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Space Environmental Effects on Additively Manufactured Materials – Results from MISSE-9 and MISSE-10

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July 2023

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

AMS	Aerospace Material Specification
ABS	acrylonitrile-butadienestyrene
AM	additively manufactured
AO	atomic oxygen
CC	Contamination Control
ELC-2	Express Logistics Carrier 2
ESD-PEKK	electrostatic-dissipative polyetherketoneketone
ESH	Equivalent sun hours
GRCop-84	Glenn Research Copper 84 alloy
IR	Infrared
ISS	International Space Station
LEO	low earth orbit
LPSR	Laboratory Portable Spectroreflectometer
MIS	Made In Space
MISSE	Materials on International Space Station Experiment
MISSE-FF	Materials on International Space Station Experiment Flight Facility
MSC	MISSE Sample Carrier
MSFC	Marshall Space Flight Center
PC-ISO	polycarbonate biocompatible per ISO 10993 USP Class VI

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS (Continued)

SEE	Space Environmental Effects
UV	ultraviolet radiation
α_s	solar absorptance
ε_{IR}	infrared emittance

TECHNICAL MEMORANDUM

SPACE ENVIRONMENTAL EFFECTS ON ADDITIVELY MANUFACTURED MATERIALS – RESULTS FROM MISSE-9 AND MISSE-10

1. INTRODUCTION

The Materials on International Space Station Experiment (MISSE) project has been a vital testbed on the outside of the International Space Station (ISS) to expose candidate spacecraft materials to Low-Earth Orbit (LEO). Samples can be exposed for a set period to evaluate performance and durability and to understand the synergism of space environment components. Samples are currently mounted on the MISSE Flight Facility (MISSE-FF) located on the Express Logistics Carrier 2 (ELC-2) in the ram, wake, zenith, and nadir directions (fig. 1). The MISSE Sample Carriers are launched on commercial cargo missions, robotically deployed on the MISSE-FF, exposed to space (fig. 2), then retrieved and returned to Aegis Aerospace.

Figure 1. The MISSE Flight Facility located on ELC-2. Clockwise from left: ram face, zenith face, wake face, nadir face.

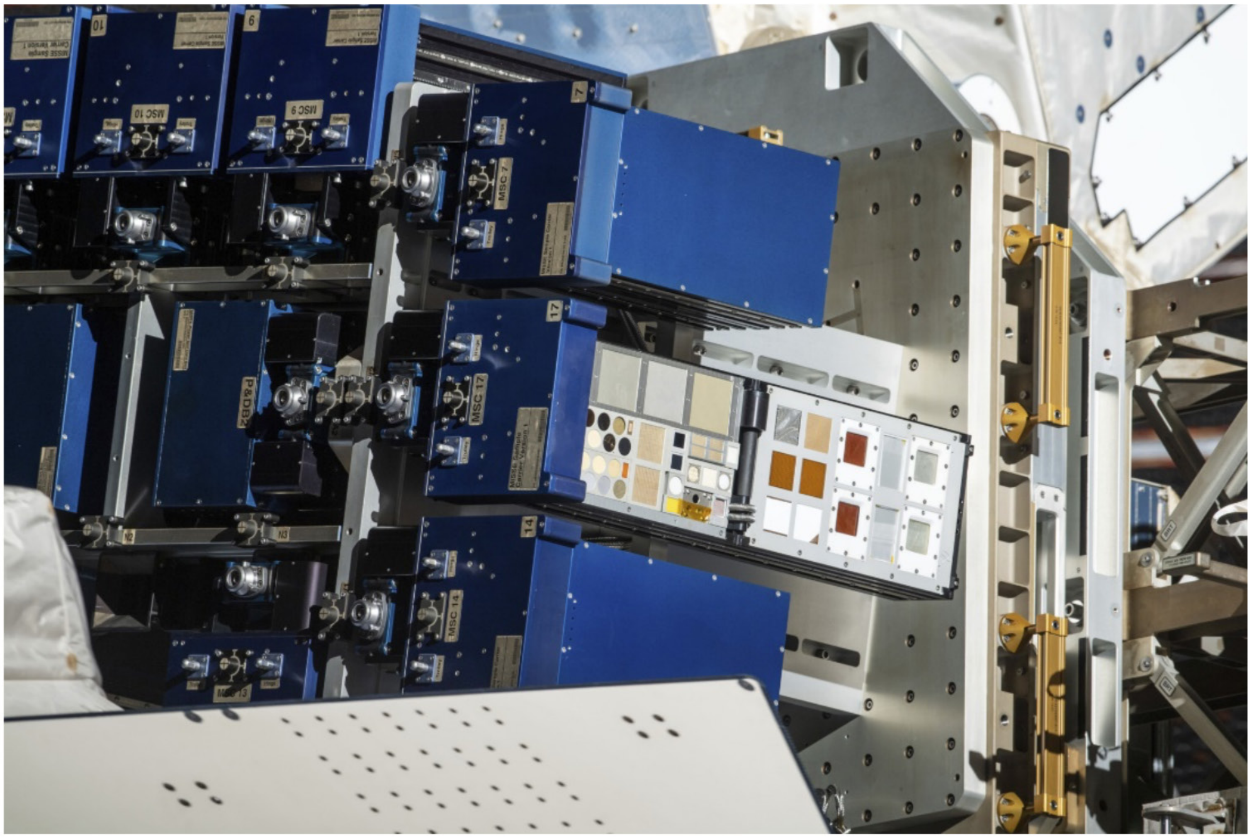

Figure 2. (Labeled top to bottom) MISSE-FF wake face with one closed MSC, one open MSC, one closed MSC.

The NASA Marshall Space Flight Center (MSFC) Space Environmental Effects (SEE) and Contamination Control (CC) teams prepared and characterized MISSE-9 and MISSE-10's additively manufactured (AM) materials samples to investigate the effect of ultraviolet (UV) radiation, thermal cycling, outgassing, and temperature and provide data on the durability of these samples. Materials studied were polyetherimide (Ultem 1010 and 9085), electrostatic dissipative polyetherketoneketone (ESD-PEKK), also known commercially as Antero 840CN03, polycarbonate biocompatible per ISO 10993 USP Class VI (PC-ISO), and Inconel 718. Glenn Research Copper 84 alloy (GRCop-84) was studied in ground tests but not chosen for flight. Some samples were manufactured at MSFC, while 3D printer manufacturers Stratasys and Made In Space, Inc. (MIS) (now Redwire) participated in this effort to compare different vendors and printing setups.

To clarify, "Made In Space" refers to the company. These samples were printed on the ground, not actually made in space. For actual samples made in space, the authors recommend "3D Printing in Zero G Technology Demonstration Mission: Complete Experimental Results and Summary of Related Material Modeling Efforts" in the International Journal of Advanced Manufacturing Technology, Volume 101, Issue 1-4. This was done with acrylonitrile-butadienestyrene (ABS). ABS was not chosen for the MISSE-9 and MISSE-10 effort because of the low glass transition temperature.

This document gives no recommendation, endorsement, or preference, either expressed or implied, concerning materials and vendors used.

Pre-flight and post-flight analysis included solar absorptance, infrared (IR) emittance, electrical resistivity, mass measurements, and tensile tests (post-flight only) which examined the durability of these materials in the space environment. At the same time, laboratory simulators were improved for better fidelity to the space environment. Increased fidelity reduces risk. Space simulations focused on thermal vacuum, atomic oxygen (AO), and UV radiation, advancing from no data available for these additively manufactured materials to TRL7. The ground testing is detailed in NASA/TP—2018–220123, Space Environmental Effects on Additively Manufactured Materials.[1]

2. PRE-FLIGHT SAMPLE PREPARATION

2.1 Sample Delivery

MIS, MSFC's AM team, and Stratasys provided samples to the SEE team to investigate once NASA Headquarters allotted the space on the MISSE-9 and -10 manifests. These samples were printed in tensile sample form so they could be destructively tested post-flight, (ASTM D638 Type IV and ASTM E8 for the polymer and metal samples, respectively). On MISSE-9, 15 samples were designated for launch. Of these, MSFC AM provided three Inconel 718 printed using a Laser Powder Bed Fusion (L-PBF) and three Ultem 9085 dogbones printed using a Stratasys printer. Made in Space provided three Ultem 9085 dogbones, and Stratasys provided three Ultem 1010 samples and three ESD-PEKK (Antero 840CN03) samples. On MISSE-10, 19 samples were designated for launch. Of these, MSFC provided three Inconel 718 and three Ultem 9085 dogbones. Made in Space provided three Ultem 9085 dogbones, and Stratasys provided three Ultem 1010 samples, three ESD-PEKK samples, and four polycarbonate samples. MSFC maintained two control samples (one for each MISSE flight) that underwent the same pre-flight preparation and post-flight analysis.

2.2 Thermal Vacuum Bakeout

All samples underwent thermal vacuum bakeout prior to flight. This ensured that any molecular contamination due to outgassing on the ISS would be minimized and that any mass loss would be due to other interactions with the space environment such as atomic oxygen erosion. All the samples were weighed before bakeout on a Sartorius CPA225D balance using the hygroscopic method described below, placed into the chamber, and pumped down to approximately 1×10^{-6} torr. Once pumped down, quartz lamp heaters heated the samples to around 60 °C ± 1 °C and the samples baked out for 24 hours before they were removed. Once taken out, the samples are weighed again on the same balance. The weights were compared between each other to determine how much outgassing occurred. Any mass change of over 1% would indicate a limited-use material for flight.

2.3 Hygroscopic Mass Measurement Method

Mass measurements were made using the method for hygroscopic samples to eliminate humidity effects on weight. One sample at a time was placed in a small vacuum chamber with a roughing pump and pumped down to 50 millitorr. Once a sample reached 50 millitorr, the chamber was vented, and a timer started. The sample was then moved quickly to the nearby Sartorius CPA225D balance. Mass measurements were made every 30 seconds from the one-minute mark to the four-minute mark, and regression analysis was used to determine mass at time zero.

2.4 Optical Property Measurements

Solar absorptance (α_s) for air mass zero (space) was calculated from spectral reflectance measurements made from 250 to 2,800 nm with an AZ Technology Laboratory Portable Spectroreflectometer (LPSR) model 300. ASTM E-903 was the test method used under normal laboratory conditions, and ASTM E-490 was the solar spectral irradiance data used to calculate α_s. The LPSR has repeatability of approximately ± 1%. A blackbody was used as a backing for the Ultem and polycarbonate samples to prevent any transmission errors, i.e., these samples likely had a small amount of transmission in the wavelength band, but this was not directly measured.

IR emittance (ε_{IR}) measurements were made with an AZ Technology TEMP 2000A infrared reflectometer. This instrument measures the total hemispheric reflectance averaged over 3–35 μm wavelengths. ASTM E-408 was the test method used under normal laboratory conditions. The TEMP 2000A has repeatability of approximately ± 0.5%.

2.5 Electrical Conductivity

Surface resistivity measurements were made with the Magne-Tron Instruments M-700 four-point probe to measure the conductivity of the ESD PEKK samples in ohms per square. The four-point probe was checked using standards of known resistivity prior to measuring the flight samples.

3. ENVIRONMENT DEFINITIONS

MISSE-9 was launched on the SpaceX-14 Dragon mission on April 2, 2018. MISSE-9 was deployed April 19, 2018, on the wake side. The wake orientation faces away from the direction of travel and has essentially no AO while having moderate solar exposure and thousands of thermal cycles in hard vacuum. When cargo and crew vehicles approached the ISS for docking, the sample carriers remained closed to minimize any possible contamination. The sample carriers were closed in December 2018 and retrieved June 2019 and then returned to earth on June 3, 2019, in the SpaceX-17 Dragon capsule. Pre-flight and post-flight of the AM samples can be seen in figure 3.

Figure 3. Pre-flight (left) and post-flight (right) pictures of the MISSE-9 tray.

MISSE-10 was launched on the Northrop Grumman Cygnus ship (NG-10) on November 17, 2018. MISSE-10 was deployed on April 26, 2019, on the nadir side (viewing down toward the Earth). The nadir orientation is towards the Earth with grazing AO and albedo UV radiation. The samples were then retrieved April 2020 and returned to earth on April 7, 2020. Pre-flight and post-flight of the AM samples can be seen in figure 4.

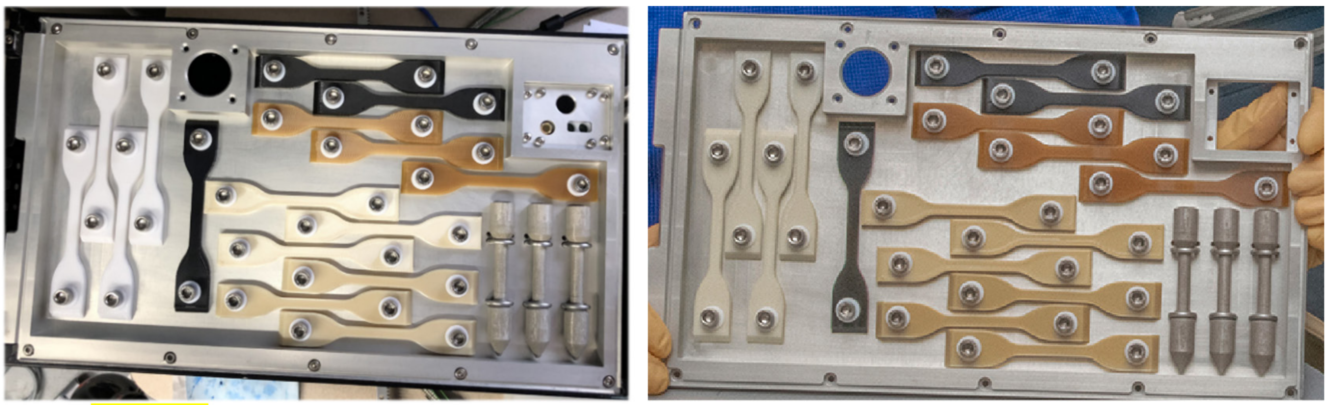

Figure 4. Pre-flight (left) and post-flight (right) pictures of the MISSE-10 tray.

Atomic oxygen fluence was calculated from mass loss of the Teflon washers used in fastening the samples to the base plate. Most of the washer mass losses were zero or within error of the balance. The fluence given for the MISSE-10 nadir is based on worst case mass loss (table 1). Equivalent sun-hours (ESH) were calculated from the UV sensor data, which was measured every second.

Table 1. Space environment exposures for the two AM flights.

Environment	MISSE-9 Wake	MISSE-10 Nadir
First open	19 Apr 2018	26 Apr 2019
Last closed	26 Dec 2018	12 Mar 2020
Total days open	198 days	250 days
Total days in vacuum	411 days	455 days
Thermal cycles	3,069	3,876
Atomic oxygen	Negligible	< 3E19 atoms/cm^2
Ultraviolet Radiation	720 ESH	561 ESH

Post-flight inspection included scans for micrometeoroid/space debris impacts using a 4× magnifying glass. No impacts were noted on any of the tensile samples.

4. POST-FLIGHT NON-DESTRUCTIVE ANALYSIS

4.1 Mass Measurements

During sample preparation, all MISSE-9/10 samples underwent the same thermal bakeout procedure, where mass measurements were taken before and after the bakeout (pre- and post-bakeout). After flight, samples were weighed again to determine any mass change due to space environmental exposure. The polymer samples underwent hygroscopic mass measurements to remove absorbed water in the sample that could provide error. Inconel samples were not hygroscopic, so regular mass measurements were conducted post-bakeout and post-flight (table 2). From post-bakeout, some polymer mass loss due to outgassing effects was expected. Post-flight saw a minor weight gain in polymers on MISSE-9 wake side, possibly due to contamination, and negligible mass change on the nadir side on MISSE-10. Polycarbonate only flew on MISSE-10.

Table 2. Summary of mass loss for MISSE-9/10.

MISSE-9/10 Mass Changes				
	MISSE-9		MISSE-10	
Sample	Post-Bakeout	Post-Flight	Post-Bakeout	Post-Flight
MSFC Ultem 9085	–0.28%	0.26%	–0.02%	0.08%
MiS Ultem 9085	–0.45%	0.38%	N/A	0.04%
Stratasys Ultem 1010	–0.62%	0.65%	–0.01%	0.06%
Stratasys ESD PEKK	–0.27%	0.24%	–0.07%	0.04%
Stratasys Polycarbonate			–0.02%	0.07%
Inconel 718		0.00%		0.00%

4.2 Optical Property Measurements

Reflectance data was completed for the post-flight and control MISSE-9/10 for the Ultem 9085 and 1010, ESD PEKK, PC-ISO, and Inconel samples. Solar absorptance was calculated from pre-flight and post-flight samples and compared MISSE-9 (wake) to MISSE-10 (nadir). The three flight samples in each set were averaged together to obtain an average α_s during pre-flight and post-flight measurements. A percent change was calculated between pre-flight and post-flight.

The first samples looked at were the MSFC Ultem 9085 in figure 5 from MISSE-9. MISSE-10 has nearly identical appearances to MISSE-9. "Rings" around the fastener holes are where Teflon washers covered the samples. The post-flight samples were yellowed with an overall decrease in reflectance of 5.53% for the MISSE-9 samples and 6.50% for the MISSE-10 samples (fig. 6). Any change in infrared emittance was negligible.

Figure 5. MISSE-9 MSFC Ultem 9085 three post-flight samples (U1-U3) and one control sample (U4).

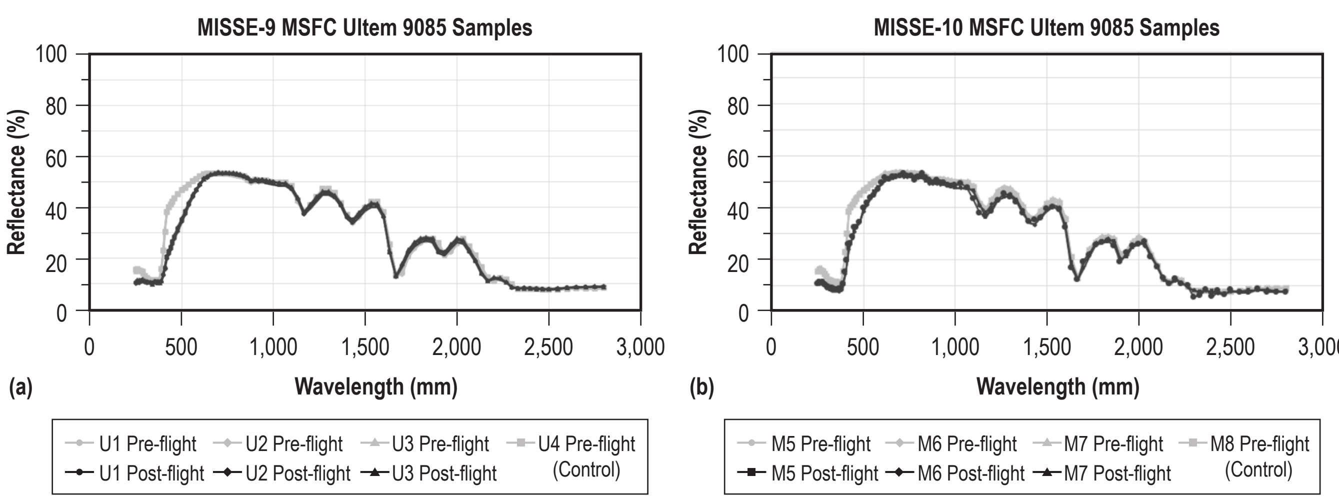

Figure 6. Reflectance data on MSFC Ultem 9085 for (a) MISSE-9 and (b) MISSE-10.

The MIS Ultem 9085 samples were similar to the MSFC Ultem 9085 (see fig. 7) except that the solar absorptance was slightly lower overall and varied more from batch to batch (fig. 8), but the darkening due to UV was approximately the same.

Figure 7. MISSE-9 MIS Ultem 9085 post-flight samples (2170, 2181, and 2186) and one control sample (2180).

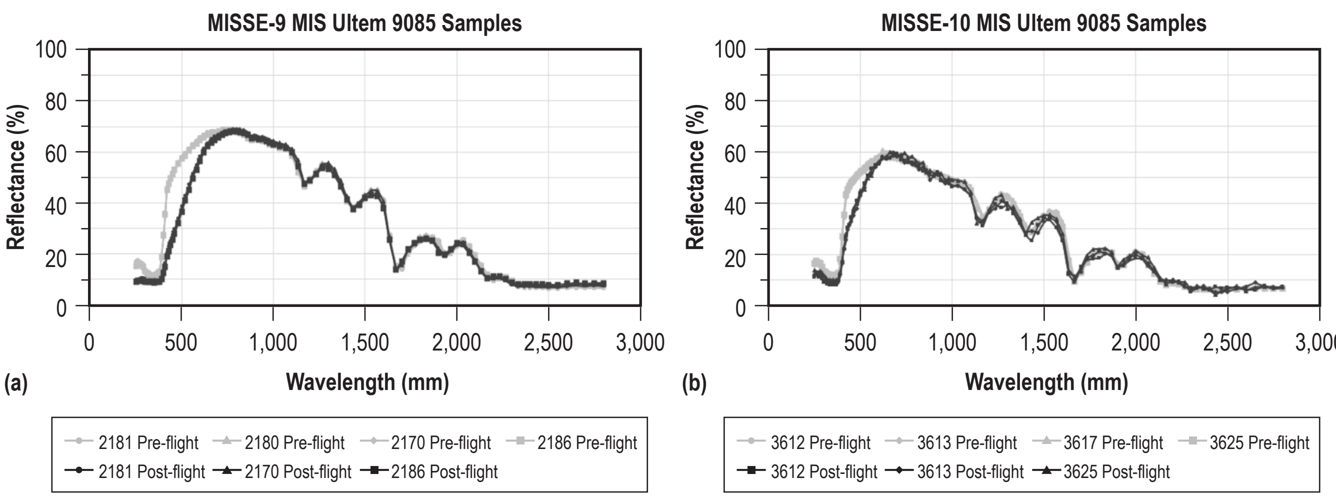

Figure 8. Reflectance data on MIS Ultem 9085 for (a) MISSE-9 and (b) MISSE-10.

With the Stratasys Ultem 1010 samples, the MISSE-9 samples indicated no obvious physical discoloration (fig. 9), and this was supported by the negligible change in solar absorptance. However, when handling the samples, the post-flight samples experienced embrittlement. Post-flight MISSE-10 samples on the nadir side were slightly less reflective than the MISSE-9 samples on the wake side, possibly from more atomic oxygen exposure producing a textured surface (fig. 10).

Figure 9. MISSE-9 Stratasys Ultem 1010 post-flight samples (S1–S3) and one control sample (S4).

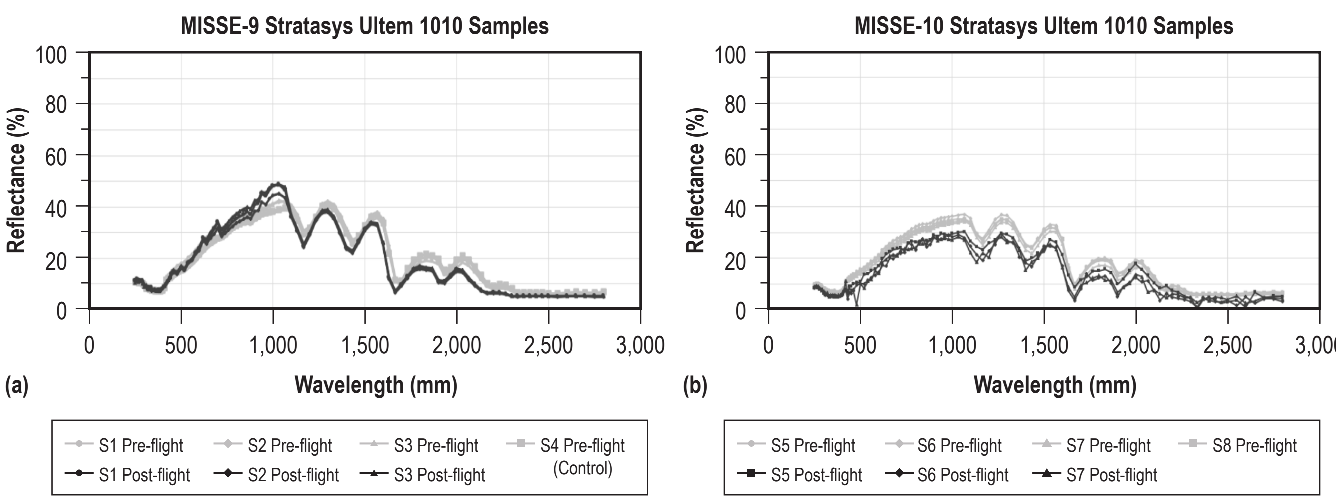

Figure 10. Reflectance data on Stratasys Ultem 1010 for (a) MISSE-9 and (b) MISSE-10.

Comparing the post-flight samples of the ESD PEKK to the control (E4), there was no obvious physical difference in appearance (fig. 11). The reflectance data in figure 12 shows the flight samples were slightly less reflective but overall solar absorptance changed less than 0.5%. Changes in infrared emittance were within machine error.

Figure 11. Stratasys ESD PEKK MISSE-9 post-flight samples (E1–E3) and one control sample (E4).

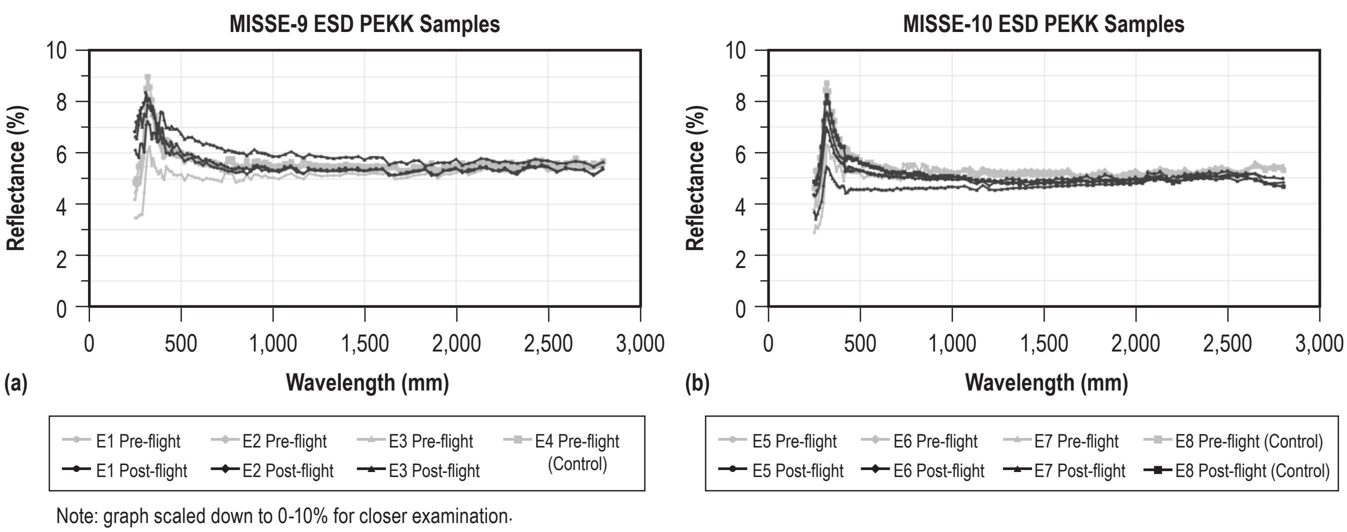

Figure 12. Reflectance data on Stratasys ESD PEKK for (a) MISSE-9 and (b) MISSE-10.

The polycarbonate samples (fig. 13) appeared to be significantly yellowed from the UV radiation, which was unexpected given that the nadir exposure was only albedo UV. The solar absorptance for these samples increased 12.2% (note the reflectance curves between 400–600 nm). Infrared emittance was not significantly changed in figure 14.

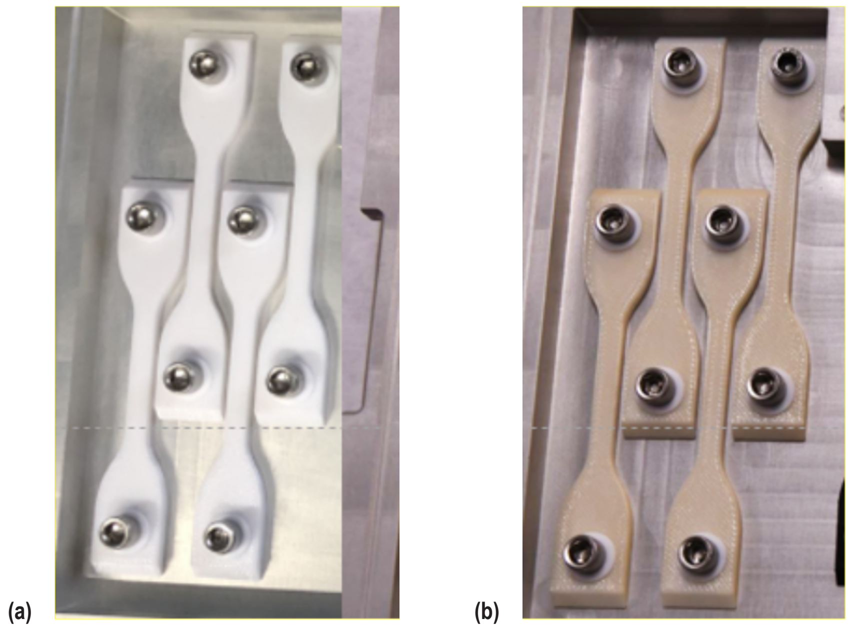

Figure 13. MISSE-10 PC-ISO (a) pre-flight samples and (b) post-flight samples.

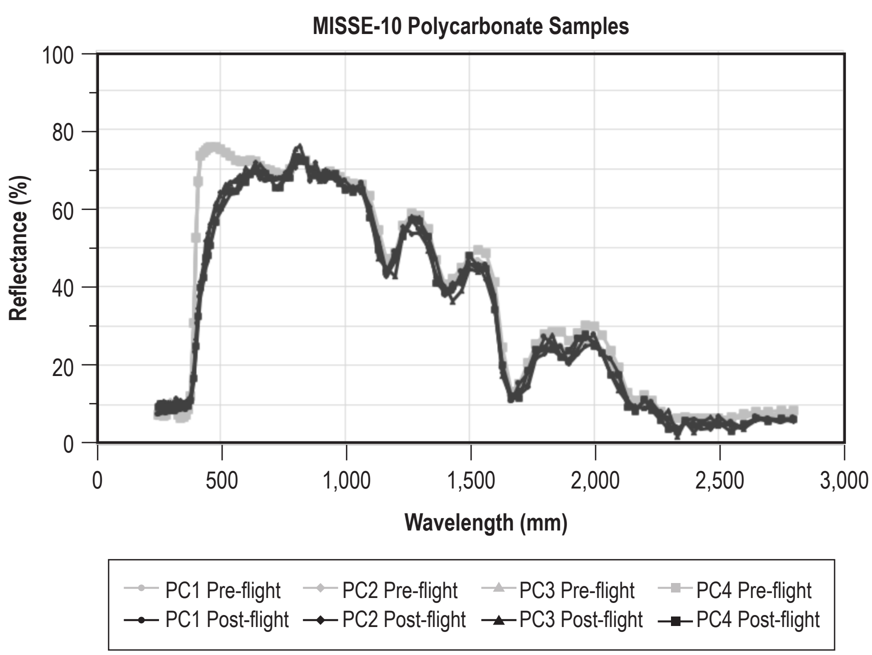

Figure 14. Reflectance data on PC-ISO with MISSE-10.

The Inconel samples (fig. 15) physically show little difference between the control and the flight samples. However, the flight samples are numerically slightly less reflective from both directions as shown in figure 16.

Figure 15. Inconel 718 MISSE-9 post-flight samples (top three) and one control sample (bottom).

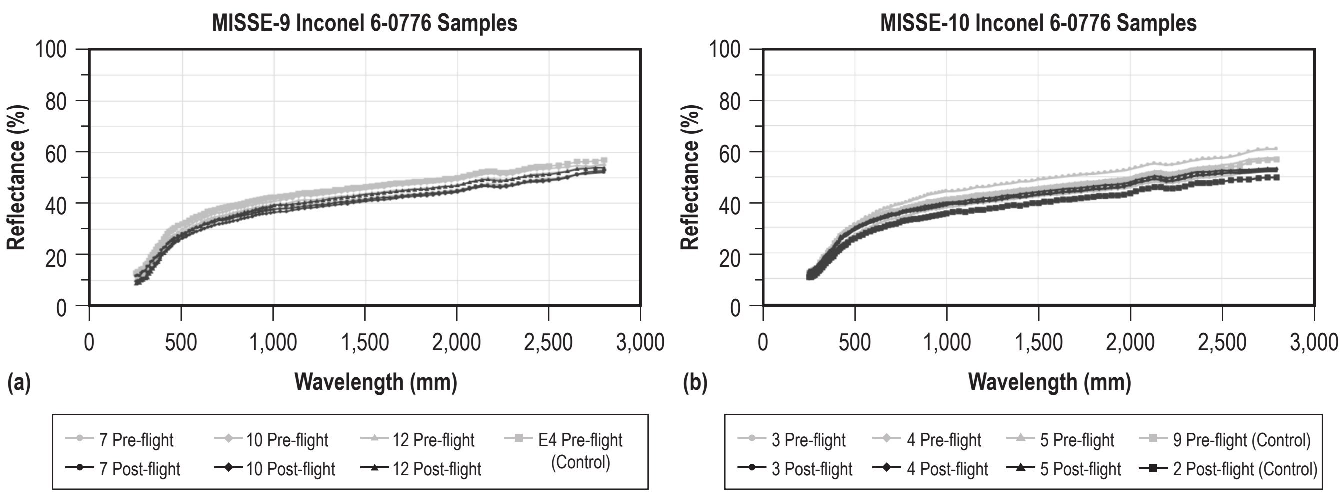

Figure 16. Reflectance data on PC-ISO with MISSE-10.

4.3 Electrical Conductivity

The Magne-Tron Instruments M-700 four-point probe measured surface resistivity for pre-flight and post-flight MISSE-9/10 samples. The control samples (E4 and E8) remained on the ground and were tested with the flight samples. Both the flight and control samples showed a significant increase in resistivity (fig. 17). This indicates that the space environment did not play a major role in the increase in resistivity. However, all the samples remained static dissipative (10^6–10^{12} ohms/square).

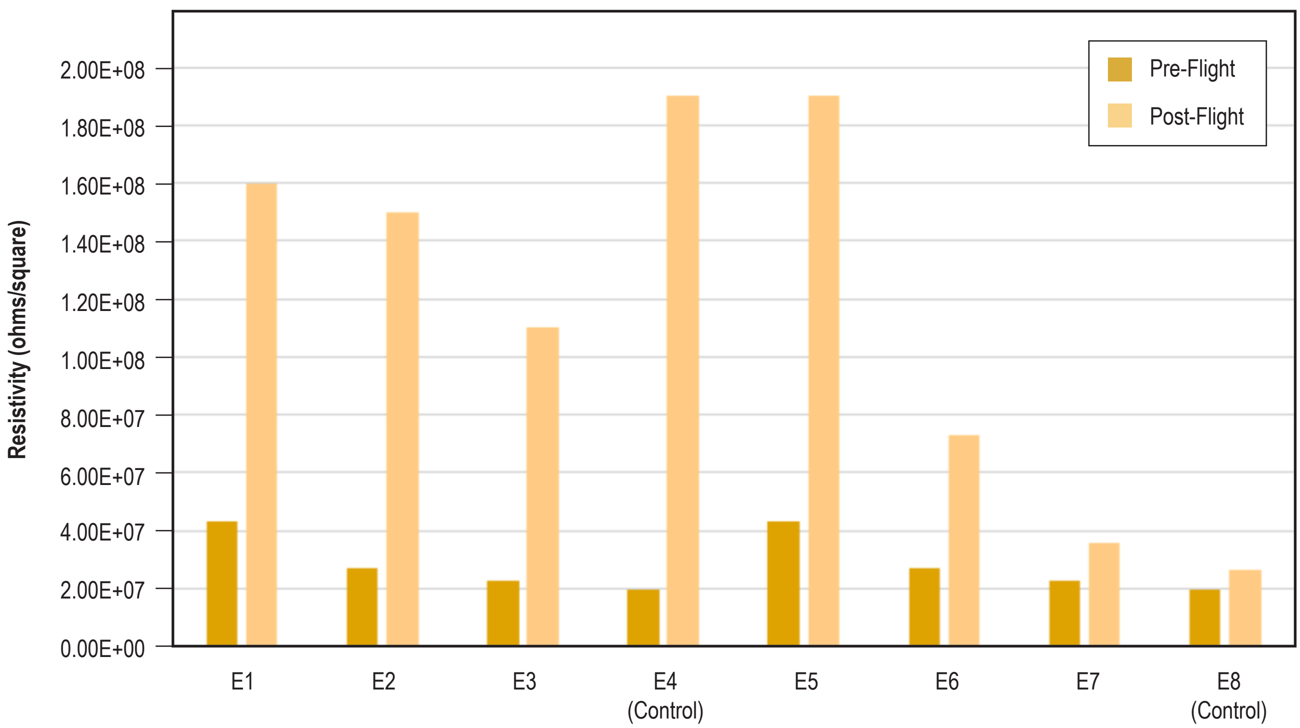

Figure 17. Resistivity pre-flight and post-flight comparison for ESD PEKK samples on MISSE-9/10.

5. POST-FLIGHT MECHANICAL TESTING

Once all non-destructive evaluation was completed, mechanical testing was conducted on all the ground and flight samples to determine material properties of the polymers and the Inconel samples. Fifty flat dogbone (Type IV) specimens were tested according to guidelines established in ASTM D638 at room temperature (approximately 70 °F). The specimens had a nominal gage length of one inch. Test specimens were tested on polymer and metallic pull tests stations at MSFC (shown in fig. 18 and fig. 19) that consisted of a test frame equipped with an electromechanical actuator and reaction member. Stress measurements on the test station were derived from a load cell calibrated to 1,000 pounds. Strain measurements were derived from a 1-inch extensometer calibrated to 50% strain. The specimens were tested in displacement control at a rate of 0.2 in/min. Ultimate stress and fracture elongation values were determined from the resulting stress-strain curve according to procedures outlined in ASTM D638. Modulus of elasticity is also reported for reference. However, note that specific modulus tests are needed for true values.

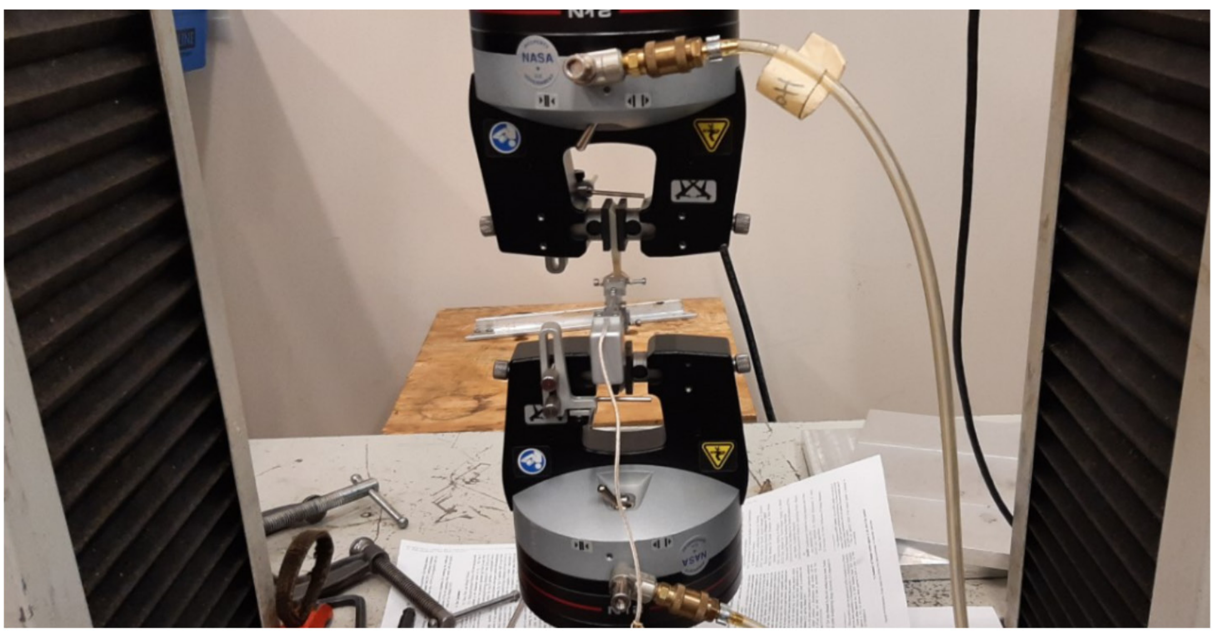

Figure 18. Test station at NASA MSFC used for polymer mechanical testing.

Figure 19. Test station at NASA MSFC used for metallic mechanical testing.

The mechanical test data can be summarized in table 3 for the polymers for both MISSE-9/10. Tensile and fracture stress and strain data was included. Averages of the three flight samples (four flight samples for polycarbonate) were taken and compared to the ground control sample.

Table 3. Summary of mechanical properties for MISSE-9/10 polymers.

	Stress (ksi)		Load (lbs)		Strain (%)	
Samples	Tensile	Fracture	Tensile	Fracture	Tensile	Fracture
MSFC Ultem 9085						
MISSE-9 Flight Average	10.71	9.95	413.21	384.07	6.21	9.02
MISSE-10 Flight Average	10.53	10.12	406.45	390.64	5.91	7.23
Control	10.60	10.00	408.58	385.38	6.09	9.02
Made In Space Ultem 9085						
MISSE-9 Flight Average	10.41	9.43	396.67	359.20	5.72	7.44
MISSE-10 Flight Average	10.00	9.81	352.47	345.77	5.53	6.07
Control	10.18	9.89	354.52	344.56	6.27	7.89
Stratasys Ultem 1010						
MISSE-9 Flight Average	12.07	12.05	464.80	463.82	3.77	3.78
MISSE-10 Flight Average	11.50	11.50	436.35	436.35	3.38	3.38
Control	12.30	12.30	458.69	458.69	3.48	3.48
Stratasys ESD PEKK						
MISSE-9 Flight Average	13.14	7.90	507.44	305.10	4.65	8.50
MISSE-10 Flight Average	12.77	8.28	489.33	317.43	4.61	7.77
Control	12.21	7.93	474.45	308.16	4.73	13.57
Polycarbonate						
MISSE-10 Flight Average	7.54	6.96	296.79	274.30	4.59	5.47
Control	8.19	8.09	307.82	304.19	4.67	5.22

The Ultem 9085 flight samples from both MIS and MSFC both had no overall significant changes in stress and load compared to the control sample. Ultem 9085's strain decreased in the nadir side and remained unchanged in ram direction. Ultem 1010's stress decreased with both missions due to embrittlement, but MISSE-10 samples experienced more weakening. Strain for both ISS directions varied slightly. ESD PEKK's stress slightly increased (specifically tensile stress) for both directions, which allowed the sample to hold more load. Strain decreased in both directions. Polycarbonate experienced degradation in both stress and load for both ram and nadir directions due to embrittlement.

Table 4 summarizes the mechanical properties of Inconel 718 for both MISSE-9 and MISSE-10. It was found that there was not a significant change in stress at both tensile and fracture stress, showing great durability in the space environments exposed. Like stress, no significant changes in load and strain were found.

Table 4. Summary of mechanical properties for MISSE-9/10's metallic sample.

	Stress (ksi)			Load (lbs)			Strain (%)		
Inconel 718	**Tensile**	**Yield**	**Fracture**	**Tensile**	**Yield**	**Fracture**	**Tensile**	**Yield**	**Fracture**
MISSE-9 Flight Average	143.36	105.71	129.61	8.37	6.17	7.57	20.71	0.84	27.95
MISSE-10 Flight Average	143.77	104.42	130.06	8.35	6.07	7.38	20.60	0.83	27.44
Control	142.63	103.91	126.94	8.41	6.13	7.48	20.80	0.89	28.11

6. GROUND SIMULATION COMPARISON

6.1 Mass Properties

The MIS and MSFC Ultem 9085 samples tested in ground simulations lost between 0.17% and 0.23% due to bakeouts and UV exposures. The differences between the ground, MISSE-9, and MISSE-10 exposure bakeout mass losses may be due to aging of the samples or differences in printing. All samples had less than 1% total mass loss, which meets the ASTM E595 outgassing standard.

6.2 Optical Properties

As mentioned earlier, the ground testing is detailed in NASA/TP—2018–220123, Space Environmental Effects on Additively Manufactured Materials. Selected samples were exposed to AO and UV in the lab, and the reflectance data for all samples gathered using the LPSR and the AZ Technology TEMP 2000A infrared reflectometer.

With the MSFC Ultem 9085, the ground samples were exposed to AO in the MSFC Atomic Oxygen Beam Facility and exposed to 500 ESH of UV. The AO erosion did not influence optical properties, but the samples experienced darkening due to UV. When comparing reflectance in figure 20, the ground samples exposed to AO were mostly identical to the post-flight control, other than at approximately 1,950 nm where water in post-flight samples was removed.

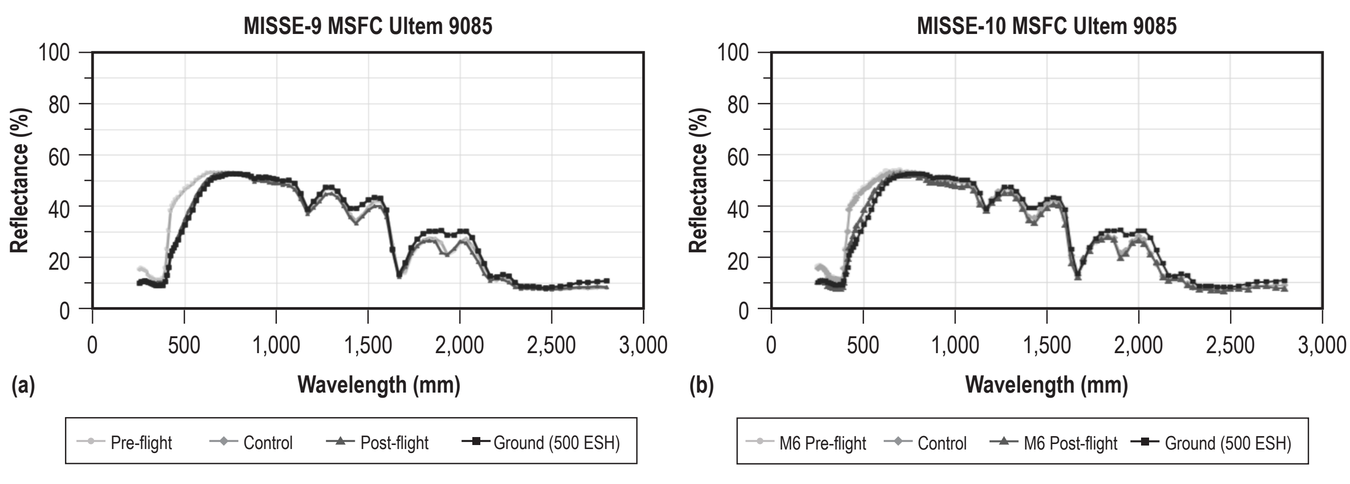

Figure 20. Comparing reflectance on MSFC Ultem 9085 on ground samples (500 ESH) and flight samples for (a) MISSE-9 and (b) MISSE-10.

Looking at the optical data in table 5, the differences in UV darkening is not significant between 500 and 1,000 ESH in ground simulation, and 720 and 561 ESH on MISSE-9 and -10, respectively.

Table 5. Optical property comparison for MSFC Ultem 9085 flight and ground test samples.

Material UV1 = 500 ESH UV2 = 1,000 ESH	Solar Absorptance		Infrared Emittance	
	Pre-exposure	Post-exposure	Pre-exposure	Post-exposure
MSFC Ultem UV1	0.599	0.626	0.90	0.90
MSFC Ultem UV2	0.596	0.637	0.90	0.90
MISSE-9 MSFC Ultem	0.590	0.626	0.90	0.91
MISSE-9 MSFC Ultem	0.592	0.624	0.90	0.91
MISSE-9 MSFC Ultem	0.589	0.619	0.90	0.91
MISSE-10 MSFC Ultem	0.584	0.618	0.91	0.92
MISSE-10 MSFC Ultem	0.589	0.623	0.91	0.92
MISSE-10 MSFC Ultem	0.582	0.621	0.91	0.92

With the MIS Ultem 9085, the ground samples were exposed to 500 ESH of UV. MISSE-9 tested a batch in the 2,000 series Ultem 9085 and MISSE-10 tested a batch numbered in the 3,000 series, so the ground samples were not comparable to MISSE-10. The ground sample exposed to AO were mostly identical to the post-flight control like MSFC where at approximately 1,950 nm water in post-flight samples was removed (fig. 21 and table 6).

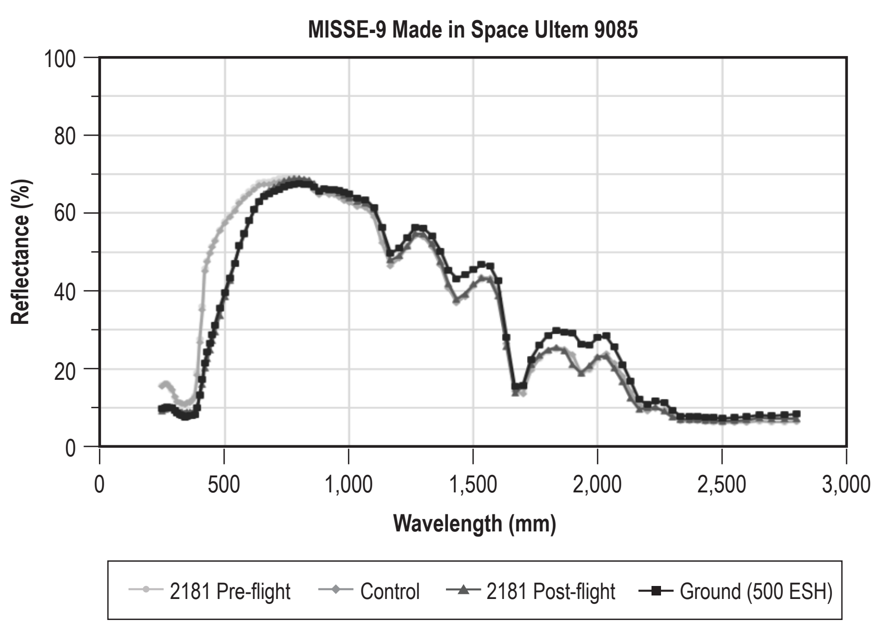

Figure 21. Comparing reflectance on MIS Ultem 9085 on ground samples (500 ESH) and flight samples.

Table 6. Optical property comparison for MIS Ultem 9085 flight and ground test samples.

Material UV1 = 500 ESH UV2 = 1,000 ESH	Solar Absorptance		Infrared Emittance	
	Pre-exposure	Post-exposure	Pre-exposure	Post-exposure
MiS Ultem UV1	0.506	0.541	0.91	0.90
MiS Ultem UV2	0.494	0.547	0.91	0.90
MISSE-9 MiS Ultem	0.499	0.554	0.90	0.91
MISSE-9 MiS Ultem	0.492	0.551	0.91	0.91
MISSE-9 MiS Ultem	0.499	0.559	0.91	0.91
MISSE-10 MiS Ultem	0.564	0.596	0.90	0.92
MISSE-10 MiS Ultem	0.581	0.609	0.91	0.92
MISSE-10 MiS Ultem	0.571	0.602	0.91	0.92

Stratasys Ultem 1010 did not have a ground test that underwent AO or UV exposure; however, it is important to note that there was a difference between the ground control sample and the pre-flight and post-flight samples. The post-flight and control were nearly identical (fig. 22).

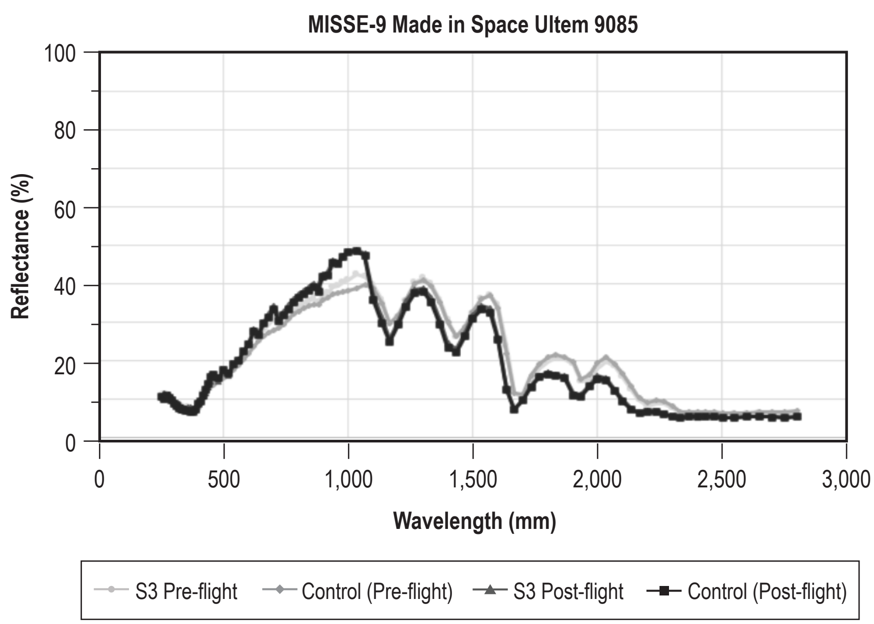

Figure 22. Comparing reflectance on ground control samples for Stratasys Ultem 1010 flight samples.

ESD PEKK samples were exposed to AO and UV on the ground, and the 500 ESH ground samples were more accurate to compare since α_s and ε_{IR} were closer to the post-flight samples. The ESD-PEKK flight samples were exposed to much less AO than the ground study (fig. 23 and table 7).

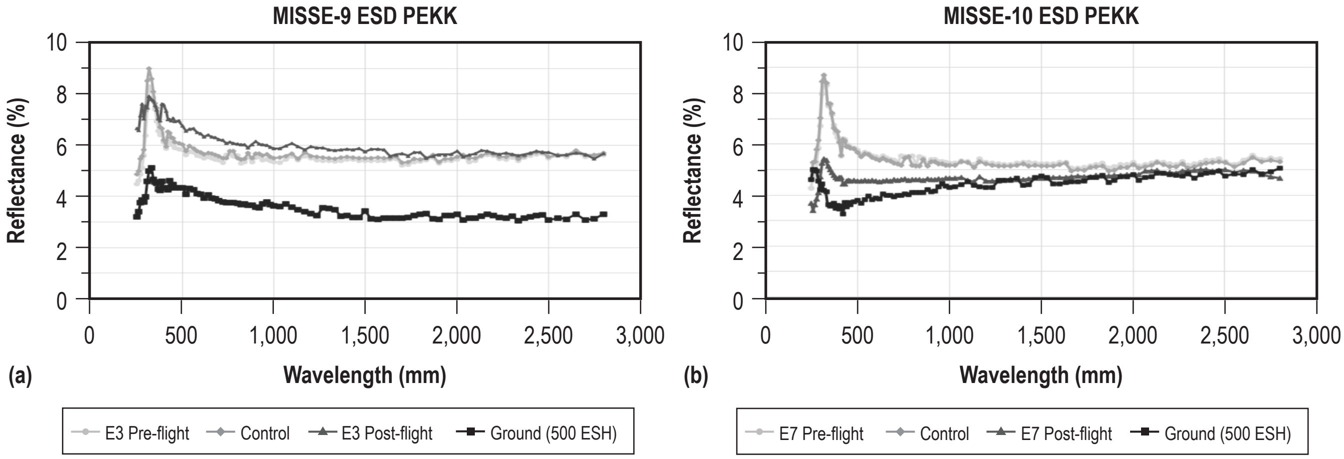

Figure 23. Comparing reflectance on ESD PEKK on ground samples (500 ESH) and flight samples (scaled between 0% to 10% for visual) for (a) MISSE-9 and (b) MISSE-10.

Table 7. Optical property comparison for Stratasys ESD PEKK flight and ground test samples.

Material UV1 = 500 ESH UV2 = 1,000 ESH	**Solar Absorptance**		**Infrared Emittance**	
	Pre-exposure	**Post-exposure**	**Pre-exposure**	**Post-exposure**
ESD PEKK UV1	0.955	0.959	0.91	0.91
ESD PEKK UV2	0.955	0.943	0.91	0.90
MISSE-9 ESD PEKK	0.944	0.942	0.90	0.91
MISSE-9 ESD PEKK	0.949	0.944	0.90	0.91
MISSE-9 ESD PEKK	0.943	0.937	0.90	0.91
MISSE-10 ESD PEKK	0.945	0.962	0.91	0.92
MISSE-10 ESD PEKK	0.949	0.960	0.91	0.92
MISSE-10 ESD PEKK	0.944	0.968	0.91	0.92

7. DISCUSSION AND CONCLUSION

The consistency of optical and mechanical properties for the AM samples indicate durability for a year in low Earth orbit if not exposed to AO. AO erosion of polymeric materials should be considered when designing AM parts (i.e., additional thickness may be required for a long exposure in low Earth orbit). Pre-flight thermal vacuum bakeout did result in some mass loss for these samples but nothing that would exceed ASTM E595 total mass loss requirements. Mass slightly increased for samples on the MISSE-9 wake side, though the hygroscopy of the polymeric samples introduced error into these calculations. The average solar absorptance increased slightly with all samples other than ESD PEKK, as expected. The average infrared emittance remained unchanged within the error of the machine. Resistivity in ESD PEKK was found to increase, but the same behavior occurred on the ground samples. The cause of this might be from the material losing its ESD properties over time. However, all the samples remained in the static dissipative range (10^6–10^{12} ohms/square).

The tensile tests showed some changes in mechanical properties with stress and strain. Ultem 9085 showed no significant change in yield and ultimate stress but did indicate a reduction in strain. The Ultem 1010 and polycarbonate experienced reduced overall yield and ultimate strength due to embrittlement. This reduction in strength can be linked to chain scission where atomic bonds are broken and the length in polymer chains reduces, ultimately causing reduction in strength. ESD PEKK slightly increased in tensile stress for both sets of flight samples. ESD PEKK's strain increased on MISSE-9 and decreased in MISSE-10, possibly due to the differences in UV exposure (full vs. albedo) and thermal cycling. Inconel samples indicated no significant effects on stress or strain.

While the samples tested performed well, there are some considerations that would help improve the strength of the material. These include strategic modifications to the printing process and/or the material composition. The three-dimensional deposition inherent to AM gives rise to a great deal of control over the fabrication process. As such, there is future potential to adjust printing parameters such as infill percentage/infill pattern (density), number of shells (or perimeters), layer height, and reduced cooling. Increasing infill can allow for higher strength and certain patterns can be optimal depending on the infill percentage (honeycomb pattern for < 50% infill and rectilinear pattern for > 50% infill), but an increase will result in slightly heavier parts. Increasing shells/perimeters can allow parts to experience more strain on the outside, which can be more effective than increasing infill. Meanwhile, smaller layer heights can allow for better adhesion between subsequent layers but will increase the lead time of parts. In addition to bonding, slow cooling allows for better adhesion between layers (where cooling can vary between materials).

A benefit of melt-processible thermoplastic materials is that many material composition modifications are relatively easy to achieve. Thermoplastic materials are often modified by performing a melt mix between the polymer matrix and various filler materials. The ESD PEKK material evaluated in this briefing is a prime example. Higher electrical conductivity is achieved in this material through the addition of carbon nanotubes. Similarly, filler materials can be added to Ultem 9085 and Ultem 1010 to enhance stiffness and strength. Carbon fiber and glass fiber are two such additives that are commonly employed for this purpose. Solutions for improving the UV and AO erosion resistance of polymers with the use of additives are currently being explored as well.

The above described process and composition modifications would be ideal candidates for investigation in future MISSE missions similar to MISSE-9/10.

APPENDIX

Table 8. Averaged solar absorptance values for pre-flight and post-flight for MISSE-9/10.

Solar Absorptance for MISSE-9/10				
Flight	**Material**	**Pre-Flight (averaged)**	**Post-Flight (averaged)**	**Percent Change (%)**
MISSE-9	MSFC Ultem (9085)	0.590	0.623	5.53%
	MiS Ultem (9085)	0.498	0.551	10.78%
	Stratasys Ultem (1010)	0.760	0.758	–0.26%
	Stratasys ESD PEKK	0.945	0.941	–0.46%
	Inconel	0.649	0.668	2.88%
MISSE-10	MSFC Ultem (9085)	0.585	0.623	6.50%
	MiS Ultem (9085)	0.572	0.597	4.43%
	Stratasys Ultem (1010)	0.784	0.831	6.04%
	Stratasys ESD PEKK	0.946	0.950	0.42%
	Stratasys Polycarbonate	0.436	0.489	12.16%
	MSFC Inconel	0.637	0.657	3.18%

Table 9. Averaged IR emittance values for pre-flight and post-flight for MISSE-9/10.

Infrared Emittance for MISSE-9/10				
Flight	**Material**	**Pre-Flight (averaged)**	**Post-Flight (averaged)**	**Percent Change (%)**
MISSE-9	MSFC Ultem (9085)	0.900	0.907	0.78%
	MiS Ultem (9085)	0.907	0.912	0.59%
	Stratasys Ultem (1010)	0.912	0.913	0.07%
	ESD PEKK	0.900	0.911	1.22%
	Inconel	0.480	0.476	–0.95%
MISSE-10	MSFC Ultem (9085)	0.909	0.921	1.36%
	MiS Ultem (9085)	0.909	0.920	1.25%
	Stratasys Ultem (1010)	0.911	0.926	1.61%
	ESD PEKK	0.906	0.920	1.47%
	Polycarbonate	0.913	0.930	1.81%
	MSFC Inconel	0.443	0.455	2.82%

Table 10. Averaged resistivity values for pre-flight and post-flight for ESD PEKK in MISSE-10.

Resistivity (ohms/square) for ESD PEKK in MISSE-9/10			
Flight	Material	Pre–Flight	Post–Flight
MISSE-9	E1	4.33E+07	1.60E+08
	E2	2.70E+07	1.50E+08
	E3	2.27E+07	1.10E+08
	E4 (Control)	1.97E+07	1.90E+08
MISSE-10	E5	4.33E+07	1.90E+08
	E6	2.70E+07	7.30E+07
	E7	2.27E+07	3.60E+07
	E8 (Control)	1.97E+07	2.66E+07

Table 11. Complete mechanical properties data for MISSE-9/10 polymers.

	Stress (ksi)		Load (lbs)		Strain (%)	
Samples	Tensile	Fracture	Tensile	Fracture	Tensile	Fracture
MSFC Ultem 9085						
Flight #1	10.61	9.83	412.70	382.29	6.28	9.00
Flight #2	10.76	10.03	415.61	387.71	6.21	8.54
Flight #3	10.76	9.99	411.33	382.20	6.15	9.52
Flight Average	10.71	9.95	413.21	384.07	6.21	9.02
Control	10.68	9.95	412.62	384.50	6.19	8.82
Made In Space Ultem 9085						
Flight #1	10.40	9.77	395.09	371.06	5.67	7.73
Flight #2	10.45	9.25	394.70	349.40	5.80	7.99
Flight #3	10.38	9.26	400.23	357.14	5.69	6.60
Flight Average	10.41	9.43	396.67	359.20	5.72	7.44
Control	10.24	8.86	388.19	335.94	5.98	11.20
Stratasys Ultem 1010						
Flight #1	12.02	12.02	463.45	463.45	3.64	3.64
Flight #2	11.71	11.64	457.19	454.25	3.87	3.89
Flight #3	12.49	12.49	473.77	473.77	3.81	3.81
Flight Average	12.07	12.05	464.80	463.82	3.77	3.78
Control	12.84	12.84	486.77	486.77	3.99	3.99
Stratasys ESD PEKK						
Flight #1	13.65	8.43	519.38	320.84	4.62	5.12
Flight #2	13.46	8.15	521.05	315.55	4.61	8.52
Flight #3	12.32	7.13	481.89	278.91	4.71	11.87
Flight Average	13.14	7.90	507.44	305.10	4.65	8.50
Control	13.34	12.84	514.23	319.65	4.38	3.72

Table 12. Complete mechanical properties data for MISSE-10 polymers.

Samples	Stress (ksi)		Load (lbs)		Strain (%)	
	Tensile	Fracture	Tensile	Fracture	Tensile	Fracture
MSFC Ultem 9085						
Flight #1	10.34	9.95	401.94	386.84	5.79	7.00
Flight #2	10.72	10.21	413.14	393.59	5.95	7.36
Flight #3	10.53	10.20	404.28	391.50	5.99	7.32
Flight Average	10.53	10.12	406.45	390.64	5.91	7.23
Control	10.60	10.00	408.58	385.38	6.09	9.02
Made in Space Ultem 9085						
Flight #1	9.84	9.75	339.25	336.30	5.17	5.44
Flight #2	9.97	9.83	351.30	346.23	5.43	5.84
Flight #3	10.19	9.86	366.86	354.78	5.99	6.92
Flight Average	10.00	9.81	352.47	345.77	5.53	6.07
Control	10.18	9.89	354.52	344.56	6.27	7.89
Stratasys Ultem 1010						
Flight #1	11.62	11.62	444.48	444.48	3.25	3.25
Flight #2	12.96	12.96	493.32	493.32	4.37	4.37
Flight #3	9.91	9.91	371.24	371.24	2.51	2.51
Flight Average	11.50	11.50	436.35	436.35	3.38	3.38
Control	12.30	12.30	458.69	458.69	3.48	3.48
Stratasys ESD PEKK						
Flight #1	13.61	9.00	517.95	342.54	4.58	6.11
Flight #2	12.31	7.75	474.57	298.94	4.63	6.46
Flight #3	12.39	8.10	475.48	310.80	4.62	10.74
Flight Average	12.77	8.28	489.33	317.43	4.61	7.77
Control	12.21	7.93	474.45	308.16	4.73	13.57
Polycarbonate						
Flight #1	7.62	6.90	297.24	269.39	4.57	5.75
Flight #2	7.68	7.25	299.88	283.06	4.54	4.78
Flight #3	7.43	6.79	296.08	270.56	4.65	5.73
Flight #4	7.41	6.91	293.94	274.17	4.58	5.60
Flight Average	7.54	6.96	296.79	274.30	4.59	5.47
Control	8.19	8.09	307.82	304.19	4.67	5.22

Table 13. Complete mechanical properties data for MISSE-9 metallic samples.

Inconel 718	Stress (ksi)			Load (lbs)			Strain (%)		
	Tensile	Yield	Fracture	Tensile	Yield	Fracture	Tensile	Yield	Fracture
Flight #1	144.95	106.57	132.08	8.42	6.19	7.67	20.85	0.86	27.52
Flight #2	144.02	107.35	127.10	8.37	6.24	7.39	21.09	0.84	29.34
Flight #3	141.12	103.21	129.64	8.32	6.09	7.64	20.20	0.83	27.00
Flight Average	143.36	105.71	129.61	8.37	6.17	7.57	20.71	0.84	27.95
Control	144.50	105.84	130.73	8.32	6.10	7.54	20.26	0.84	27.45

Table 14. Complete mechanical properties data for MISSE-10 metallic samples.

Inconel 718	Stress (ksi)			Load (lbs)			Strain (%)		
	Tensile	Yield	Fracture	Tensile	Yield	Fracture	Tensile	Yield	Fracture
Flight #1	144.96	105.01	131.69	8.36	6.06	7.06	20.71	0.81	27.02
Flight #2	145.16	105.06	129.86	8.37	6.06	7.49	20.71	0.83	27.92
Flight #3	141.18	103.19	128.63	8.32	6.08	7.58	20.39	0.86	27.39
Flight Average	143.77	104.42	130.06	8.35	6.07	7.38	20.60	0.83	27.44
Control	142.63	103.91	126.94	8.41	6.13	7.48	20.80	0.89	28.11
Ground #1	145.94	106.18	132.24	8.36	6.08	7.57	21.22	0.82	27.80
Ground #2	144.50	105.84	128.63	8.34	6.10	7.42	20.98	0.83	28.32
Ground #3	143.50	105.72	126.71	8.34	6.14	7.36	20.64	0.93	28.63

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FOR FURTHER READING

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