An Analysis of the Laboratory and Environmental Impacts of Space Weathering on Novel Materials in the Low Earth Orbit (LEO)

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Abstract

The Materials International Space Station Experiment (MISSE) project is a National Aeronautics and Space Administration (NASA) initiative that was launched in 2001 with the aim of studying the effects of the low Earth orbit (LEO) space environment on a variety of materials. Since its inception, the MISSE project has tested approximately 4,000 different material samples and specimens, evaluating their durability and performance in the harsh and challenging conditions of space**.** This paper provides an overview of the 16th MISSE project performed by the versatile team of researchers led by the Georgia Tech Research Institute (GTRI) from 08/31/22 to 02/23/23. Details of the orbital environment during the mission, MISSE platform hardware upgrade, and space data acquisition process are discussed.

1 Introduction

The space environment encompasses a range of environmental elements, including various forms of ionizing radiation, electrons, protons with varying energy levels, oxygen ions, micrometeoroids and orbital debris (MMOD), vacuum conditions, and wide temperature fluctuations [1]. These factors typically exert both physical and chemical damage on polymer materials utilized in spacecraft, leading to a degradation of spacecraft components and a reduced mission lifespan. The primary space weather components responsible for polymer degradation in low Earth orbit (LEO) are exposure to atomic oxygen (AO), vacuum ultraviolet (VUV) radiation, and ionizing radiation [2]. It is essential to comprehend the impact of these individual hazards and their potential synergistic effects when selecting suitable materials for specific space projects.

Conducting materials exposure experiments during space missions is the most effective approach to assess material sustainability. The International Space Station Materials International Space Station Experiment (MISSE) program plays a crucial role in advancing our understanding of how materials behave and perform in the challenging environment of space. The MISSE program was initiated in the early 2000s as a collaborative effort between NASA's Langley Research Center and the United States Air Force Research Laboratory (AFRL). Since its inception, the MISSE project has tested approximately 4,000 different material samples and specimens, evaluating their durability and performance in the harsh and challenging conditions of space. From 2001 to 2013, individual flight experiments were carried out using Passive Experiment Containers (PECs), which were suitcase-like containers placed outside the ISS either in a Ram/Wake or a Zenith/Nadir orientation by an astronaut during a spacewalk [3]. In 2018, the MISSE-FF, a modular robotically serviceable external platform that can be configured to carry out a wide range of passive and active experiments, was launched [4].

The project discussed here was part of the MISSE-16 space mission, which commenced with the launch of the SpaceX-25 spacecraft from Kennedy Space Center on July 15, 2022. The installation of MISSE-16 Science Carriers (MSCs) onto the MISSE-FF took place between July 31 and August 2, 2022, with essential support provided by the ISS Robotic Systems Team of the Canadian Space Agency. Over the course of the 6-month mission, we captured red, green, and blue (RGB) together with infrared (IR) images of 14 distinct polymer materials positioned on the zenith, wake, and ram faces of the ISS. Initially, daily image capture was conducted during the first week of the experiment, followed by weekly captures for the subsequent two months, and finally, monthly captures until the conclusion of the mission. In this paper, we offer a comprehensive overview of the orbital environment during the MISSE-16 mission, present a detailed account of experiments conducted in orbit, summarize the array of materials studied, and provide an in-depth analysis of the data collected during the mission.

2 Details of the orbital environment during the MISSE-16 experiment

MISSE-16 launch was performed on July 15th, 2022, at 00:44 UTC from the Kennedy Space Center on LC-39A. Docking occurred on July 16th, 2022, at 15:12 UTC. The mission was completed on March 14, 2023, with all MISSE-16 Science Carriers (MSCs) closed. MSCs were powered off on March 27th, 2023, and on April 15th, 2023, SpaceX-27 undocked from ISS at 10:05 AM CT and splashed down at 3:57 PM CT near Tampa, FL.

To measure the optical changes that occur in each studied material as a function of exposure to neutral atomic oxygen (AO), unfiltered solar ultraviolet (UV) radiation, and electrons, respectively, we installed identical test fixtures on the ram, zenith, and wake positions of the MISSE-FF and collecting spectrally resolved images of the materials throughout the mission along with concomitant measurement of the ambient space environment. The LEO exposure times of each MSC with our payload were 193 days (wake 3 slot), 173 days (zenith 3 slot), and 183 days (ram 3 slot). During the MISSE-16 mission, one of the samples (from a different experiment) was coming loose from the sample holder on the MSC zenith swing 3 side. To prevent creating a Foreign Object Damage (FOD) event in the ISS environment, zenith 3 MSC has been closed earlier compared to ram 3 and wake 3 MSCs. The UV dose (J/cm^2) obtained for the swing and mount sides of each MSC was calculated as a product of measured UV intensity (W/cm^2) and exposure time (seconds), as summarized in Fig. 1. Whereas MISSE-16 mission was officially docked on July 16th, 2022, the first data were taken only on mid-August. It is interesting to note that, while it is assumed that the largest dose of UV irradiation is obtained by the samples located at the zenith side of the ISS, the analysis of UV data summarized in Fig.1 suggests that the majority of the UV radiation is actually received on the ram face.

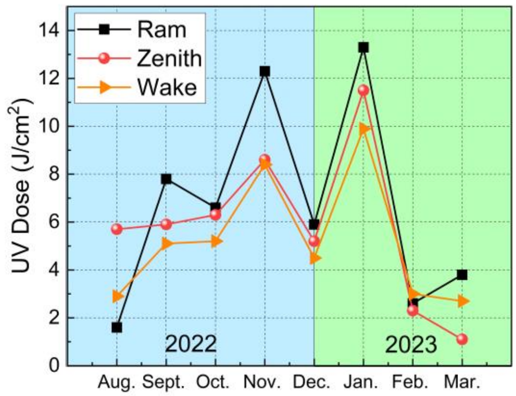


Figure 1. UV dose received by MSCs at different ISS faces.

Regarding temperature fluctuations experienced by the MSCs during the 6 months of the mission shown in Fig. 2, the temperature did not go down below negative 34.3 °C (noticed in Dec. 2022 on the swing side of the MSC mounted on wake ISS face) and did not rise above positive 44.8 °C (noticed in Oct. 2022 the on the swing side of the MSC mounted on zenith ISS face).

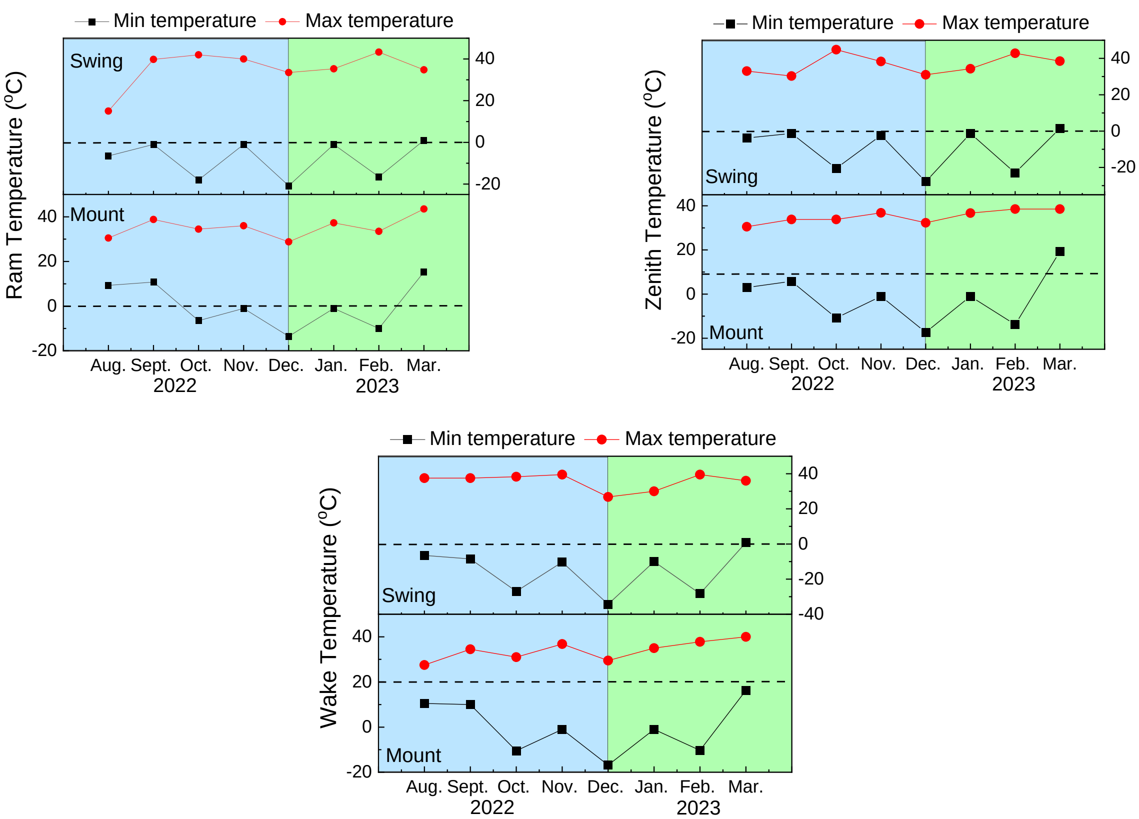


Figure 2. Measured temperatures of the mount and swing sides of each MSC during MISSE-16 mission.

The total AO fluence experienced by each MSC is summarized was 1.6 x 10^{19} atoms/cm^2 (wake), 7.01 x 10^{18} atoms/cm^2 (zenith), and 3.07 x 10^{20} atoms/cm^2 (ram). AO fluence was determined using the mass loss technique based on dehydrated mass measurements before and after flight [5]. The Kapton witness sample on each MSC had an exposed area of 4.661 cm^2.

Finally, to evaluate the electron dose received by each MSC carrier, passive radiation sensors from Landauer were utilized (Luxel+ PA dosimeters and the units are in mrem). The Luxel+ PA samples were stored below the sample tray, inside the MSC. The power radiation sensor was also utilized for the characterization of the LEO environment, however, the results were inconclusive. The deep dose equivalent (DDE) electron irradiation dose received by each MSC was 1.8 x 10^4 mrem (wake), 1.5 x 10^4 mrem (zenith), and 1.2 x 10^4 mrem (ram).

In addition to the above mentioned loose-sample anomaly observed on zenith 3 MCS, several other anomalies were registered during the MISSE-16 mission. On Dec. 14th, 2022, a coolant leak was observed on the Soyuz spacecraft docked at MRM 1 (Nadir docking port); the exact cause has not been confirmed. The leak was spraying away from MISSE-FF and not impacting the MSCs. On Feb. 11th, 2023, another coolant leak occurred from the Russian Progress spacecraft. The Progress spacecraft was located at MRM 2 (Poisk) docking port and it appeared that the leak direction was away from MISSE-FF and did not appear to contaminate MISSE-16 samples. This Soyuz spacecraft was undocked on Feb. 18th, 2023.

3 Details of the orbital experiments

One of the specific objectives of the MISSE-16 project includes measurement of changes in spectral reflectivity for a variety of novel and heritage spacecraft materials as a function of LEO environmental exposure. To achieve this goal, the camera and lighting scheme of each MSC used was upgraded. The Basler daA1600-60uc camera with IR LED illumination provides broad illumination ranges and detection in IR region. In previous MISSE-FF camera configuration, imaging on the night side was performed with LEDs with peak wavelengths at 450 nm and 600 nm for more consistent illumination. We added LED illumination using LUXEON IR Compact Line LEDs, with peak wavelengths at 850 nm and 940 nm, to cover the IR portion of the new camera's spectral response. During the MISSE-FF mission, images were taken with all the LEDs (visible and IR) shining simultaneously.

The utilized imaging cadence of MISSE-16 samples included daily images of each sample located at ram, zenith, and wake ISS faces taken for the first 7 days (7 measurements total), weekly images of each sample for the next two months (8 measurements total), and monthly images for the remaining duration of the mission. A summary of orbital measurements performed during the MISSE-16 mission is presented in Table 1.

Table 1. Dates of orbital measurements performed during MISSE-16 mission. Blue and green cells correspond to the year 2022 and 2023, respectively.

M16-C3 Zenith 3						**M16-C3 Ram 3**						**M16-C3 Wake 3**					
Daily		Weekly		Monthly		Daily		Weekly		Monthly		Daily		Weekly		Monthly	
1	08/16	1	08/31	1	08/09	1	08/30	1	09/12	1	08/30	1	08/22	1	09/06	1	08/22
2	08/17	2	09/06	2	09/06	2	08/31	2	09/19	2	09/12	2	08/23	2	09/12	2	09/06
3	08/18	3	09/12	3	10/12	3	09/01	3	09/26	3	10/12	3	08/24	3	09/19	3	10/13
4	08/19	4	09/19	4	11/09	4	09/02	4	10/05	4	11/10	4	08/25	4	09/26	4	11/09
5	08/20	5	09/26	5	12/05	5	09/03	5	10/12	5	12/05	5	08/26	5	10/06	5	12/05
6	08/21	6	10/05	6	01/18	6	09/04	6	10/19	6	01/18	6	08/27	6	10/12	6	01/18
7	08/22	7	10/12	7	02/19	7	09/05	7	10/26	7	02/23	7	08/30	7	10/19	7	02/19
		8	10/19	8	02/24			8	11/02	8	03/12			8	10/26	8	03/14

4 Launched materials

Table 2 presents a comprehensive list of the materials investigated during the MISSE-16 mission. Identical sets of these materials were mounted on ram, wake, and zenith faces of ISS. This selection encompassed various classes of polymers, including the extensively studied Kapton-HN® film, which serves as our reference material. Additionally, we included several novel Kapton variations in the mission, specifically CR (corona-resistant, crucial for shielding sensitive spacecraft equipment), CS (clear, smooth, a potential alternative to traditional PI film in Multi-Layer Insulation blankets), WS (a possible substitute for traditional PI film in Multi-Layer Insulation blankets), XC (electrically conductive, significant for mitigating space charge on spacecraft), and TF (thermoformable, a prospective material for small satellite component manufacturing). Lastly, we introduced the innovative 200DR9 polymer material, representing an unexplored high-performance organic polymer for spacecraft applications, to our polyimide selection list.

PET film (Mylar®) plays a pivotal role in the construction of Multi-Layer Insulation (MLI) blankets, vital for passive thermal control on the exterior surfaces of spacecraft. In our research, we incorporated two innovative Mylar variants, namely Melinex® 454 and Mylar® MO21, with the specific aim of enhancing MLI performance and durability. Liquid crystal polymer (LCP) resin stands out as a distinctive material category renowned for its exceptional dimensional stability, characterized by fatigue resistance, and its remarkable high dielectric strength across a broad temperature spectrum. These remarkable qualities, combined with its lightweight nature, render LCP materials highly appealing for space applications. However, before proposing LCP materials to spacecraft designers, a rigorous evaluation of their durability under the challenging conditions of LEO is imperative. We included Zenite® LCP film manufactured by DuPont into the list of launched materials.

PI/Polyhedral Oligomeric Silsesquioxane (POSS) hybrid materials, such as NeXolve's AO-resistant CORIN® XLS and Thermalbright® N, have already been identified as excellent AO-resistant materials. A detailed study of their optical properties will be of great utility to the remote sensing community for the characterization of orbital debris and operational resident space objects (RSOs).

Carbon Fiber Reinforced Polymer (CFRP, Economyplate™) and Glass Fiber Reinforced Polymer (GFRP, G-10/FR4 Glass Epoxy) are advanced materials used in modern LEO satellites. However, there is limited laboratory data on their optical properties and potential degradation in the LEO environment. Our objective in studying these materials is to establish a baseline understanding of their behavior in harsh LEO conditions, employing optical monitoring for improved space situational awareness. CFRP, known for its low albedo, has exhibited fragmentation into plate-like and needle-like fragments in laboratory impact tests [6]. However, it remains uncertain whether these fragments alter their albedo, posing a risk for ground-based observations in the orbital debris environment. Meanwhile, GFRP, which tends to be translucent, lacks comprehensive laboratory studies on its degradation over time. The alumina coupons were included in every set of launched materials to serve as an imaging calibration standard. Thin materials were mounted in layers to the nominal thickness of the stack equal to 10 mils.

Table 2. Materials corresponding to #1-15 in the MISSE-16 sample tray

	Material	Type	Thickness (mil)
1	Kapton® CR	PI/PMDA	2
2	Kapton® CS		2
3	Kapton® WS		1
4	Kapton® XC		2
5	Kapton® TF		4
6	DR9		2
7	Kapton® HN		3
8	Economyplate™ Carbon Fiber	CFRP	29
9	G-10/FR4 Glass Epoxy	GFRP	66
10	Zenite®	LCP	3
11	Melinex® 454	PET	5
12	Mylar® M021		9
13	CORIN®XLS	POSS	0.6
14	Thermalbright®N		0.8
15	Alumina	Alum. Oxide	3.8

5 Representative orbital measurement results

In this section, representative results of orbital measurements performed during the MISSE-16 mission are presented. It's important to highlight that a hardware anomaly hindered AEGIS Aerospace from fully extending both wake 3 and ram 3 sides of the MSC. While the wake 3 swing and ram 3 swing sides of the MSC were visually observed to have partially opened, there was a malfunction in the sensor indicating its full opening and locking status. Consequently, although AEGIS could confirm the swing side's partial opening, they lacked confirmation of it being completely open and securely locked in place. This raised concerns about the possibility of the camera trolley encountering issues, such as crashing or becoming stuck, if it passed over the hinge. As a risk mitigation measure, AEGIS opted to restrict the camera's movement only up to the hinge, thereby avoiding movement beyond it (i.e., only on the mount side). Thus, no images from samples mounted on the wake 3 swing and ram 3 swing sides of the MSC, which are samples #12 (Mylar® M021), #13 (CORIN XLS), #14 (Thermalbright® N), and #15 (Alumina), were taken during the mission.

Fig. 3 presents visible and IR images of Kapton® CS taken on the LEO orbit during the 6 months of the MISSE-16 mission. To characterize potential changes in the exposed materials, images captured the first day MSCs were open (representing initial condition in a pristine state), one week after initial data collection, and routinely on a monthly cadence till of the mission, are presented.

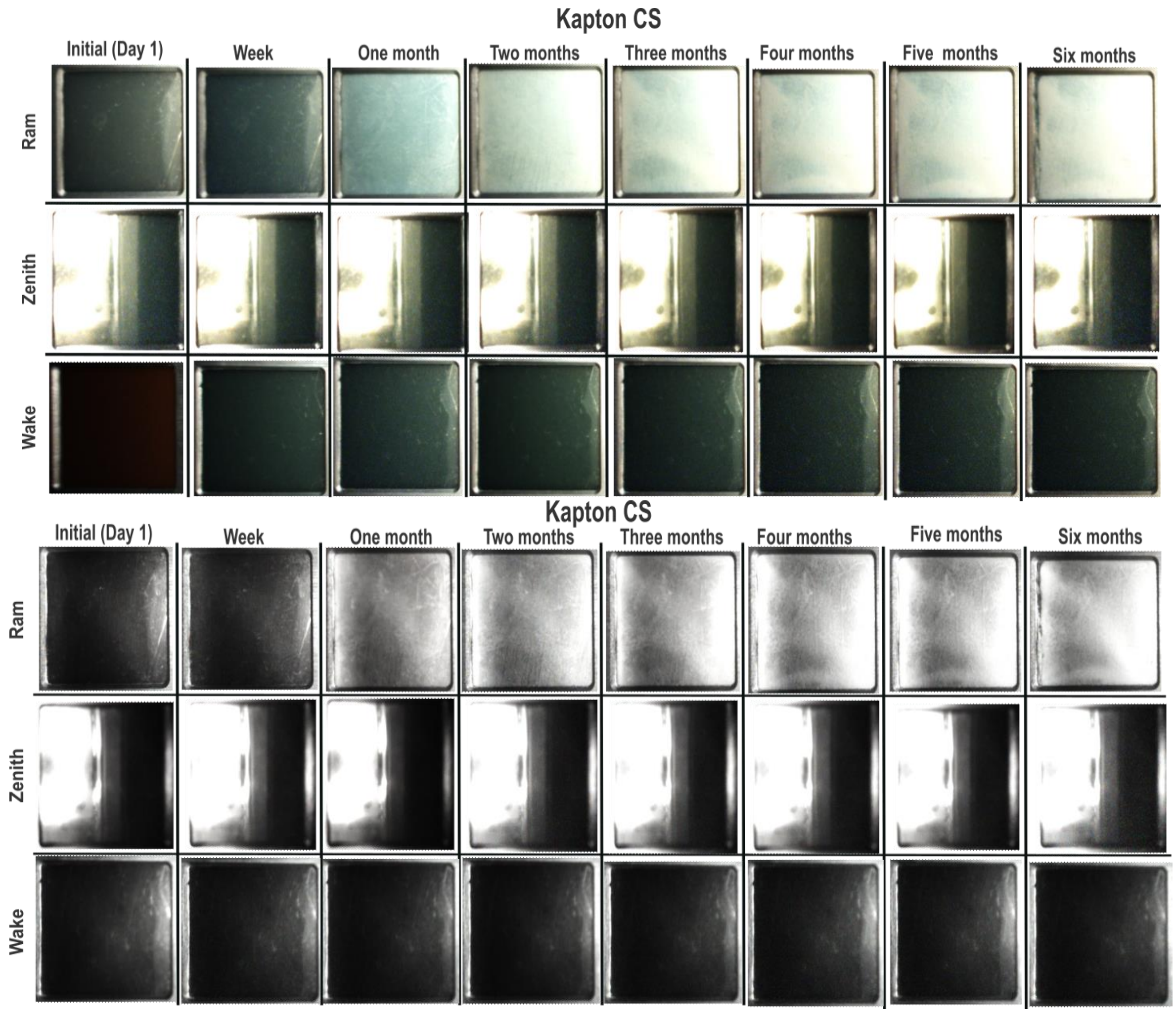


Figure 3. (Top) Visible and (bottom) IR images of Kapton® CS evolution on ram, wake, and zenith faces of ISS during the MISSE-16 experiment. Image credit: AEGIS Aerospace.

The camera images effectively recorded Kapton® CS's response to atomic oxygen, showcasing erosion of glossy surfaces and the development of a cloudy appearance on previously transparent samples due to surface roughening. Additionally, we observed color degradation on Kapton CS coupons exposed to the predominant electron (wake) and VUV (zenith) irradiation. Importantly, there were no signs of mechanical damage induced by the space environment, such as holes or scratches.

Orbital images were delivered to the ground for analysis after each performed measurement. Then, a machine learning (ML) approach based on a radial basis function (RBF) network [7] developed by GTRI was utilized to extract reflectance spectra from RGB/IR images. Once images were downloaded from the on-orbit MISSE-FF cameras, the RGB data were selected from non-oversaturated regions under both visible and IR lighting conditions. Next, these pixel counts were white-balanced given the scene context, which is possible because the same settings have been applied to the flight and ground cameras. Finally, the RGB MISSE-FF data were converted into the L*a*b* color space as shown in Fig. 4 below and fed into the RBF network. The ML algorithm produced an estimated reflectance spectrum for each image. A summary of the approach utilizing ML and computer vision algorithms to retrieve reflectance data from RGB images is shown in Figure 4.

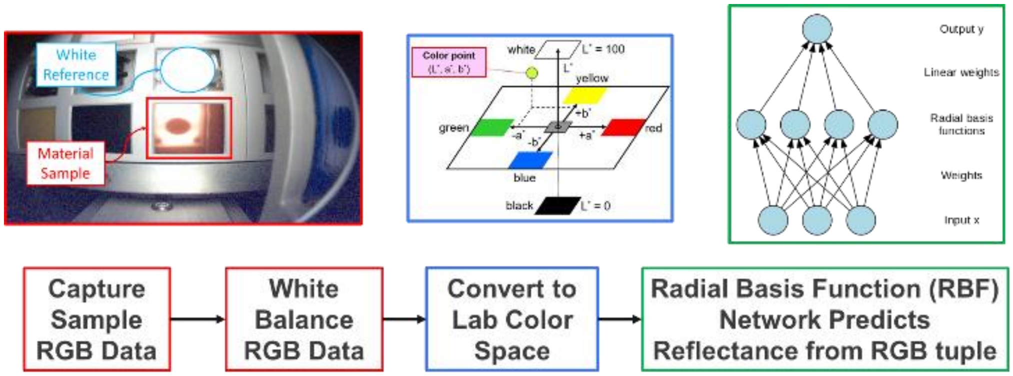


Figure 4. Summary of approach utilizing ML and computer vision algorithms to retrieve reflectance data from RGB images.

6 Returned materials

The de-integration of MISSE-FF materials took place on May 15, 2023, at the AEGIS Aerospace facilities, conducted by our team. Subsequently, our team conducted examinations of samples and aluminum frames from the ram, zenith, and wake MSCs to assess potential micrometeoroid and orbital debris (MMOD) impacts. No MMOD indications were detected on the experiment/sample side of the MSCs. Furthermore, on May 22, 2023, members of the NASA Hypervelocity Impact Technology (HVIT) team conducted MMOD examinations on the exterior surfaces of the MSCs that did not contain experimental/sample materials. Fig. 5 presents the mount and swing sides of ram 3 MSC with our payload still integrated.

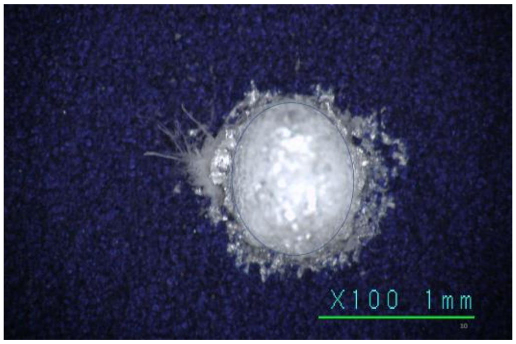

Figure 5. Ram 3 MSC with integrated MISSE-16 samples. Image credit: GTRI.

The objective of the MMOD inspection carried out by the NASA HVIT team was to identify all potential MMOD impacts/features using a 0.5 mm threshold for further examination. Although many features were identified below this threshold, they were noted in the internal report, but not further analyzed for the purpose of this evaluation. There were smaller craters identified but were not fully characterized. The eleven MMOD indications were discovered on the exterior surfaces of MSCs carrying our payload. Results are summarized in Table 3. Fig. 6 demonstrates representative images of craters observed during the MMOD inspection.

Table 3. Summary of the MMOD inspection results related to MSCs carried our payload.

Slot location	# of craters	Equivalent diameter (mm)	Depth* (mm)
Ram 3	3	0.61 – 0.88	0.21 – 0.39
Zenith 3	3	0.34 – 0.52	0.17 – 0.36
Wake 3	1	0.82	0.41

* Crater’s depth was accessed by an optical micrometer



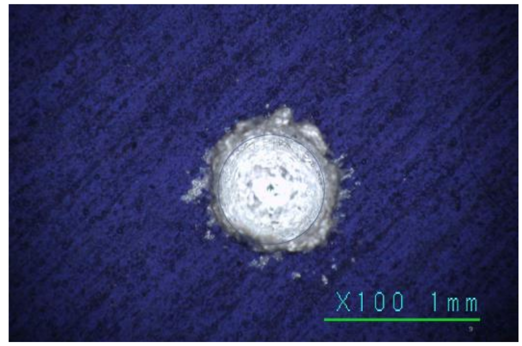


Figure 6. Representative images of MMOD craters observed on MSCs. The length x width (L x W) dimensions are (left) 0.98 mm (L) x 0.78 mm (W) and (right) 0.70 mm (L) x 0.68 mm (W). Image credit: NASA.

For vetting of newly developed materials for space situation awareness/space domain awareness applications under the LEO environment together with the development of accurate models describing novel and heritage material weathering on LEO, returned MISSE-16 materials need to be thoroughly characterized focusing on their space-induced optical, surface morphology, mechanical, and chemical properties changes. Next, these results need to be compared with flight-duplicate samples to establish correlation factors between true space exposure and accelerated space weather experiments. The feasible characterization measurements were conducted as part of the current project, however, it's important to acknowledge that the scope of these measurements is not exhaustive, and there remains a considerable amount of work to be undertaken. It is likely that further comprehensive characterization efforts will be pursued in the future, requiring a different level of commitment and resources.

The results of the characterization measurements on the returned Kapton® CS material, along with a comprehensive comparison to flight duplicate coupons of the same materials exposed to atomic oxygen (AO), high-energy electrons, and VUV irradiation at ground facilities, are extensively elaborated in the associated papers included in proceedings of the 2nd International Orbital Debris Conference and authored by Shah et al., “Overview of the MISSE-16 Mission and Preliminary Characterization of Novel Space Weathered Materials” (#6006), and Westrick et al., “Micrometeoroid and atomic oxygen impacts on materials International Space Station Experiment (MISSE)-16 flight samples” (#6008).

7 Conclusion

In conclusion, the MISSE-16 mission has provided valuable insights into the behavior and response of various space materials in the challenging environment of LEO. Through meticulous experiments and comprehensive analysis, we have gained a deeper understanding of how these materials endure exposure to atomic oxygen, high-energy electrons, and VUV irradiation. The results presented in this paper, and in related work by J. Shah and S. Westrick, alongside the meticulous comparisons with ground-based experiments, underscore the significance of studying the space weathering effects on materials intended for space applications. We have observed changes in optical properties, surface roughening, and color degradation, all of which have critical implications for spacecraft design and longevity.

As we continue to explore and utilize space for various purposes, the knowledge gained from missions like MISSE-16 is invaluable for enhancing the resilience and performance of space materials. The data collected here not only advances our understanding of space weathering but also contributes to the development of more durable and reliable spacecraft components. Moreover, the collaboration with Aegis Aerospace and NASA has been instrumental in the success of this mission, and we express our sincere gratitude for their unwavering support and expertise. We look forward to continued collaboration and exploration as we strive to push the boundaries of our understanding of space weathering and its implications for the future of space exploration and technology.

8 Acknowledgements

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9 Public Release Clearance

10 References

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