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Ground-Based Imaging and Data Analysis for the MISSE-22 Spaceflight Experiment

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Abstract

The low Earth orbit (LEO) environment presents unique challenges for spacecraft materials causing their progressive degradation. While ground-based simulations and mathematical models attempt to replicate these conditions, they cannot fully capture the nature and extent of material degradation in LEO. This research characterizes natural space environment effects on material stress using the Materials International Space Station Experiment Flight Facility (MISSE-FF). Building on MISSE-16, which captured temporal spectral changes in spacecraft materials, the current MISSE-22 mission evaluates mechanical property alterations in innovative materials under LEO exposure. We utilize the photoelastic

effect, where mechanical stress induces birefringence, assessed through a specialized polariscope integrated within MISSE-FF. Shifts in color patterns serve as qualitative indicators of mechanical stress in thin films. Details of the MISSE-22 mission parameters, material selection criteria, payload integration testing, and pre-launch control data serving as ground truth for evaluating space-exposed materials are discussed.

Keywords: Spacecraft Materials, ISS, MISSE, atomic oxygen, photoelasticity

1 Introduction

The harsh environments found in Earth’s orbits lead to progressive degradation of spacecraft materials, affecting their mechanical, optical, and chemical properties ultimately compromising system performance and mission longevity. The effects of exposure to the low Earth orbit (LEO) environment include surface erosion, microcracking, changes in reflectivity and transmissivity, and increased corrosion susceptibility due to exposure to ionizing radiation, charged particles, atomic oxygen (AO), and extreme thermal cycling [1–3]. While laboratory-based studies attempt to simulate such conditions on Earth, they often fail to fully replicate the dynamic and multifactorial nature of the actual LEO environment. Variables such as solar activity, orbital velocity, and concentrations of chemical species are difficult to reproduce accurately in ground-based facilities [4–6]. Further, the determination of the accuracy of space-weathering simulations can be ambiguous without directly comparable on-orbit measurements.

The International Space Station (ISS), through the Materials International Space Station Experiment Flight Facility (MISSE-FF), offers a unique opportunity to overcome these limitations by serving as a true space environment testbed [7]. It enables direct, long-term exposure of test articles to LEO conditions under closely monitored settings and the ability to perform quantitative measurements on-orbit. As such, data obtained from experiments conducted onboard the ISS provide a crucial baseline reference for validating and calibrating ground-based material degradation simulations.

Our team previously investigated the spectral degradation (in four color bands, B,G,R, and near-infrared, NIR) of a variety of novel and heritage spacecraft polymer materials exposed to the space environment aboard the MISSE-16 mission, returned from the ISS in 2023 after six months LEO exposure [8–10]. Material sets were mounted in three orientations on the MISSE-FF, allowing us to study the effects of high-energy particle exposure (wake face), vacuum ultraviolet (VUV) radiation (zenith face), and AO impact (ram face), each representing a unique component of the LEO environment.

Building upon MISSE-16, which captured temporal changes in the visual and IR spectral properties of heritage and novel spacecraft materials, the upcoming MISSE-22 mission (scheduled for Spring 2026 launch) evaluates how mechanical properties of innovative materials evolve under prolonged LEO exposure. Among LEO environmental factors, AO is recognized as the most aggressive threat to spacecraft

surfaces [11, 12]; therefore, the experimental payload is positioned on the ram-facing surface of the MISSE-FF science carrier to maximize AO fluence.

Historically, MISSE projects have primarily focused on post-flight assessment of materials exposed to LEO space weather, with limited emphasis on in-situ mechanical property evaluation. Notable exceptions include MISSE-1, which employed a tensile test fixture to subject samples to strain during exposure; post-retrieval analysis subsequently measured tensile strength and elongation to failure of surviving materials [13]. Similarly, MISSE-7 utilized a flexural stress fixture to investigate bending effects on samples [14]. The Active Polymer Strain Experiment (APSE) aboard MISSE-6 examined environmentally induced shrinkage in free-standing polymers as a function of exposure duration [15]. Despite these efforts, no prior mission has captured dynamic, real-time changes in material mechanical properties under continuous LEO exposure.

This study addresses this gap by characterizing temporal evolution of mechanical properties in novel materials under AO exposure through integration of an advanced photoelasticity-based imaging system. The approach utilizes the photoelastic effect, wherein mechanical stress induces birefringence in a material [16, 17]. When polarized light enters a stressed birefringent material, it splits into two component beams traveling at different velocities. This velocity difference, termed optical retardation, produces characteristic interference fringe patterns with distinct color bands when viewed through a polarizing filter. These fringe patterns directly correspond to the stress distribution within the material, enabling visualization of internal mechanical states that evolve as materials degrade under LEO exposure.

To exploit this phenomenon for LEO material characterization, we developed a specialized polariscope purpose-built for MISSE-FF integration. Samples are subjected to controlled tensile stress through mechanical deformation, producing baseline interference patterns prior to launch. Throughout the mission, shifts in fringe color patterns and distributions serve as qualitative indicators of mechanical property changes in the thin films resulting from cumulative AO exposure.

The material suite comprises eleven novel AO-resistant polymers, including siloxane-, polyhedral oligomeric silsesquioxane (POSS)-, and polyimide (PI)-based films. To monitor temporal evolution of mechanical properties, polariscopic images will be captured at monthly cadence, complemented by standard RGB imaging to track surface degradation throughout the mission duration.

This paper details the MISSE-22 mission parameters, material selection criteria, and payload integration and functional testing conducted by our partner, Aegis Aerospace. We establish pre-launch control datasets serving as ground truth baselines, describe the photoelastic imaging methodology, and outline the polariscope design enabling continuous in-situ stress monitoring. By correlating temporal stress evolution with cumulative AO exposure, this research bridges critical gaps between ground-based testing and actual LEO conditions. The resulting data will inform predictive models for material degradation and support development of next-generation space-resistant polymers essential for long-duration missions beyond Earth orbit.

2 Materials and Methods

2.1 Materials

Material candidates for this mission were required to meet several key criteria: optical transparency or translucency to enable photoelastic imaging, sufficient birefringence to produce detectable stress-induced interference patterns, mechanical flexibility to accommodate controlled tensile loading, and novelty in AO-resistant formulation or design approach. To identify optimal candidates, we conducted extensive ground-based screening of 32 materials, evaluating photoelastic response in both pristine and AO-exposed states using laboratory hardware. This down-selection process yielded eleven polymers demonstrating favorable optical and mechanical characteristics suitable for flight. Discussion herein focuses exclusively on these flight-selected materials

Unlike MISSE-16, which utilized commercially available polymers, the MISSE-22 payload comprises a diverse suite of novel, purpose-developed materials representing collaborative efforts across industry, academia, and government research institutions. Partner-contributed materials include: novel AO-resistant compounds developed by DuPont; polyhedral oligomeric silsesquioxane (POSS)-based films synthesized at Georgia Institute of Technology (GT); Bendable Electrostatic Dust Shield (BEDS) components fabricated by Hedgefog Research Inc. (HFR); and siloxane-based films designed and synthesized at Air Force Research Laboratory (AFRL), Wright-Patterson Air Force Base. For reference purposes, two well-characterized heritage materials, Melinex[®] 453 and Kapton[®] HN, were included to enable direct comparison between novel compounds and materials with extensively documented LEO degradation behavior. These reference standards provide established benchmarks against which the AO resistance performance of experimental materials can be assessed. Table 1 and Figure 1 detail MISSE-22 material specifications and pristine form appearance.

Table 1 MISSE-22 Examined Materials.

ID	Material	Type	Thickness (μm)	Manufacturer
1	AFRL RX-1	PI/D4HV	25	WPAFB
2	AFRL RX-2	PI D4HV	25	WPAFB
3	BEDS-1	BEDS	125	HFR
4	BEDS-2	BEDS	50	HFR
5	GT-1	PI/POSS	25	GT
6	GT-2	PI/POSS	25	GT
7	GT-3	PI/POSS	25	GT
8	Kapton [®] CRC	PI	25	DuPont
9	Kapton [®] CR	PI	25	DuPont
10	Kapton [®] HN	PI	50	DuPont
11	Melinex [®] 453	PET	75	DuPont

Siloxane-based polymers constitute promising class of materials for LEO applications. Their silicon-oxygen backbone structure with organic side groups provides

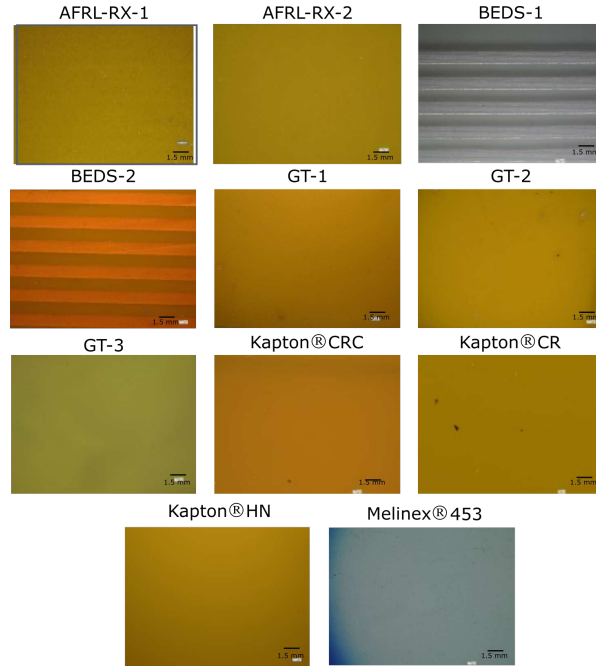


Fig. 1 Optical micrographs of pristine MISSE-22 payload materials acquired using a Keyence VHX-7000 microscope at 20x magnification.

excellent resistance to VUV radiation, vacuum-induced outgassing, and extreme thermal cycling [18, 19]. The siloxane-based composites prepared for the MISSE-22 mission consist of a single layer of oxide fiber embedded in a highly cross-linked siloxane-based matrix. Further details on the synthesis of materials and exact molecular structure remain restricted.

The BEDS is a dust-mitigation technology developed by HFR in collaboration with NASA Kennedy Space Center [20]. BEDS utilizes electrodynamic principles to actively repel and remove dust particles from surfaces through application of oscillating electric fields, addressing a critical challenge for long-duration lunar and planetary missions. While BEDS demonstrates proven dust-mitigation capabilities, its polymer substrate and embedded electrode system remain vulnerable to AO degradation in LEO transit. Inclusion in MISSE-22 enables evaluation of AO-induced mechanical property changes that could compromise dust shield flexibility and electrode integrity during extended space exposure. Two samples were selected for the payload, consisting of copper electrode layers deposited onto Kapton® HN and ITO electrodes on PET substrates.

POSS-based polymers represent another promising class of advanced materials for enhanced AO resilience. Under AO oxidative attack, siloxane structures convert to silica, self-organizing into a protective barrier layer [21, 22]. The cage-like silica core imparts exceptional thermal stability, radiation resistance, and oxidative durability, while the tunable organic periphery enables incorporation into diverse polymeric systems for coatings, structural composites, and multifunctional spacecraft

components. The GT samples utilize a CORIN[®] XLS polymer matrix modified with aminopropylisobutyl POSS (AM0265).

Kapton[®] CR and CRC are advanced PI films engineered to withstand the synergistic effects of coronal discharge and AO erosion. Both variants utilize a modified PI backbone and an AO-resistant coating to provide a dual-defense mechanism against ionization and reactive oxygen species. By combining these chemical enhancements with high dielectric strength, these films maintain superior thermal and structural integrity where standard PIs would otherwise fail.

Finally, two well-characterized benchmark materials were included in the MISSE-22 payload: Kapton[®] HN (polyimide, PI) and Melinex[®] 453 (polyethylene terephthalate, PET). PI films are widely utilized as lightweight, flexible substrates for multilayer insulation (MLI) due to their exceptional thermal stability, high temperature resistance, and superior dielectric properties [23]. Similarly, PET films serve as a critical component of MLI blankets, which provide passive thermal control for spacecraft exterior surfaces. By incorporating multiple layers of these thin reflectors separated by spacer materials, these composite systems effectively minimize radiative heat transfer, ensuring the thermal integrity of the spacecraft in the vacuum of space.

2.2 Flight Hardware and Optical System Design

This experimental hardware utilizes the photoelasticity phenomenon, in which birefringence is induced in a material when it is subjected to mechanical stress [24]. To capture and quantify this effect, the system employs a bottom-up, transmission-based optical setup designed to evaluate an array of 11 individual samples. At the base of the instrument, each sample is equipped with its own dedicated illumination source, consisting of a 12-volt LED light engine (DynaSquare, 150 lm, 120 mA drive current, 1" x 1" base, 5000K). To ensure a highly uniform light distribution, LEDs array is paired with a diffusion plate made of 0.02"-inch thick Delrin[®] film. The diffused light then propagates upward through a right-handed circular polarizer (0.106-inch thick soda lime float glass, 42% transmission, API Optics, Inc.), establishing a baseline polarization state before reaching the sample plane.

At the sample plane, each of the 11 samples is integrated into a custom-developed holder specifically designed to secure the material in a bent state, as shown in Figure 2. This induced mechanical stress ensures a consistent and repeatable color pattern for analysis. As the circularly polarized light travels through these stressed samples, the resulting birefringence alters the light's polarization state proportionally to the material's internal strain.

Positioned above the lower polarizer is the upper analyzer assembly. To significantly improve image contrast, this system utilizes two circular polarizers with opposite orientations; thus, the upper assembly features a left-handed circular polarization filter (16 mm outside diameter slip mount, MidOpt). This analyzer is coupled directly to a Basler daA1600-60uc camera—the same model currently utilized on the MISSE-FF. Finally, this entire upper imaging assembly is mounted to a lateral translation stage, enabling automated, horizontal scanning across all 11 independently illuminated samples without disrupting the precise optical alignment. Fully integrated MISSE-22 hardware assembly is shown in Figure 3.

The experiment is designated for installation on the ram face of the ISS to ensure appropriate environmental exposure. Once operational, the system will execute a monthly imaging sequence, translating across the sample holder to capture isolated data for each stressed material. These images will then be downlinked to Earth, allowing for time-resolved monitoring of the photoelasticity.

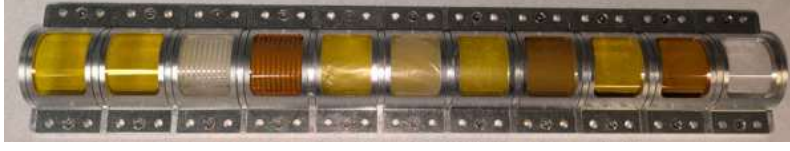


Fig. 2 MISSE-22 holder with integrated payload materials. Samples are numbered 1 through 11 in a left-to-right configuration.

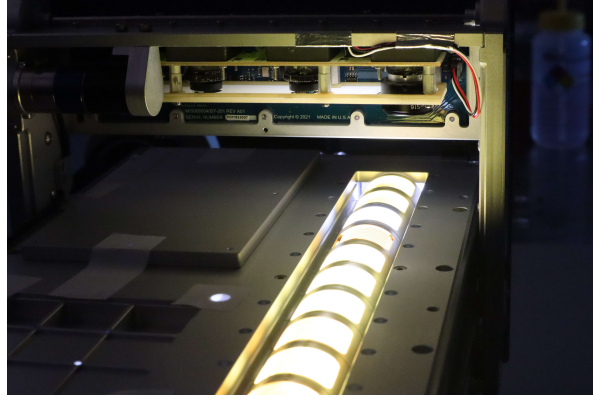


Fig. 3 MISSE-22 fully integrated hardware.

2.3 Image Analysis Approach

To estimate stress via image analysis, the stress-optic law is applied to the total fringe order distributed across the sample. In cases of pure bending, where the stress state is approximately uniaxial, the stress (σ) can be calculated using the following relationship 1:

$$\sigma = \frac{N f_{\sigma}}{t} \quad (1)$$

where (σ) is the calculated uniaxial stress (MPa), f_{σ} is the material fringe constant (N/mm) specific for each material, t is the sample thickness (mm) along the optical path, and N is the fringe order determined from the observed optical patterns.

We utilize a Gaussian mixture model (GMM) [25] to cluster each pixel based on its RGB value. A GMM is a probabilistic clustering algorithm that assumes all data

points are generated from a mixture of a finite number of Gaussian distributions. In image analysis, it is highly effective for segmentation tasks, as it can evaluate the continuous spectrum of RGB pixel values and group them into distinct, statistically defined clusters (such as individual fringes) with a high degree of precision.

3 Results and Discussion

Figure 4 presents polariscopic images of selected MISSE-22 payload samples taken during the functional testing performed by Aegis Aerospace. To clearly illustrate our GMM-based tracking methodology, this figure specifically highlights representative specimens that exhibited distinct isochromatic fringes during initial ground testing. These visible initial stress states serve as the baseline for demonstrating how the algorithm isolates and tracks fringe migration. A zero-stress optical baseline was established during ground testing for a select subset of the samples, including the AFRL RX-1, GT-synthesized, and Kapton[®] CR and CRC films. By continuously monitoring these initially featureless specimens, we can precisely isolate and quantify any environment-induced stress evolution throughout the mission.

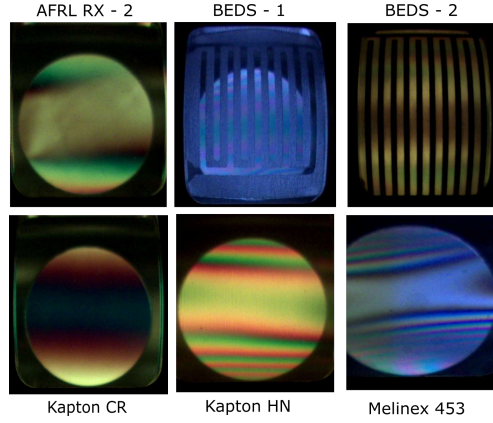


Fig. 4 Polariscopic images of selected MISSE-22 payload samples taken during the functional testing at Aegis Aerospace

Figure 4 displays characteristic photoelastic fringe patterns. These color bands represent contours of constant principal stress difference, visualizable via stress-induced birefringence. Each fringe corresponds to a specific integer or fractional fringe order, N . Specifically, the black fringe is the $N = 0$ order, marking the material's zero-stress principal stress difference and, in bending scenarios, the neutral axis.

Figure 5 illustrates the GMM-based fringe analysis applied to the Melinex[®] and Kapton[®] HN samples. Despite minor noise and isolated pixel misclassification, the algorithm successfully segments the primary fringe patterns. Because the orbital environment is expected to alter the size and spatial distribution of these fringes, we will track the centroid (center of mass) and the vertical width (along the y-axis) of each cluster as our primary metrics for stress evolution. Note that the assigned number of

clusters is specific to each sample and is determined empirically based on its initially observable fringes.

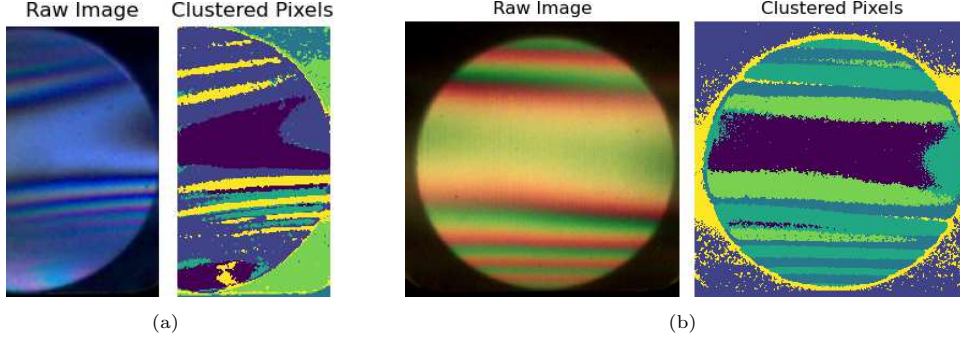


Fig. 5 Raw polariscope image alongside with the cluster assignments for (a) Melinex[®] 453 (b) and cluster assignments of Kapton[®] HN.

To establish a quantitative pre-flight baseline, the observable fringe orders for each sample were first extracted via visual inspection of the polariscopic images (Figure 4). These optical measurements were then converted into the baseline residual stress values summarized in Table 2 using the uniaxial stress-optic relationship (Equation 1). The requisite material fringe constants for these calculations were derived from established literature values for PI-based [26] and PET-based [27, 28] polymer films.

Currently, several samples exhibit identical calculated stress values, largely due to similarities in their respective stress-optic coefficients. However, we hypothesize that these internal stress states will evolve during orbital exposure. Because previous research [8] demonstrates that space aging induces significant optical and chromatic changes in these materials, it is highly probable that their underlying stress fields and associated photoelastic parameters will also undergo measurable alterations.

Table 2 Baseline calculated stress values for payload samples based on initial visual fringe orders.

Material	Thickness (mm)	Fringe constant, f_σ (N/mm)	Fringe order (N)	Calculated stress (MPa)
AFRL RX-2	0.025	0.46	1	18.4
BEDS-1	0.125	3.05	2	48.8
BEDS-2	0.050	0.46	2	18.4
Kapton [®] CR	0.025	0.46	1	18.4
Kapton [®] HN	0.050	0.46	3	27.6
Melinex [®] 453	0.075	3.05	4	162.7

Calculated stress values (table 2) reveal a that the PI-based films (AFRL RX-2, BEDS-2, and both Kapton[®] variants) exhibit relatively low and consistent initial stresses, ranging from 18.4 MPa to 27.6 MPa. In contrast, the Melinex[®] 453 sample

demonstrates a significantly higher baseline stress of 162.7 MPa, indicative of the high residual stresses inherently locked in during the biaxial orientation manufacturing process of PET films. The BEDS-1 composite, approximated here as a homogenous Melinex layer, yielded an intermediate baseline of 48.8 MPa.

4 Conclusion

This work describes the design and pre-flight validation of a photoelastic imaging system for monitoring spacecraft material stress changes during orbital flight on the MISSE-22 mission. This system enables observation of internal stress in polymer films exposed to the LEO environment.

Ground-based testing established baseline fringe patterns and stress estimates for various materials, including both heritage and novel AO-resistant polymers. These measurements serve as a reference for interpreting on-orbit changes. The stress is estimated through material-specific constants and fringe order. Fringe order was decided through visual inspection. However, for the actual on-orbit research, the stress will be determined by physical changes in the size and location of the fringes. These values will be estimated by clustering the pixels, finding the fringe clusters, and determining the overall changes in these fringe clusters during aging.

This approach moves beyond traditional post-flight analysis by enabling time-resolved, in-situ stress measurements throughout the mission. Periodic imaging of stressed samples will allow observation of changes in the stress under real environmental conditions. This work will progress over the next year as the on-orbit data is collected and analyzed. Ultimately, we will expect to have conclusive results describing how material stress changes under the LEO environmental effects.

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Declarations

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- Conflict of interest/Competing interests

On behalf of all authors, the corresponding author states that there is no conflict of interest.

- Consent for publication

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- Data availability

Not applicable.

- Materials availability

Not applicable.

- Code availability

Not applicable.

- Author contribution

Not applicable.

References

- [1] Grossman, E., Gouzman, I.: Space environment effects on polymers in low earth orbit. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **208**, 48–57 (2003)
- [2] Rooij, A.: Corrosion in space. *Encyclopedia of aerospace engineering*, 1–15 (2010)
- [3] Tompros, D., Mouzakis, D.E.: Space environment effects on equipment and structures—current and future technologies. *The Journal of Defense Modeling and Simulation* **21**(3), 283–291 (2024)

-
- [4] Kleiman, J., Horodetsky, S., Sergeyev, V., Issoupov, V., Ng, R.: Critical review of the design of space environment simulators: lessons learnt. In: the 10th International Symposium on Materials in a Space Environment (2006)
 - [5] Zhai, R., Yang, X., Jiang, L., Gao, H., Zhang, Y., Jiao, Z.: Synergistic effects of atomic oxygen and thermal cycling in low earth orbit on polymer-matrixed space material. *Heliyon* **9**(8) (2023)
 - [6] Yeritsyan, H.N., Sahakyan, A.A., Grigoryan, N.E., Harutyunyan, V.V., Arzumanyan, V.V., Tsakanov, V.M., Grigoryan, B.A., Davtyan, H.D., Dekhtiarov, V.S., Rhodes, C.J., *et al.*: Space low earth orbit environment simulator for ground testing materials and devices. *Acta Astronautica* **181**, 594–601 (2021)
 - [7] deGroh, K.K., Jaworske, D.A., Pippin, G., Jenkins, P.P., Walters, R.J., Thibeault, S.A., Palusinski, I., Lorentzen, J.R.: Materials international space station experiment (misse): overview, accomplishments and future needs. In: Annual International Space Station Research and Development Conference (2014)
 - [8] Westrick, S.A., Plis, E.R., Shah, J.R., Collman, S., Hoffman, R.C., Cowardin, H.: Atomic oxygen impacts on materials international space station experiment (misse)-16 flight samples. In: 2nd International Orbital Debris Conference (2023)
 - [9] Fouchal, Y., Ramirez, R., Beloreshka, M., Plis, E.A.: Comparative evaluation of spacecraft materials properties under simulated and true space environments. *The Journal of the Astronautical Sciences* **71**(6), 53 (2024)
 - [10] Plis, E.A., Badura, G.: The spectral characterization of novel spacecraft materials in the low earth orbit environment. *The Journal of the Astronautical Sciences* **71**(2), 15 (2024)
 - [11] Leger, L.J., Visentine, J.T.: Working group written presentation: Atomic oxygen. In: NASA, Langley Research Center, NASA (SDIO Space Environmental Effects on Materials Workshop, Part 2 (1989)
 - [12] Banks, B.A., Miller, S.K., deGroh, K.K., Demko, R.: Atomic oxygen effects on spacecraft materials. In: Ninth International Symposium on Materials in a Space Environment (2003)
 - [13] Dever, J.A., Miller, S.K., Sechkar, E.A., 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**(4-5), 371–387 (2008)
 - [14] Snow, K.E., De Groh, K.K., Banks, B.A.: The misse 7 flexural stress effects experiment after 1.5 years of wake space exposure. In: 2017 International Space Station Research and Development (ISS R&D) Conference (2017)

-
- [15] Waters, D.L., Groh, K.K., Banks, B.A., Sechkar, E.A.: Polymer strain experiment on misse 6. In: Protection of Materials and Structures From the Space Environment, pp. 57–71 (2013). Springer
- [16] Post, D.: Photoelasticity. Manual on experimental stress analysis, 3rd ed. Society for Experimental Stress Analysis, Westport, Conn, 176–192 (1979)
- [17] Kuznetsova, Y., Bowman, S., Lewis, N., Nawar, N., Collman, S., Badura, G., Gibson, Z., Shah, J.R., Beauchemin, R., Wilde, J., *et al.*: Evaluation of the mechanical properties of innovative spacecraft materials under a low earth orbit-simulated atomic oxygen environment. In: Space Simulation Conference (2024). Institute of Environmental Sciences and Technology
- [18] Li, Y., Li, Z., He, Y., Cao, S., Wang, L., Gao, H., Yuan, L., Wang, K., Xu, M.: Large-area flexible plasma-polymerized hdmso thin-film coating for low-earth-orbit spacecraft polymers: Excellent resistance to atomic oxygen and uv erosion. *ACS Applied Polymer Materials* **6**(18), 11604–11613 (2024)
- [19] Prakash, P., Weerasinghe, J., Levchenko, I., Prasad, K., Alexander, K.: Polyimide nanocomposites for next generation spacesuits. *Materials Horizons* **12**(11), 3633–3666 (2025)
- [20] Bell, J.: Bendable electrodynamic dust shields (beds). In: AIAA SCITECH 2022 Forum, p. 1692 (2022)
- [21] Minton, T.K., Wright, M.E., Tomczak, S.J., Marquez, S.A., Shen, L., Brunsvold, A.L., Cooper, R., Zhang, J., Vij, V., Guenther, A.J., *et al.*: Atomic oxygen effects on poss polyimides in low earth orbit. *ACS applied materials & interfaces* **4**(2), 492–502 (2012)
- [22] Zhang, Y., Wu, H., Guo, Y.-d., Yang, Y.-b., Yu, Q., Liu, J.-g., Wu, B.-h., Lv, F.-z.: Atomic oxygen-resistant polyimide composite films containing nanocaged polyhedral oligomeric silsesquioxane components in matrix and fillers. *Nanomaterials* **11**(1), 141 (2021)
- [23] Sibin, K., Esther, A.C.M., Shashikala, H., Dey, A., Sridhara, N., Sharma, A.K., Barshilia, H.C.: Environmental stability of transparent and conducting ito thin films coated on flexible fep and kapton® substrates for spacecraft applications. *Solar Energy Materials and Solar Cells* **176**, 134–141 (2018)
- [24] Cloud, G.: Optical methods in experimental mechanics: Part 33: Photoelasticity v—fringe patterns. *Experimental Techniques* **32**(5), 13–16 (2008)
- [25] Farnoosh, R., Zarpak, B.: Image segmentation using gaussian mixture model. *IUST international journal of engineering science* **19**(1-2), 29–32 (2008)
- [26] Noe, S.C.: A prism coupling study of optical anisotropy in polymide including

moisture, stress, and thickness effects. PhD thesis, Massachusetts Institute of Technology (1992)

- [27] Lee, Y., Liu, T., Wu, C., Lin, W.: Investigation on residual stress and stress-optical coefficient for flexible electronics by photoelasticity. *Measurement* **45**(3), 311–316 (2012)
- [28] He, Q., Wang, M., Du, Y., Qin, Q., Qiu, W.: Quantitative characterization of the anisotropy of the stress-optical properties of polyethylene terephthalate films based on the photoelastic method. *Polymers* **14**(16), 3257 (2022)