar, O. C., Yi, G. T., Mitchell, G. G., Guo, A. and Sechkar, E. A., "Erosion Results of the MISSE 8 Polymers Experiment After 2 Years of Space Exposure on the International Space Station," NASA/TM—2017-219445, February 2017.
54. de Groh, K. K. and Banks, B. A., "The Erosion of Diamond and Highly Oriented Pyrolytic Graphite After 1.5 Years of Space Exposure," NASA/TM—2018-219756 (February 2018).
55. Gaier, J. R. and de Groh, K. K., "Degradation of Spacesuit Fabrics Exposed to Low Earth Orbit," NASA/TM—2018-219923, July 2018.
56. Gaier, J. R. and de Groh, K. K, "Degradation of Intercalated Graphite Epoxy Composites Exposed to Low Earth Orbit," NASA/TM—2018-219928, July 2018.
57. Snow, K. E., de Groh, K. K., Banks, B. A. and Sechkar, E. A., "Bend-Test Results of the MISSE 7 Flexural Stress Effects Experiment After 1.5 Years of Space Exposure," NASA/TM—2019-220035, March 2019.

58. de Groh, K. K. and Banks, B. A., “Atomic Oxygen Erosion Data from the MISSE 2-8 Missions,” NASA/TM—2019-219982, May 2019.
59. 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; also NASA/TM—2020-220475, February 2020.
60. Alpha Space (2018). Alpha Space Test & Research Alliance, LLC homepage. https://www.alphaspace.com/.
61. Banks, B. A., Kneubel, C. A., and de Groh, K. K., “Comparison of the Results of MISSE 6 Atomic Oxygen Erosion Yields of Layered Kapton H Films with Monte Carlo Computational Predictions,” NASA/TM—2014-218411, November 2014.
62. Banks, B. A., de Groh, K. K., Miller, S. K. and D. K. Waters, “Lessons Learned from Atomic Oxygen Interaction with Spacecraft Materials in Low Earth Orbit,” Proceedings of the 9th International Conference “Protection of Materials and Structures from Space Environment,” (May 19–23, 2008 in Toronto, Canada) Ed. J.I. Kleiman, AIP Conference Proceedings 1087, pp. 312–328, 2009; also NASA/TM—2008-215264, July 2008.

Appendix

PCE 1-4 Sample Maps

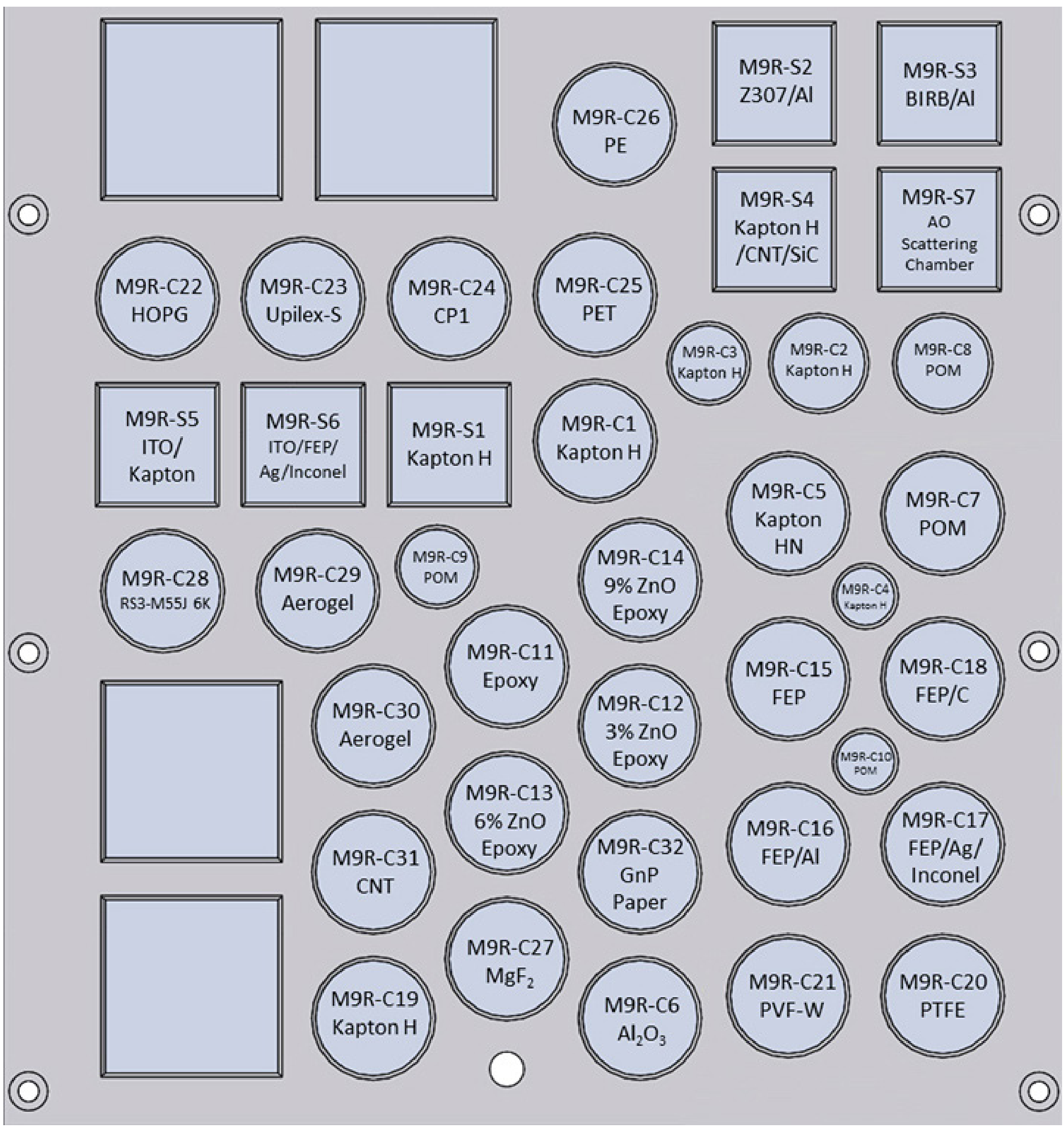
Purpose

The purpose of this Appendix is to provide sample maps for the Polymers and Composites Experiment 1-4 (PCE 1-4) flight samples. These sample maps show the location for each flight sample on the MISSE Sample Carrier (MSC) flight decks. Typically, each figure provides a pre-flight photograph of the flight deck area along with a drawing that shows the sample locations as indicated by the MISSE sample IDs.

Sample Map Figures

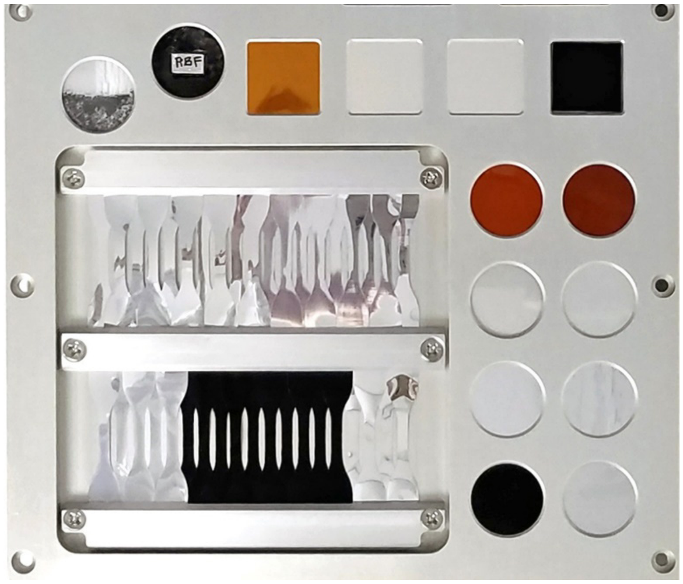
- Figure A-1: MISSE-9 PCE-1 ram samples
- Figure A-2: MISSE-9 PCE-1 wake samples
- Figure A-3: MISSE-9 PCE-1 wake tensile samples
- Figure A-4: MISSE-9 PCE-1 zenith samples
- Figure A-5: MISSE-9 PCE-1 zenith tensile samples
- Figure A-6: MISSE-10 PCE-2 ram samples
- Figure A-7: MISSE-10 PCE-2 zenith samples
- Figure A-8: MISSE-10 PCE-2 nadir samples
- Figure A-9: MISSE-12 PCE-3 ram samples
- Figure A-10: MISSE-12 PCE-3 wake samples
- Figure A-11: MISSE-12 PCE-3 zenith samples
- Figure A-12: MISSE-13 PCE-4 wake mount-side (MS) samples
- Figure A-13: MISSE-13 PCE-4 wake swing-side (SS) samples
- Figure A-14: MISSE-13 PCE-4 wake tensile samples
- Figure A-15: MISSE-13 PCE-4 zenith samples

a.

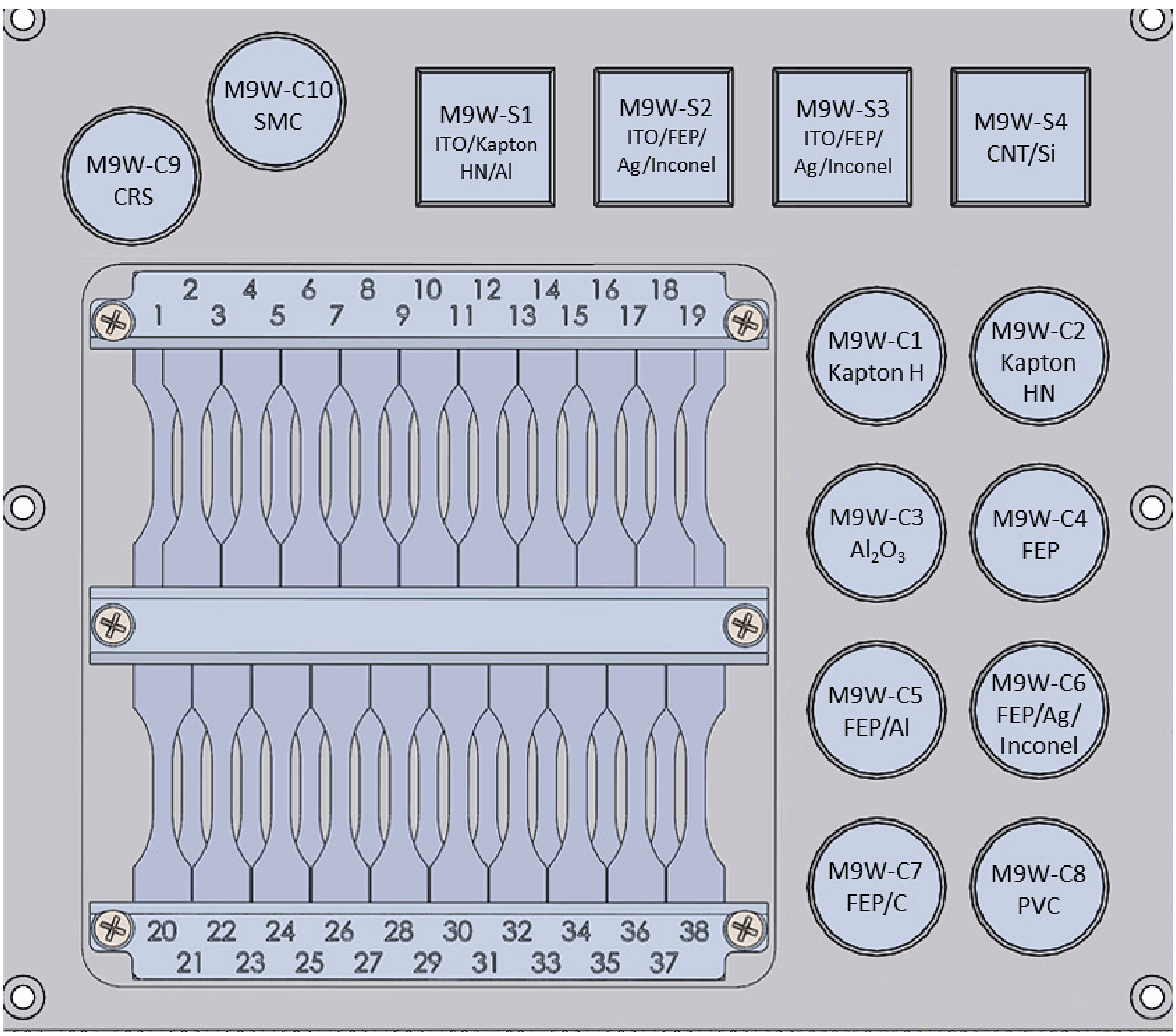


b.

Figure A-1. MISSE-9 PCE-1 ram samples: a). Pre-flight photo of the PCE-1 sample area of the M9 R2 (MSC 3) MS deck, and b). The PCE-1 M9 R2 sample map.



a.



b.

Figure A-2. MISSE-9 PCE-1 wake samples: a). Pre-flight photo of the PCE-1 sample area of the M9 W3 (MSC 8) MS deck (image taken prior to installation of tensile bars with ID numbers, which are visible in on-orbit images), and b). The PCE-1 M9 W3 sample map.

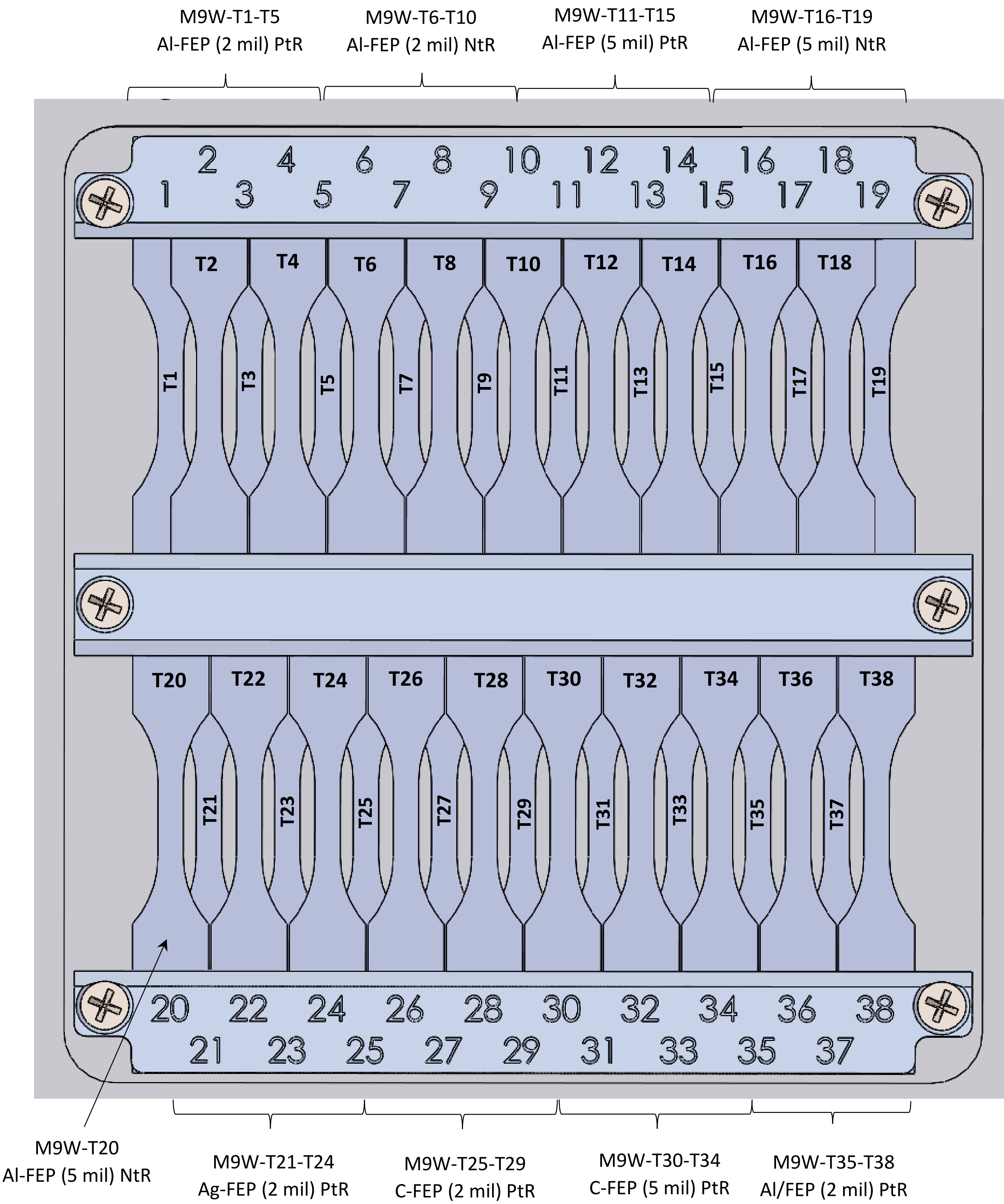
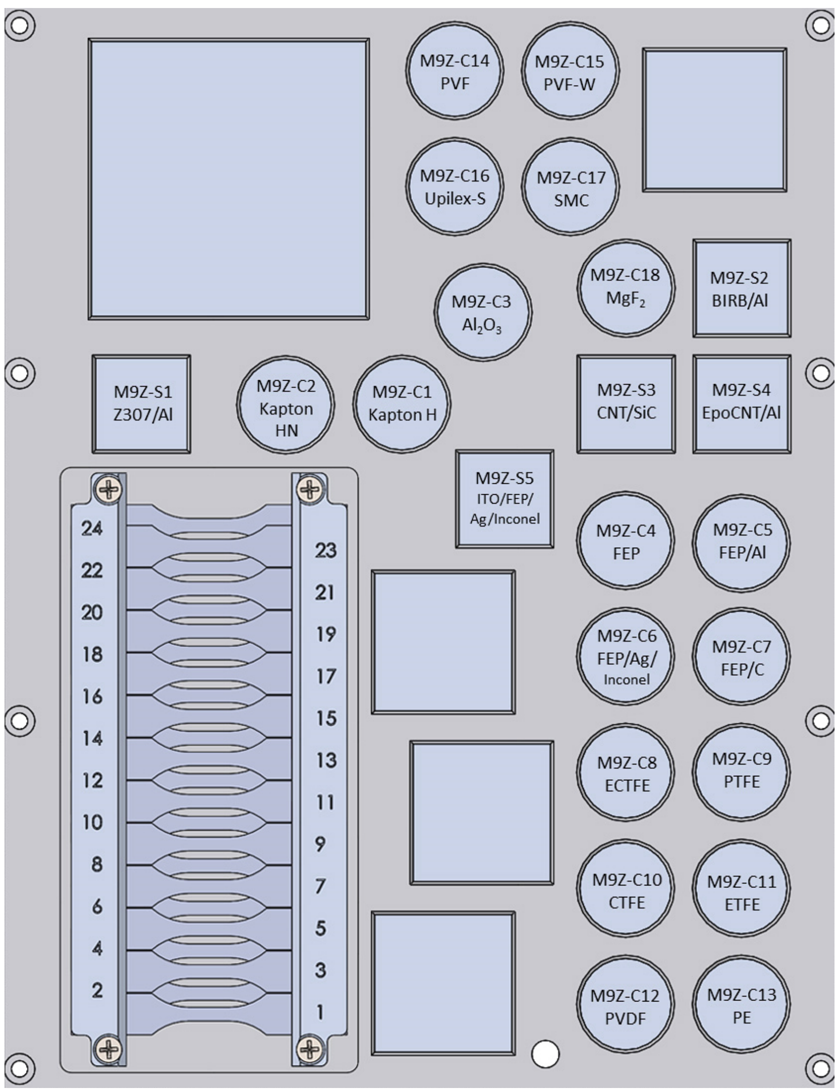


Figure A-3. MISSE-9 PCE-1 wake tensile samples. Samples cut parallel to the roll direction are designated as PtR and samples cut normal to the roll direction are designated as NtR.

a.



b.

Figure A-4. MISSE-9 PCE-1 zenith samples: a). Pre-flight photo of the PCE-1 sample area of the M9 Z3 (MSC 5) MS deck (image taken prior to installation of tensile bars with ID numbers, which are visible in on-orbit images), and b). The PCE-1 M9 Z3 sample map.

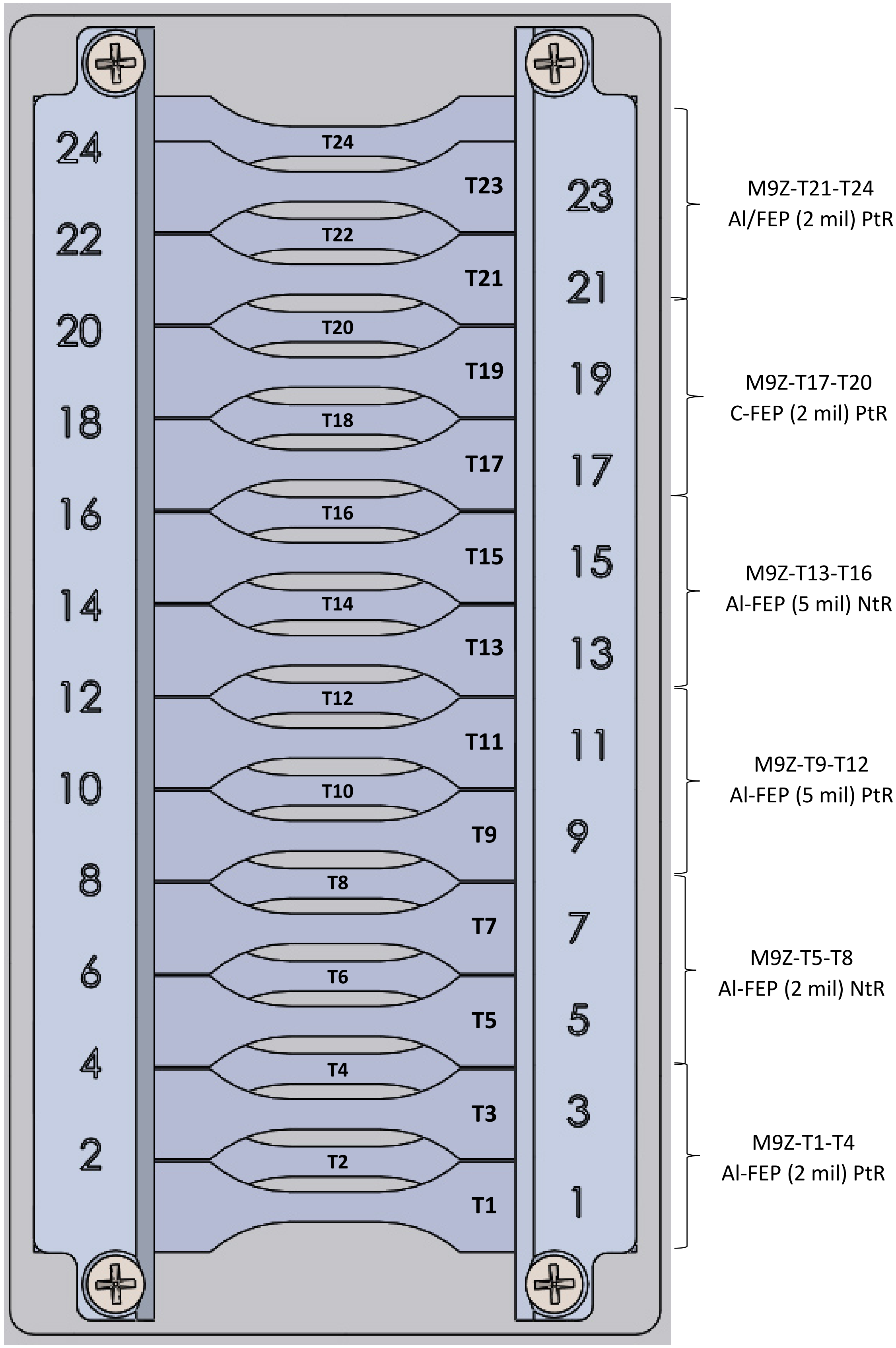
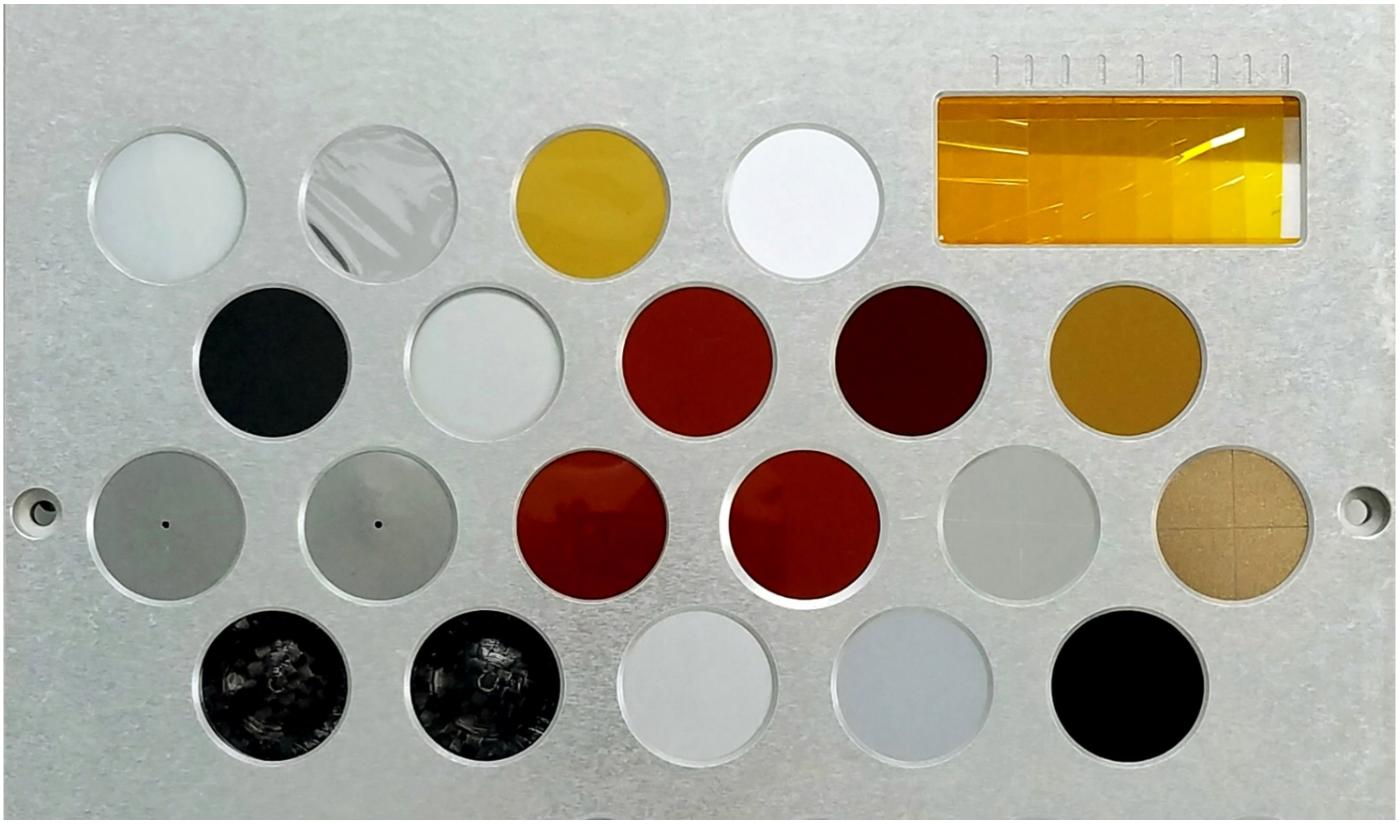
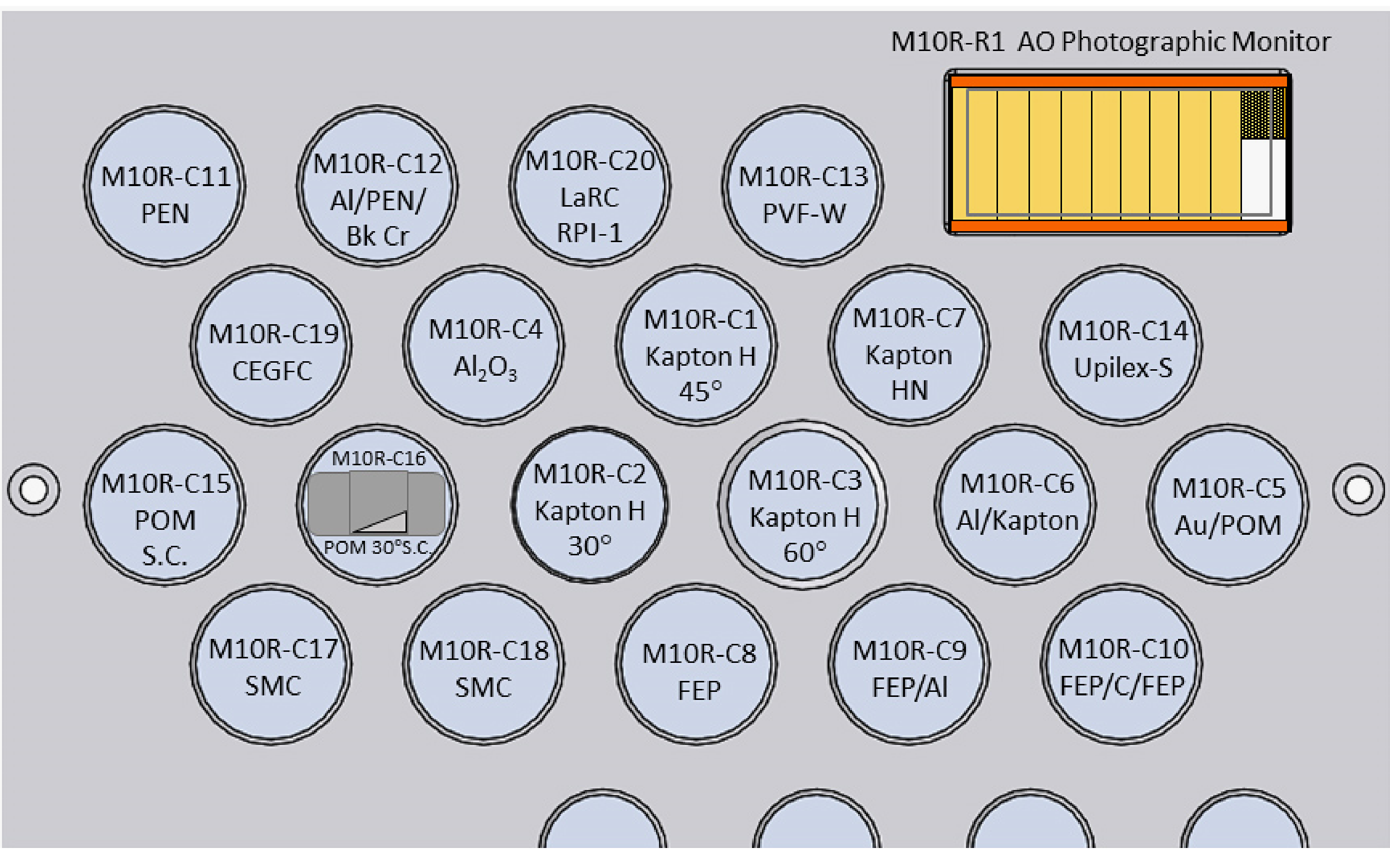


Figure A-5. MISSE-9 PCE-1 zenith tensile samples. Samples cut parallel to the roll direction are designated as PtR and samples cut normal to the roll direction are designated as NtR.

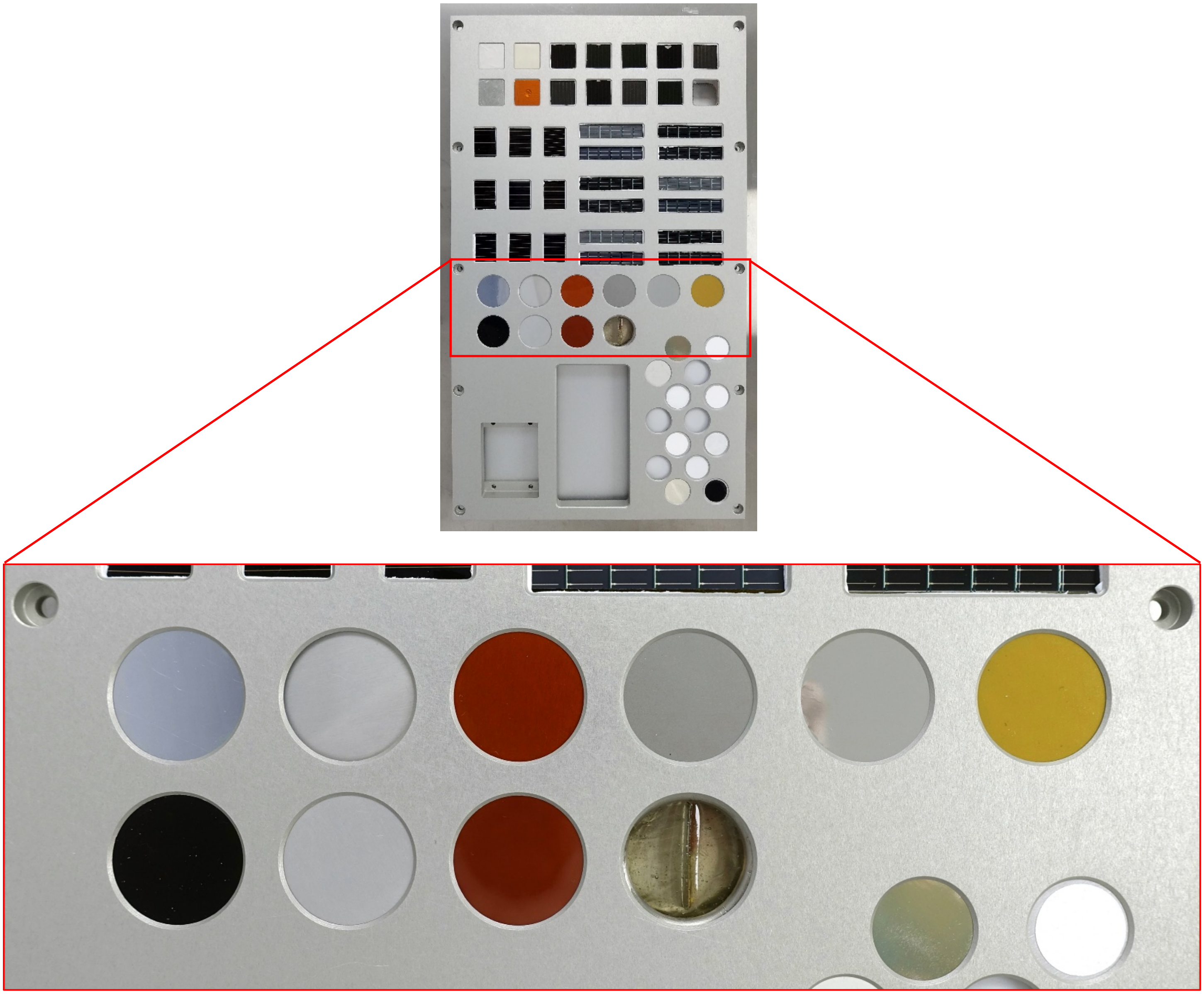


a.

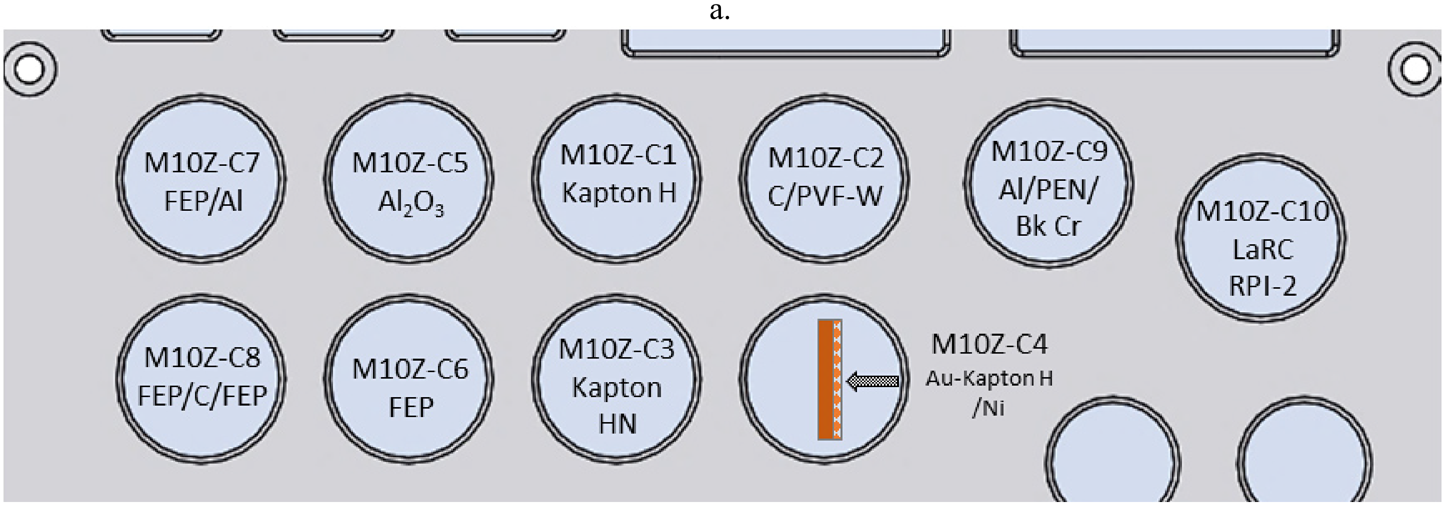


b.

Figure A-6. MISSE-10 PCE-2 ram samples: a). Pre-flight photo of the PCE-2 sample area of the M10 R1 (MSC 11) MS deck, and b). The PCE-2 M10 R1 sample map.

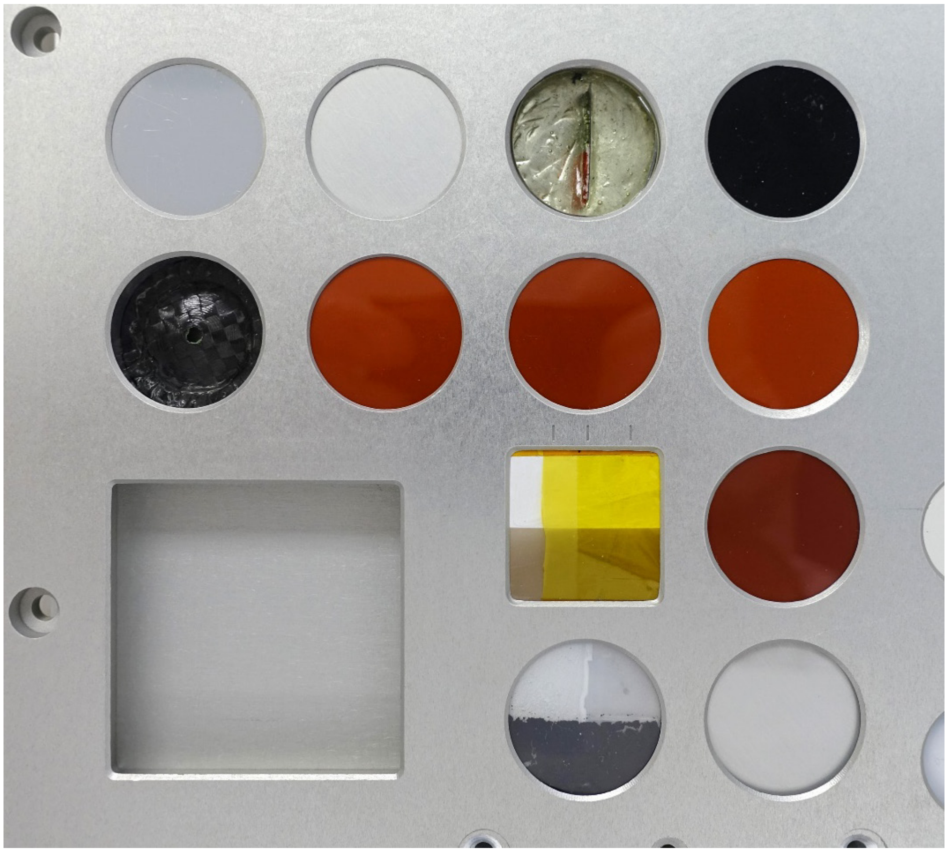


a.

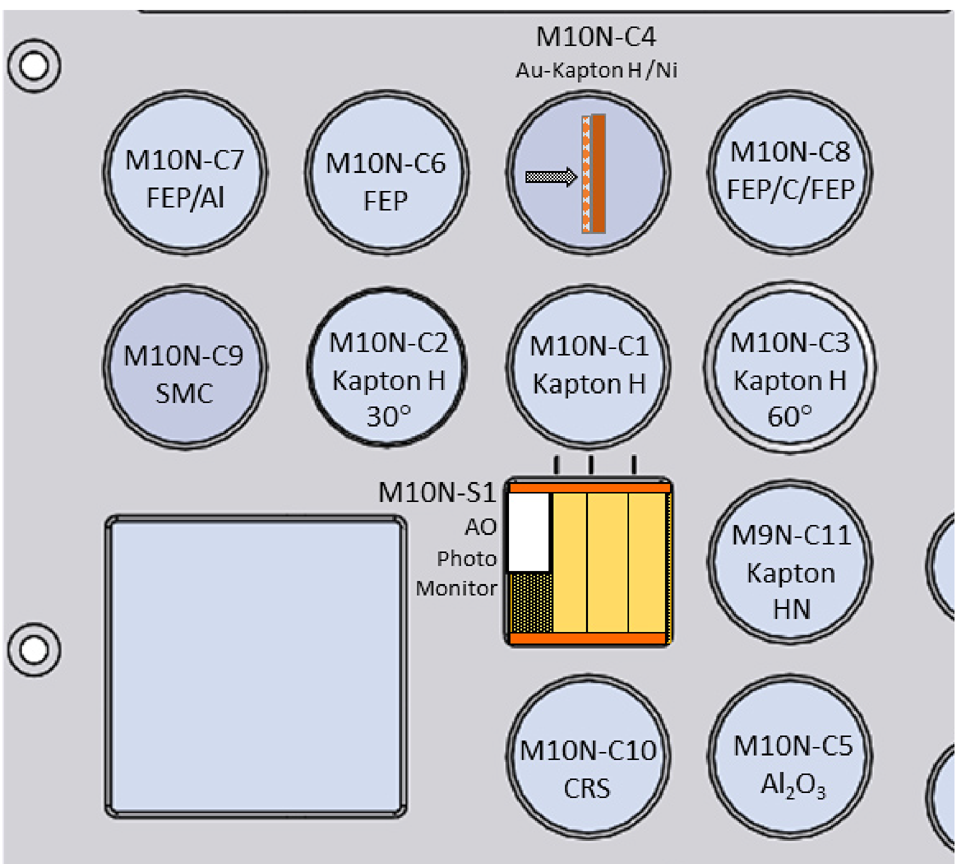


b.

Figure A-7. MISSE-10 PCE-2 zenith samples: a). Pre-flight photo of the PCE-2 sample area of the M10 Z2 (MSC 10) MS deck, and b). The PCE-2 M10 Z2 sample map.



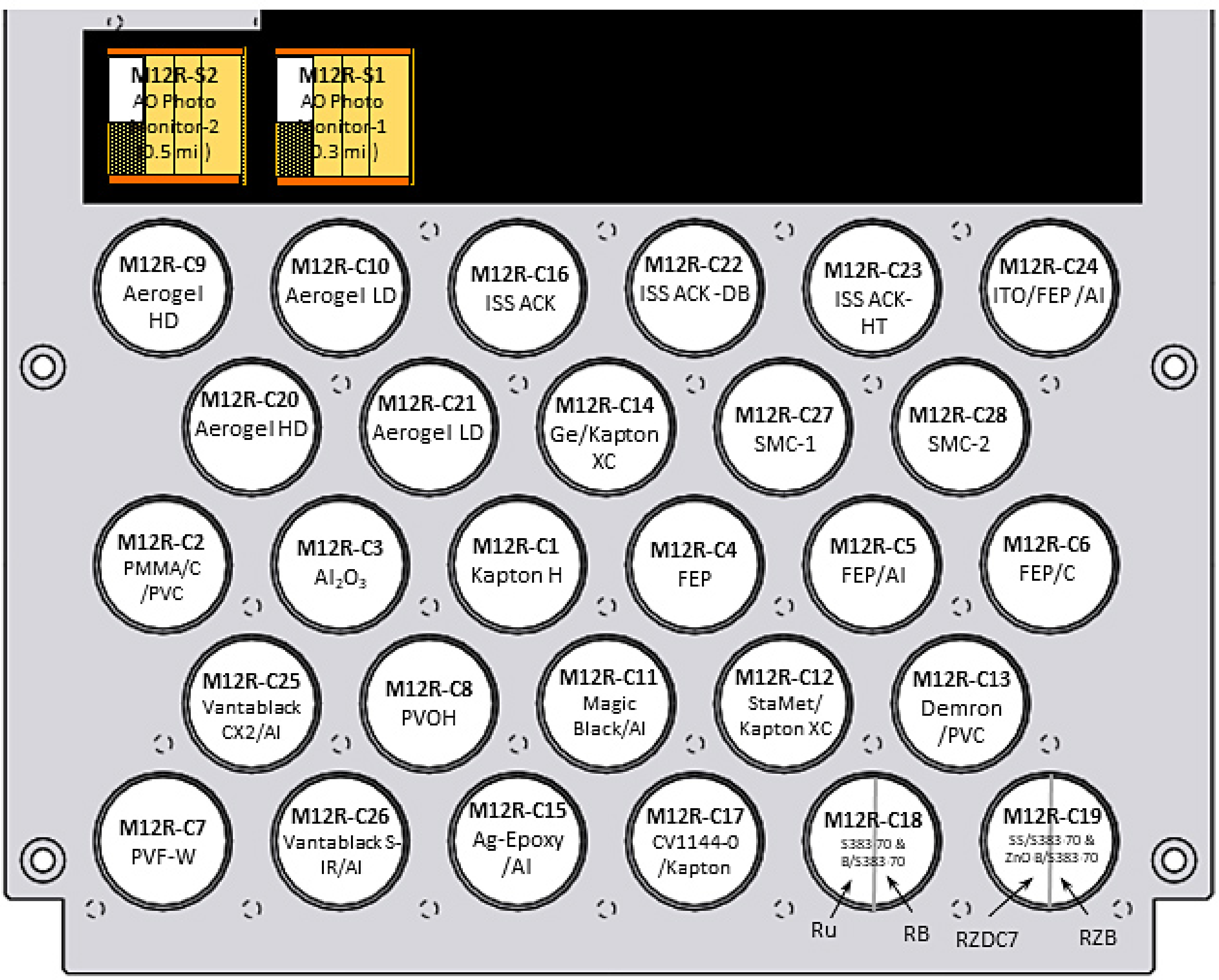
a.



b.

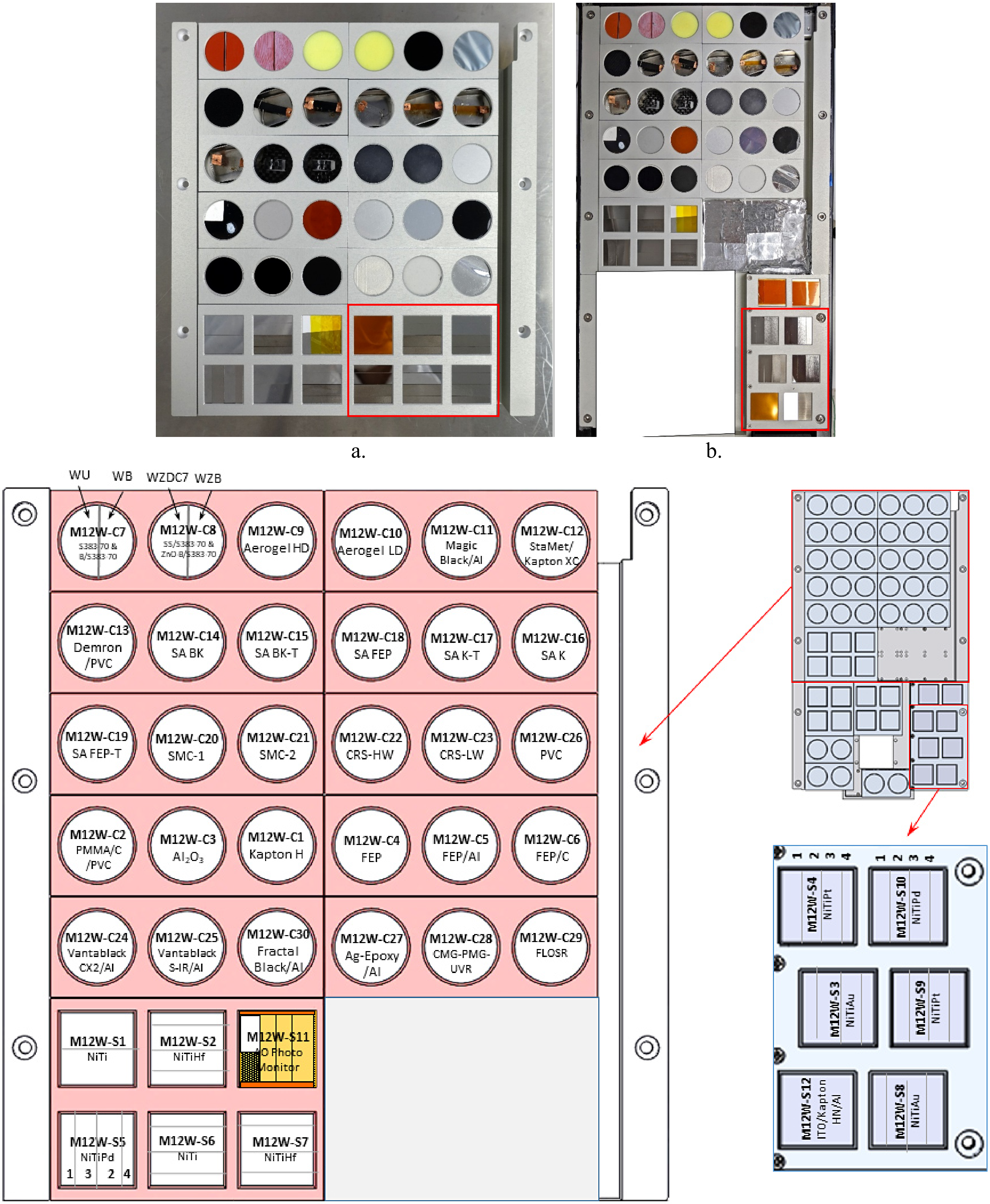
Figure A-8. MISSE-10 PCE-2 nadir samples: a). Pre-flight photo of the PCE-2 sample area of the M10 N3 (MSC 13) MS deck, and b). The PCE-2 M10 N3 sample map.

a.



b.

Figure A-9. MISSE-12 PCE-3 ram samples: a). Pre-flight photo of the PCE-3 sample area of the M12 R2 (MSC 4) SS deck, and b). The PCE-3 M12 R2 sample map.



a. b.

c.

Figure A-10. MISSE-12 PCE-3 wake samples: a). Pre-flight photo of the PCE-3 sample area of the M12 W3 (MSC 6) MS deck prior to re-positioning the bottom right 6 samples (outlined in red), b). Pre-flight photo of the PCE-3 W3 MS deck after re-positioning the 6 samples (Alpha Space photograph with other samples whited-out), and c). The PCE-3 M12 W3 sample map.

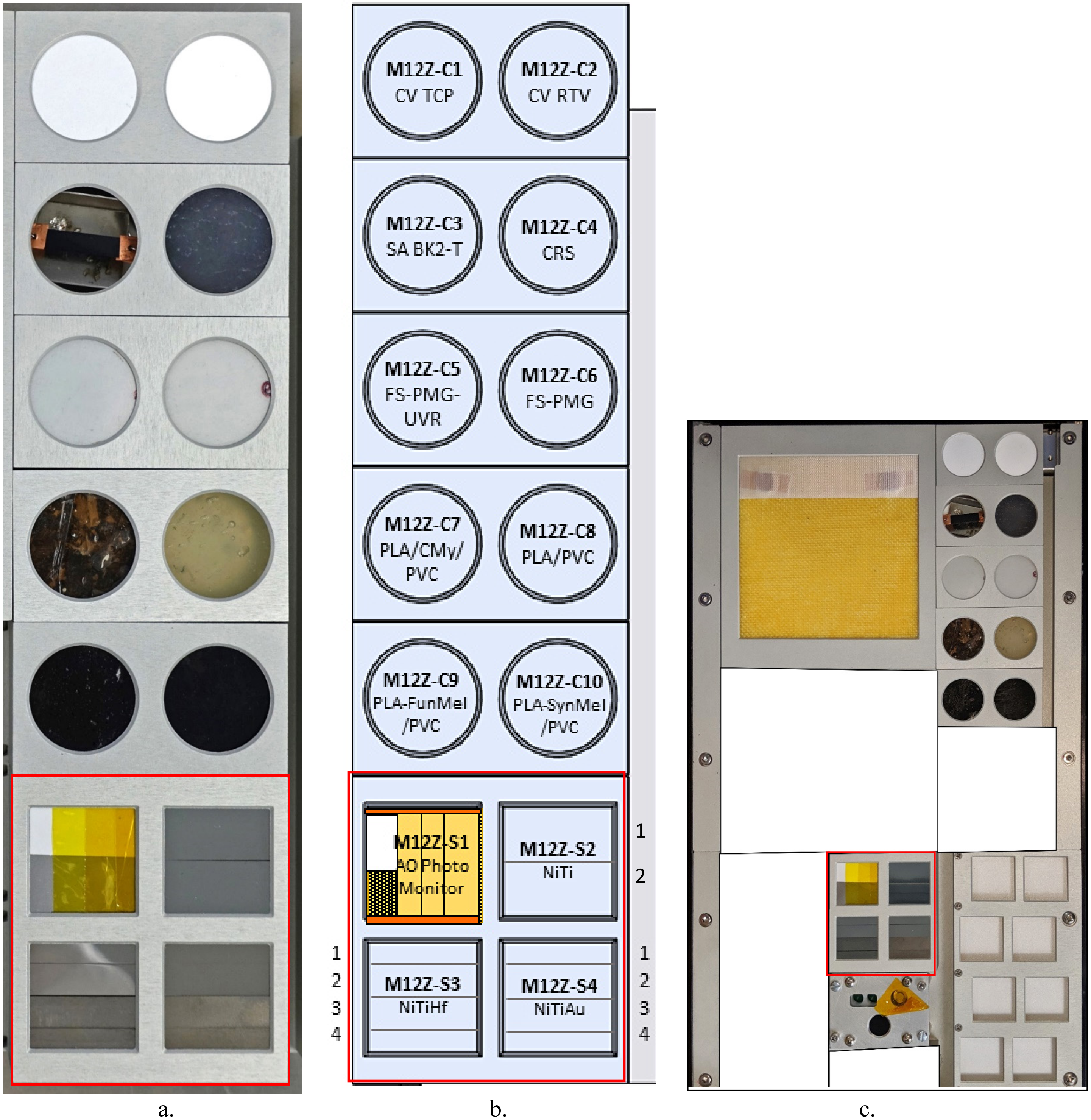
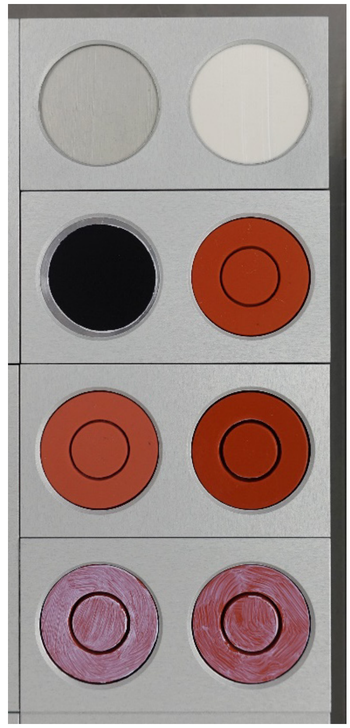
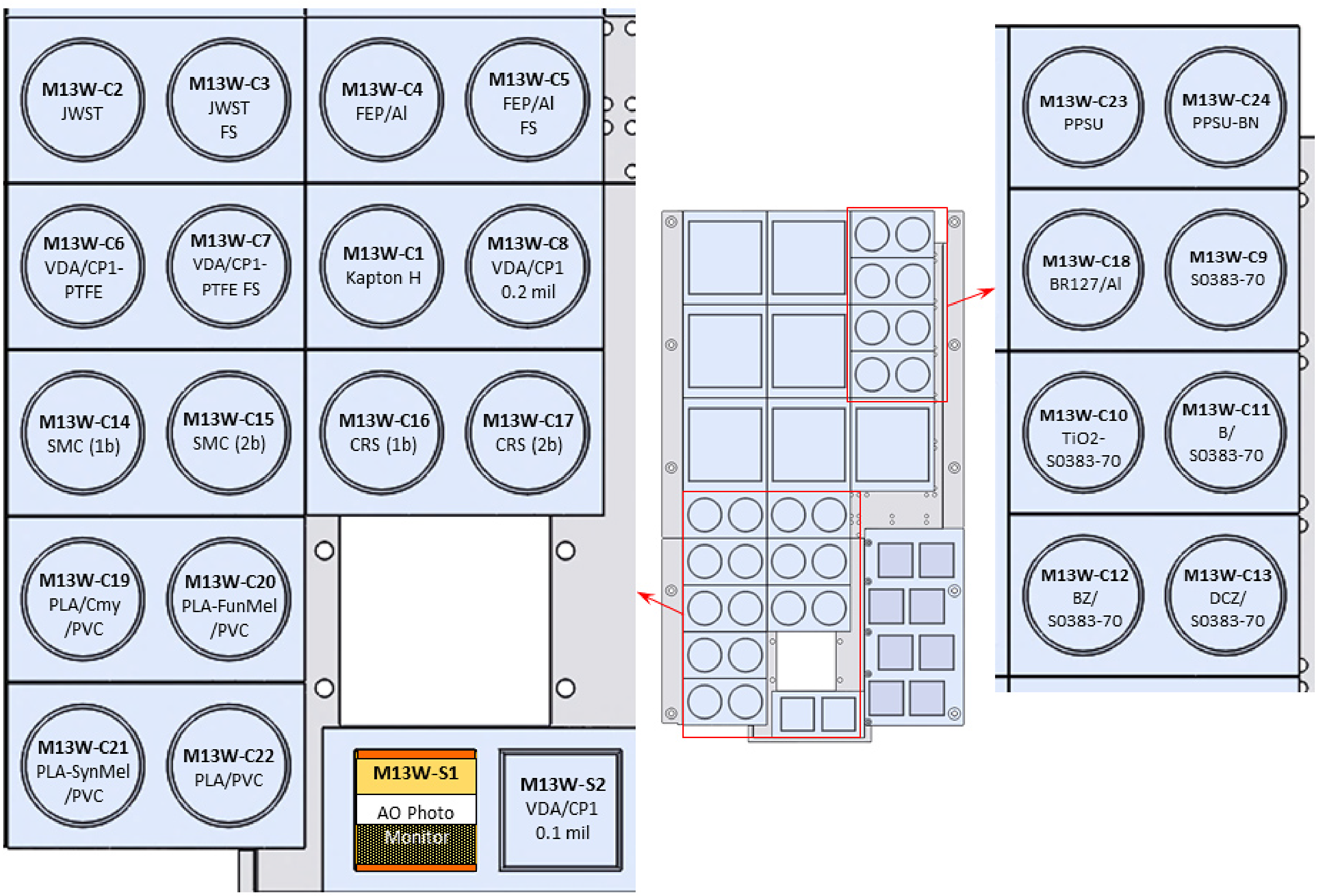


Figure A-11. MISSE-12 PCE-3 zenith samples: a). Pre-flight photo of the PCE-3 sample area of the M12 Z1 (MSC 18) MS deck prior to re-positioning the bottom 4 samples (outlined in red), b). The PCE-3 M12 Z1 sample map, and c). Pre-flight photo of the PCE-3 Z1 MS deck after re-positioning the 4 samples (Alpha Space photograph with other samples whited-out).

a.

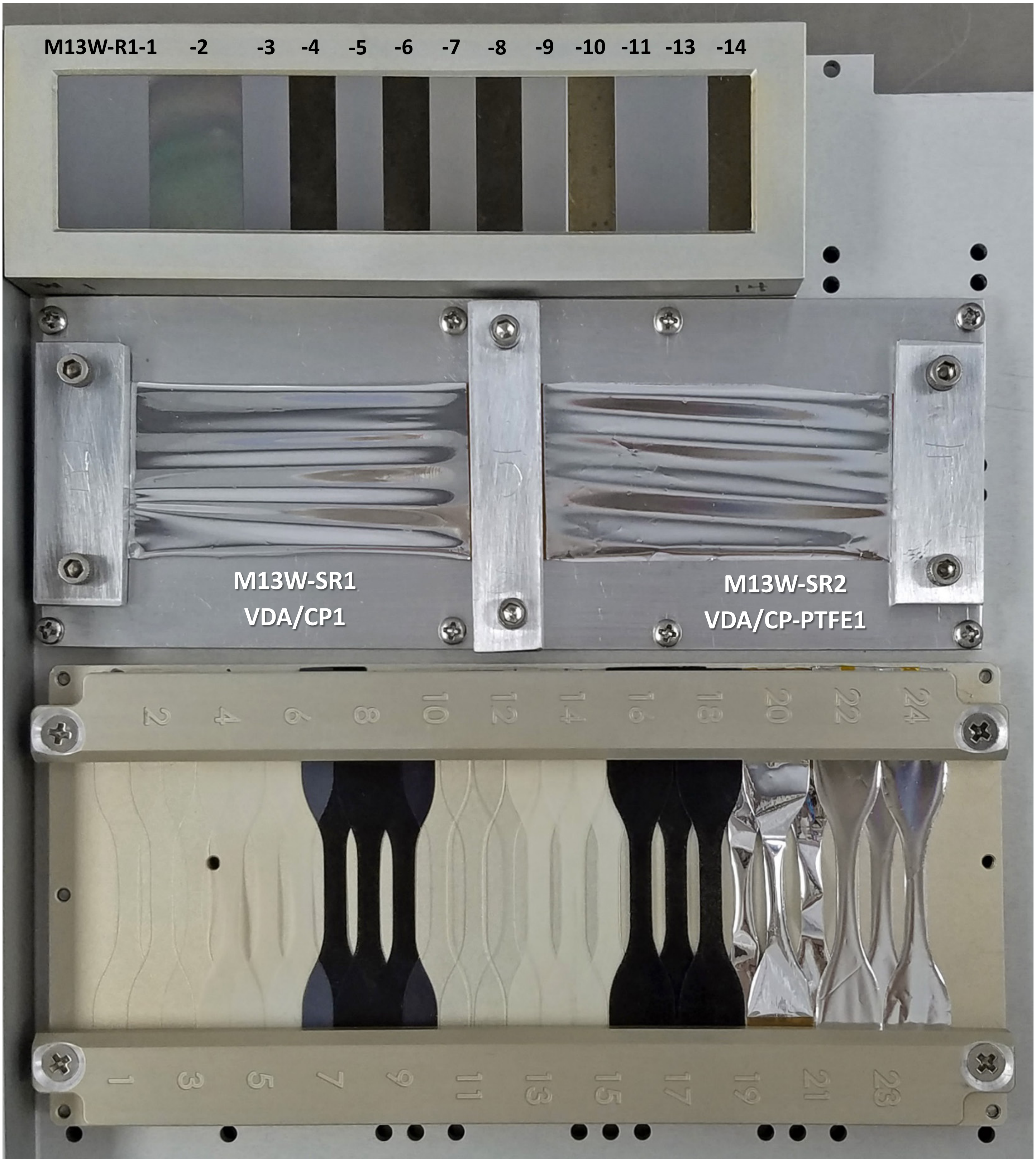


b.



c.

Figure A-12. MISSE-13 PCE-4 wake MS samples: a). Pre-flight photo of the PCE-4 lower sample area of the M13 W1 (MSC 19) MS deck, b). Pre-flight photo of the PCE-4 upper sample area of M13 W1, and c). The PCE-4 M13 W1 sample map.



M13W-T1 M13W-T24

Figure A-13. Pre-fight photograph of the MISSE-13 PCE-4 wake samples on the M13 W1 (MSC 19) SS deck with samples IDs. There is no M13W-R1-12 sample.

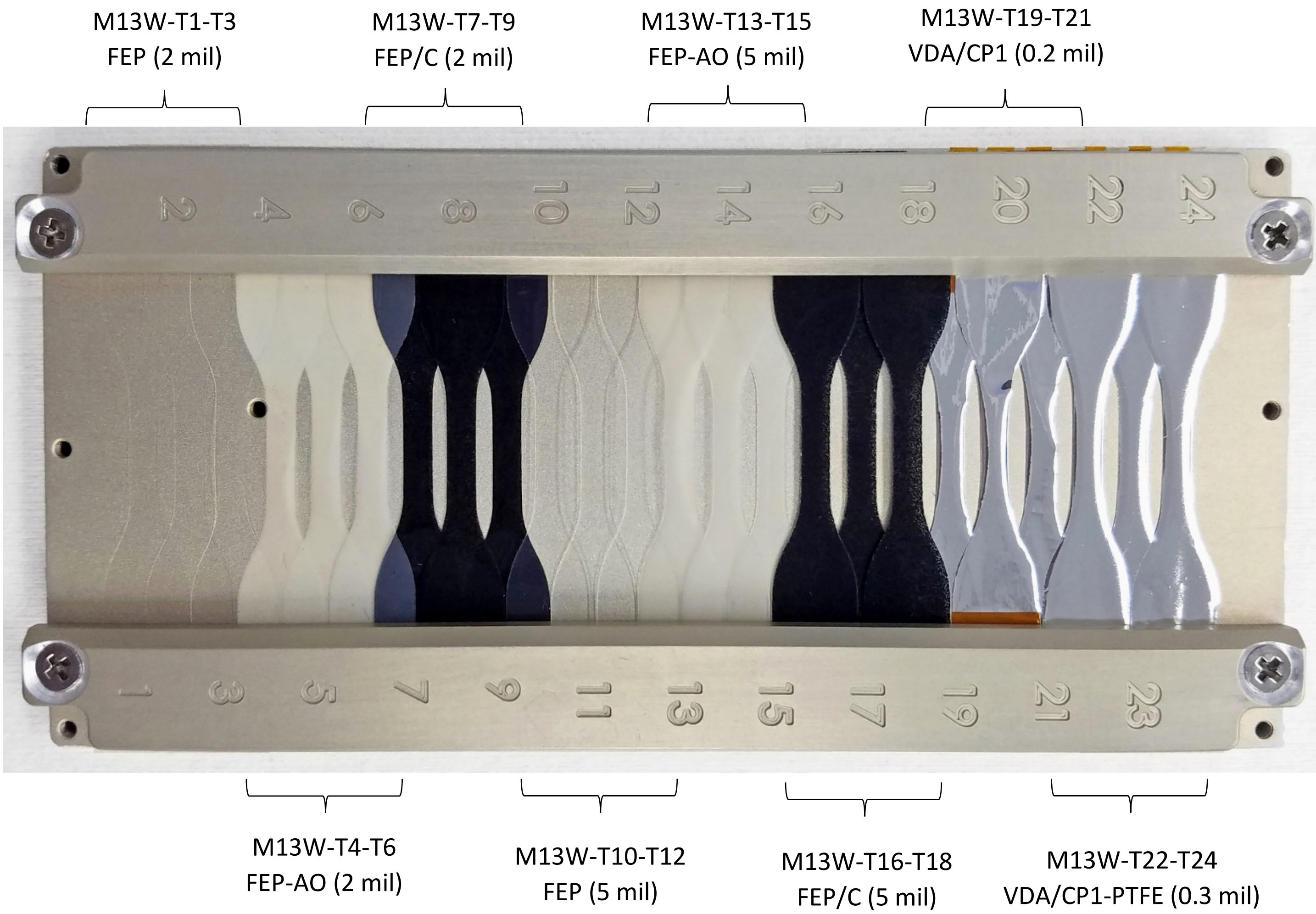
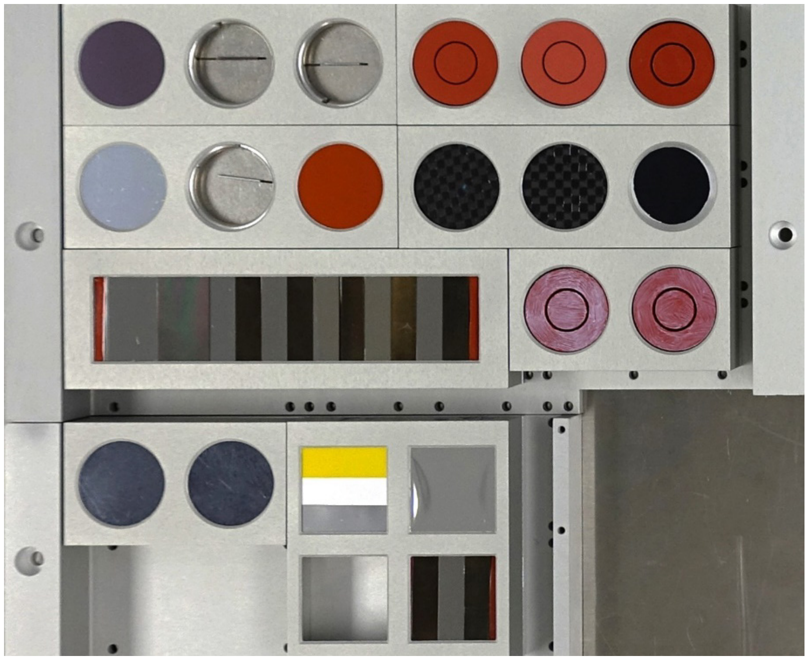


Figure A-14. MISSE-13 PCE-4 wake tensile samples. All samples are cut parallel to the roll direction (PtR).



a.

b.

Figure A-15. MISSE-13 PCE-4 zenith samples: a). Pre-flight photo of the PCE-4 sample area of the M13 Z2 (MSC 5) MS deck, and b). The PCE-4 M13 Z2 sample map.