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Comparison of High-Performance Fiber Materials Properties in Simulated and Actual Space Environments

M.M. Finckenor
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July 2017

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LIST OF ACRONYMS

AO	atomic oxygen
AOBF	Atomic Oxygen Beam Facility
ePTFE	expanded polytetrafluoroethylene
ESH	equivalent Sun hours
EVA	extravehicular activity
LPSR	laboratory portable spectroreflectometer
MISSE	Materials on International Space Station Experiment
MSFC	Marshall Space Flight Center
PBO	p-phenylene-2,6-benzobisoxazole
ProSEDS	Propulsive Small Expendable Deployer System
TM	Technical Memorandum
UHMWPE	ultra-high molecular weight polyethylene
UV	ultraviolet

TECHNICAL MEMORANDUM

COMPARISON OF HIGH-PERFORMANCE FIBER MATERIALS PROPERTIES IN SIMULATED AND ACTUAL SPACE ENVIRONMENTS

1. INTRODUCTION

A variety of high-performance fibers, including DuPont™ Kevlar®, DuPont™ Nomex®, Kuraray Vectran™, and Honeywell Spectra® have been tested for durability in the space environment, mostly the low Earth orbital environment. These materials have been tested in yarn, tether/cable, and fabric forms. Some material samples were tested in a simulated space environment, such as the Atomic Oxygen Beam Facility (AOBF) and solar simulators. Other samples were flown as part of the Materials on International Space Station Experiment (MISSE). This Technical Memorandum (TM) is a consolidation of analyses performed at NASA Marshall Space Flight Center (MSFC) with collaboration with NASA Johnson Space Center. This TM does not include data previously published in NASA/TM—2007–215073, "A One-Piece Lunar Regolith Bag Garage Prototype," which includes radiation and simulated meteoroid/space debris impact testing of Vectran, Nextel®, Gore-Tex® expanded polytetrafluoroethylene (ePTFE), Nomex, Teijin Aramid Twaron®, and Zylon®.[1]

The data within this TM are presented for information only and can be used as guidelines for design of future spacecraft, provided that the requirements of each new design and the environmental effects on these materials are taken into account. Trade names are used in this TM to illustrate the use of various commercial materials and not to imply endorsement by the United States Government. The trade names or registered trademarks are the property of the companies listed in table 1.

Table 1. Companies and trademarked products mentioned in this TM.

Company	Material Trade Names
E. I. DuPont de Nemours, Incorporated	Kevlar®, Nomex®
Kuraray America, Incorporated	Vectran™
DSM	Dyneema®
Honeywell	Spectra®
W. L. Gore and Associates	Gore-Tex®
3M	Nextel™

2. ANALYSIS METHODS

The MISSE samples were photographed in normal light. Then, weight, solar absorptance, and infrared emittance were measured when possible. The samples were also photographed in black light. Because Kevlar, Nomex, and Vectran are hygroscopic, the following method was used 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. At that moment, the chamber was vented, and a timer started, and the sample was moved quickly to the nearby balance. Mass measurements were made every minute for 5 minutes, and regression analysis was used to determine mass at time zero. Mass measurements were made using either a Mettler AT261 or a Sartorius CPA225D balance. Solar absorptance and infrared emittance were measured with an AZ Technology Laboratory Portable Spectroreflectometer-300 (LPSR-300) and an AZ Technology TEMP-2000A infrared reflectometer, respectively. Tensile testing was performed in an Instron machine with a crosshead speed of 1 inch per minute.

3. KEVLAR

Kevlar has been tested in tether, fabric (sometimes referred to as webbing), and felt forms. MSFC tested two candidate tether materials for the Tethered Satellite System in 1986 and 1987, according to "Environmental Testing of Candidate Mission Tether Materials," an internal memorandum written by Fred D. Wills in October 1987. Both tethers had an inner core of conducting wire with a Teflon insulator. One candidate tether had Kevlar for both strength fibers and an outer weave. The other candidate tether also had strength fibers of Kevlar with a Nomex outer weave; this tether material will be discussed in section 4.

Samples of the Kevlar/Kevlar tether were exposed to thermal vacuum, ultraviolet (UV) radiation, atomic oxygen (AO), and electron and proton radiation at the expected levels for a 14-day Space Shuttle mission at an altitude of 264 miles (425 km). All of the samples were 4-foot sections and were tensile tested to failure after simulated space environment exposure. The thermal vacuum testing parameters were 55 hours at 125 °C and pressure less than 1×10^{-3} torr. The UV radiation exposure was for 55 equivalent sun hours (ESH) in less than 1×10^{-3} torr vacuum. The AO exposure was only given as 'two minutes at the highest setting' in a plasma asher. Only the middle 3 inches of tether were exposed in the UV and AO tests.

Electron and proton radiation exposures were performed in the Radiation Effects Facility using the Van de Graaff accelerators available at that time. Samples were exposed to 1×10^{13} and 1×10^{14} electrons/cm^2 of 400 keV energy and 1×10^{13} and 1×10^{14} protons/cm^2 of 1 MeV energy while under vacuum on the order of 1×10^{-6} torr. Only the middle inch of tether was exposed to radiation.

Tensile testing revealed that no matter the exposure environment, the strength of the Kevlar tether dropped about the same, ranging from –12% loss for UV exposure to –15% loss for thermal vacuum. Additional samples of tether were then placed in 1×10^{-6} torr vacuum for 48 hours and then tensile tested. The average strength loss was –13.5%. Microscopic examination of the tether samples did not reveal any obvious structural differences before and after vacuum exposure, and evidence indicated that the strength loss was due to outgassing of moisture and possibly the sizing agent used in the material. The tethers were made with Kevlar 29, which has approximately 7% moisture content, compared to Kevlar 49 with 3.5%.[2] The DuPont report includes UV sensitivity of Kevlar, but one might assume from the use of a Fade-Ometer that these tests were conducted in air rather than in vacuum.

Two different tethers, Kevlar and Dyneema, were tested in a simulated space environment for the Propulsive Small Expendable Deployer System (ProSEDS) program. ProSEDS used the Kevlar 49 type.

Seven samples of each tether were cut to approximately 150 cm (60 in) to provide sufficient length for tensile testing. Of that length, approximately 6.4 cm (2.5 in) at the center was exposed to AO, except for the control sample. The following samples were exposed to the following levels of AO: 5×10^{19}, 1×10^{20}, 2×10^{20}, 5×10^{20}, 7×10^{20}, and 1.07×10^{21} atoms/cm^2. A strip of Kapton, a material with known AO reactivity, was placed in the center of the fixture to monitor AO fluence (fig. 1). After AO exposure was completed, the tethers were tensile tested to failure. The results for Kevlar are shown in figure 2. The Dyneema results are discussed in section 6.

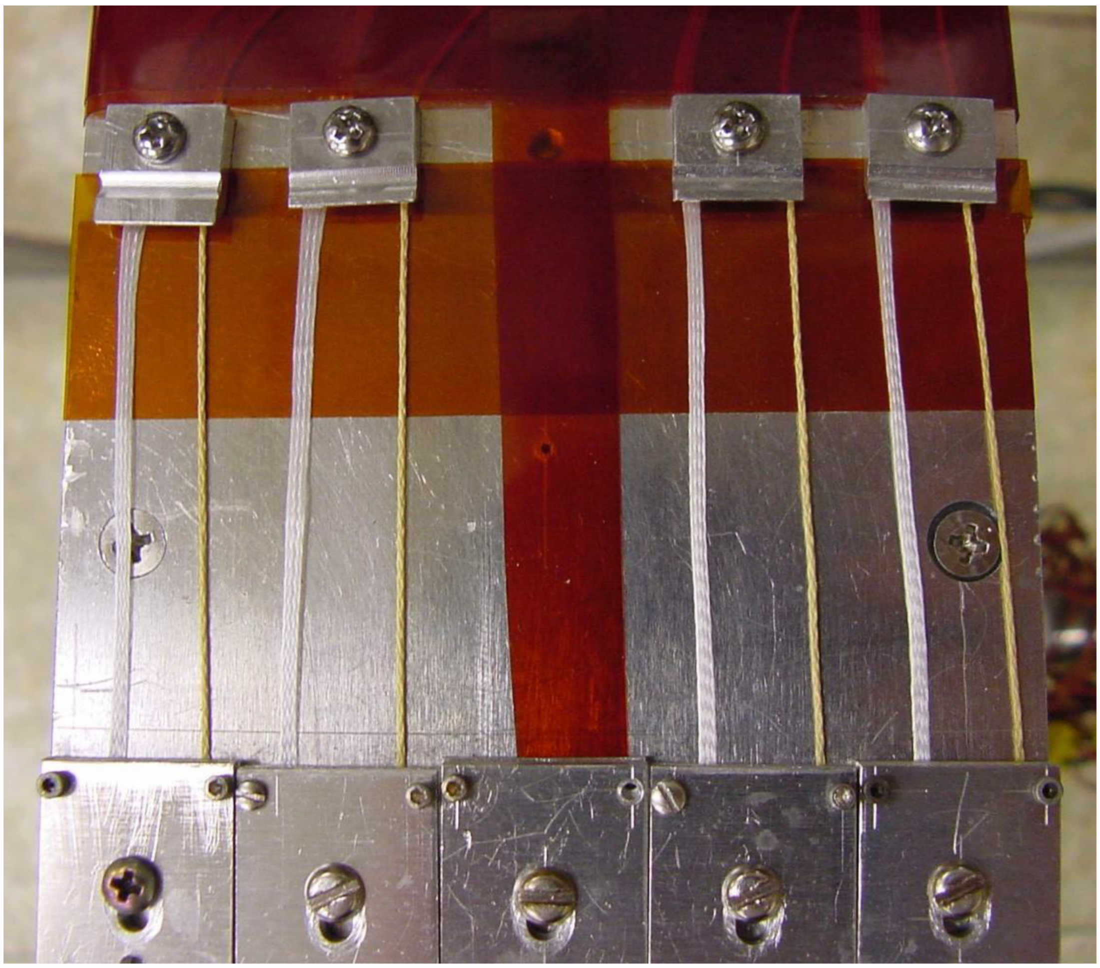


Figure 1. UHMWPE (white) and Kevlar (yellow) tethers in AO test fixture.

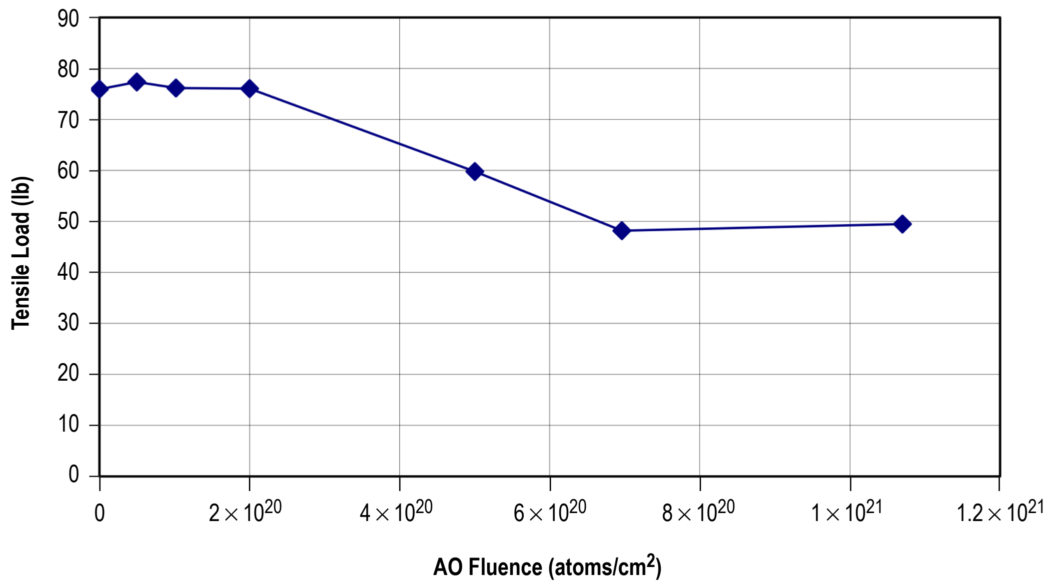


Figure 2. Tensile strength of Kevlar versus AO exposure.

The Kevlar tether exposed to 1.07×10^{21} atoms/cm^2 unexpectedly had slightly higher strength than the sample exposed to 7×10^{20} atoms/cm^2. This is the statistical problem with one sample for each level of exposure, and the author urges caution in using these data without further testing specific to a proposed design.

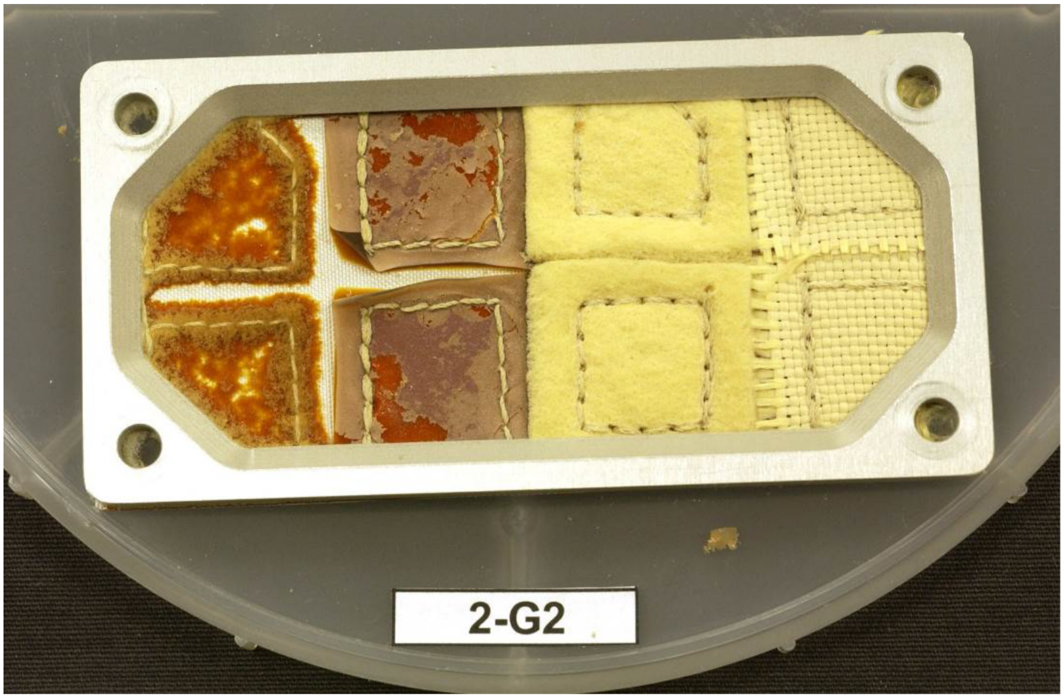
Samples of Kevlar fabric and felt were flown on MISSE-1, MISSE-2, and MISSE-4. The ram environment for MISSE-1 and MISSE-2 was $8 \pm 1 \times 10^{21}$ atoms/cm^2 of AO (depending on proximity to airlock) and 5,000–6,000 ESH of UV. The wake environment for MISSE-1 (shown in fig. 3) and MISSE-2 was $1.3 \pm 0.2 \times 10^{20}$ atoms/cm^2 of AO and approximately 5,000 ESH of UV. The MISSE-1 and MISSE-2 samples also underwent approximately 23,000 thermal cycles of –40 to 40 °C. The ram environment for MISSE-4 was $2.1 \pm 0.3 \times 10^{21}$ atoms/cm^2 of AO, approximately 1,200 ESH of UV, and approximately 5,800 thermal cycles.

Figure 3. MISSE-1 wake-side sample of Kevlar fabric.

The MISSE-2 and MISSE-4 samples, as shown in figures 4 and 5, were part of an experiment to test air bladder, insulation, and meteoroid/space debris shielding materials for TransHab. Since these samples were sewn into a larger sample and have not been disassembled, mass change is not available. These samples showed some AO erosion and no significant darkening or bleaching.

Table 2 is the measured solar absorptance and infrared emittance for the MISSE Kevlar. The solar absorptance of the MISSE-2 ram sample 2-G2 was a little less than the other Kevlar samples because it was assembled with Kapton as a backing material. The other samples were measured with a black background.

(a)



(b)

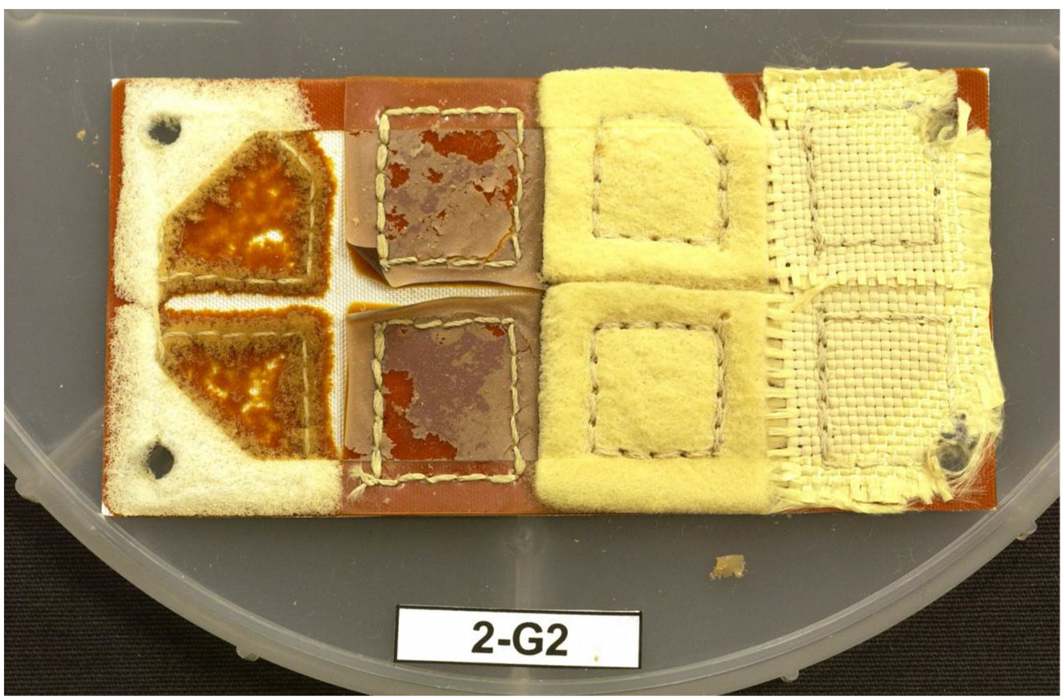


Figure 4. MISSE-2 ram-facing sample array of TransHab candidate materials: (a) With bracket in place and (b) with bracket removed to show original material. Left to right: Polyurethane foam, Combi-Therm bladder material, Kevlar felt, and Kevlar fabric, with Kapton and aluminized beta cloth for backing.

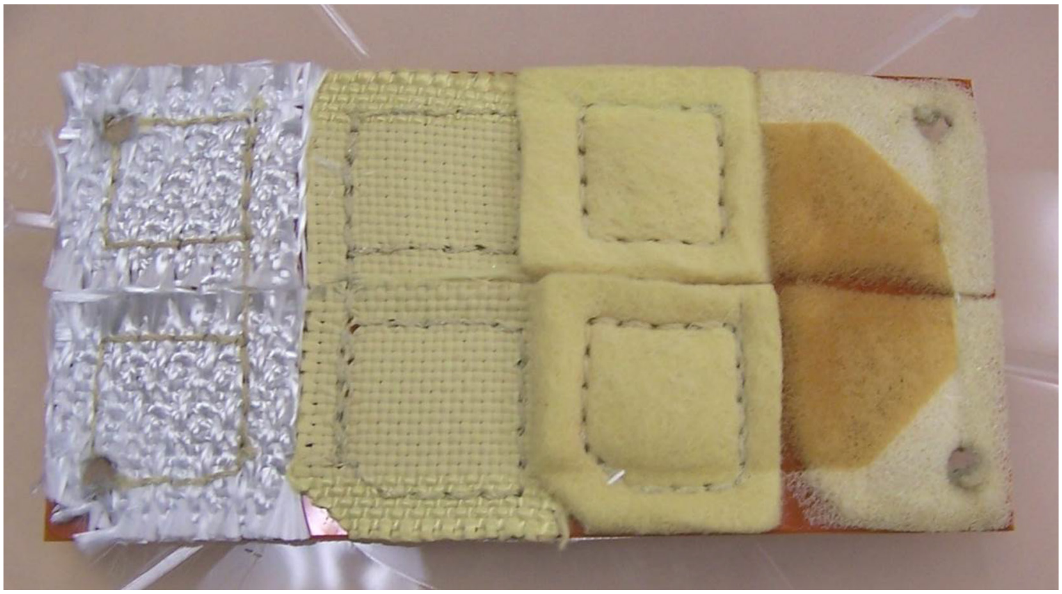


Figure 5. MISSE-4 ram-side sample array with Kapton and aluminized beta cloth backing. Left to right: Nextel fabric, Kevlar fabric, Kevlar felt, and polyurethane foam. Nextel with backing postflight: solar absorptance 0.25 and infrared emittance 0.90; preflight or control optical properties are not available.

Table 2. Optical properties of Kevlar samples.

Sample	Material	Solar Absorptance		Infrared Emittance	
		Preflight	Postflight	Preflight	Postflight
M1 Ram 1-E10-32	Felt	–	0.514	–	0.81
M1 Wake 2-E11-8	Fabric	0.413	0.445	0.83	0.83
M1 Wake 2-E11-28	Fabric	0.413	0.426	0.83	0.83
M2 Ram 2-G2-2A	Felt	–	0.399	–	0.86
M2 Ram 2-G2-2B	Felt	–	0.418	–	0.86
M2 Ram 2-G2-1A	Fabric	–	0.386	–	0.88
M2 Ram 2-G2-1B	Fabric	–	0.378	–	0.88
M2 Ram 2-E7-23	Fabric	0.416	0.432	0.84	0.86
M2 Ram 2-E7-28	Fabric	0.420	0.438	0.84	0.86
M4 Ram 2-G5-2A	Fabric	–	0.502	–	0.90
M4 Ram 2-G5-2B	Fabric	–	0.503	–	0.89
M4 Ram 2-G5-3A	Felt	–	0.447	–	0.87
M4 Ram 2-G5-3B	Felt	–	0.456	–	0.86
M7B Wake	Strap	0.413	0.465	0.84	0.84

MISSE-7B had yarn and cable samples of Kevlar and Vectran on both the ram and wake sides in the N10 sample holders. In addition, a sample of a Kevlar strap was taped down on the wake side, between trays N7-W and N9-W, taking advantage of available space. The MISSE-7B ram side was exposed to $4.2 \pm 0.1 \times 10^{21}$ atoms/cm^2 of AO and approximately 2,750 ESH of UV radiation. The MISSE-7B wake side had an AO fluence of $2.9 \pm 0.3 \times 10^{20}$ atoms/cm^2 and UV exposure of approximately 2,060 ESH. The MISSE-7B samples underwent approximately 8,700 thermal cycles, generally between –40 and 40 ºC.

Figure 6 is a preflight photo of the MISSE-7B ram-side sample holder. Figure 7 is the post-flight photo of the MISSE-7B sample holder from the ram side. Figure 8 is the same from the wake side. Figures 9 and 10 are the MISSE-7B ram-side exposed cord and yarn, respectively. Figures 11 and 12 are wake-exposed cord and yarn, respectively. Figure 13 is the Kevlar strap that was taped down.

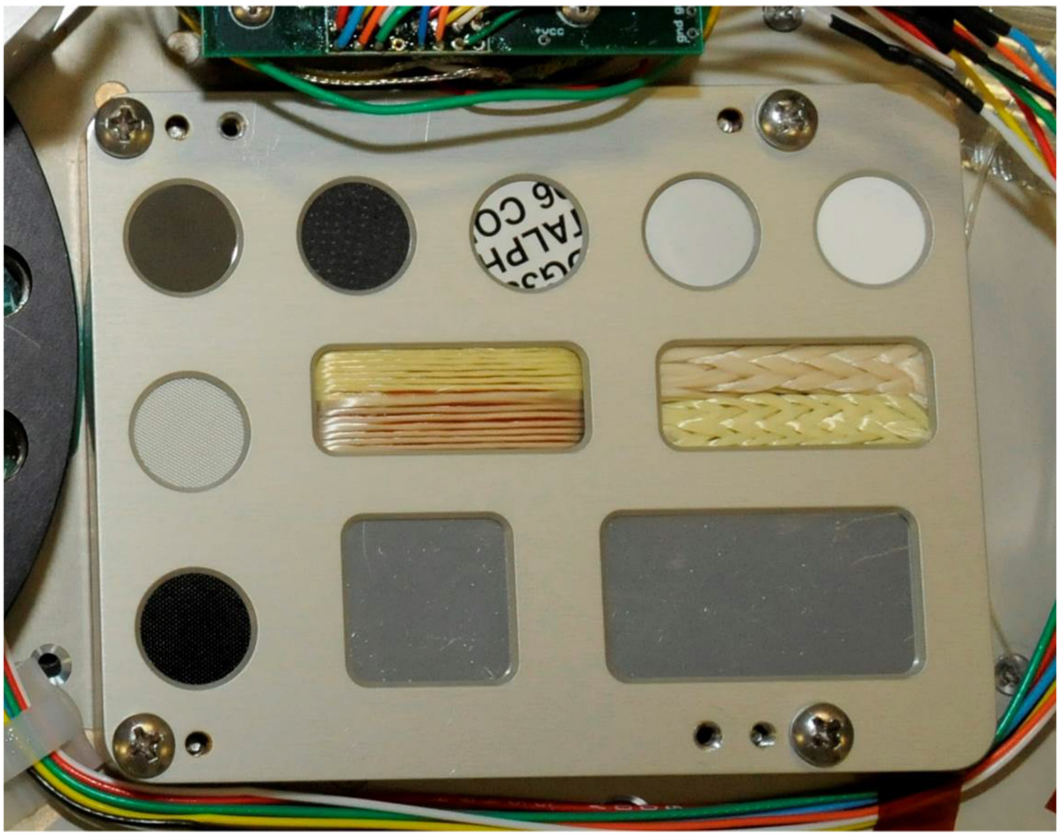


Figure 6. Preflight Kevlar and Vectran materials.

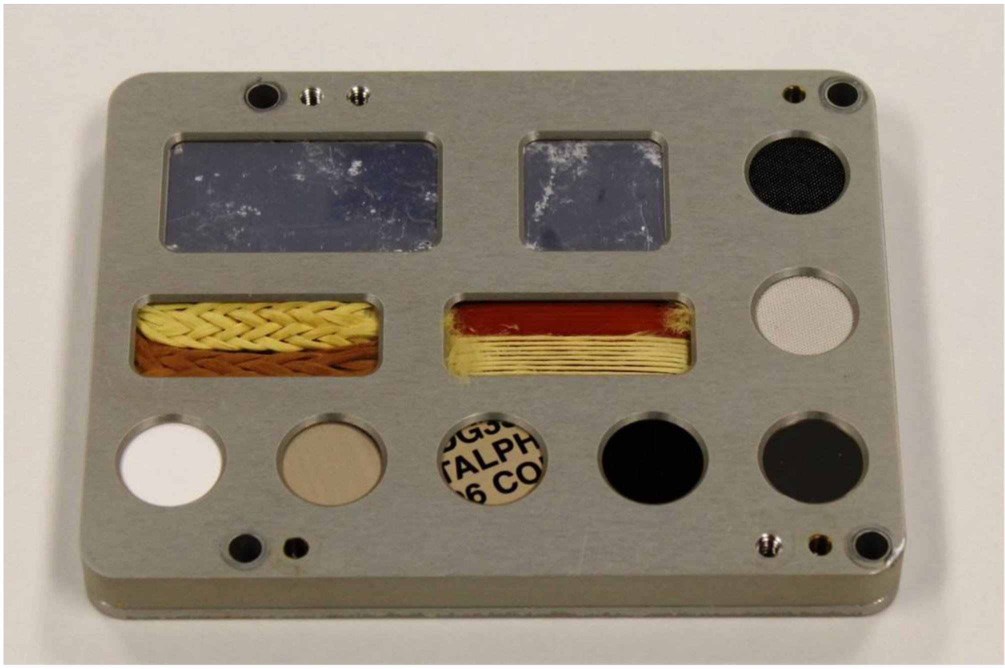


Figure 7. Sample holder from MISSE-7B ram side, postflight. Left center: Kevlar (top) and Vectran (bottom) cable. Near center, only Kevlar yarn remains. Underlying orange material is Kapton.

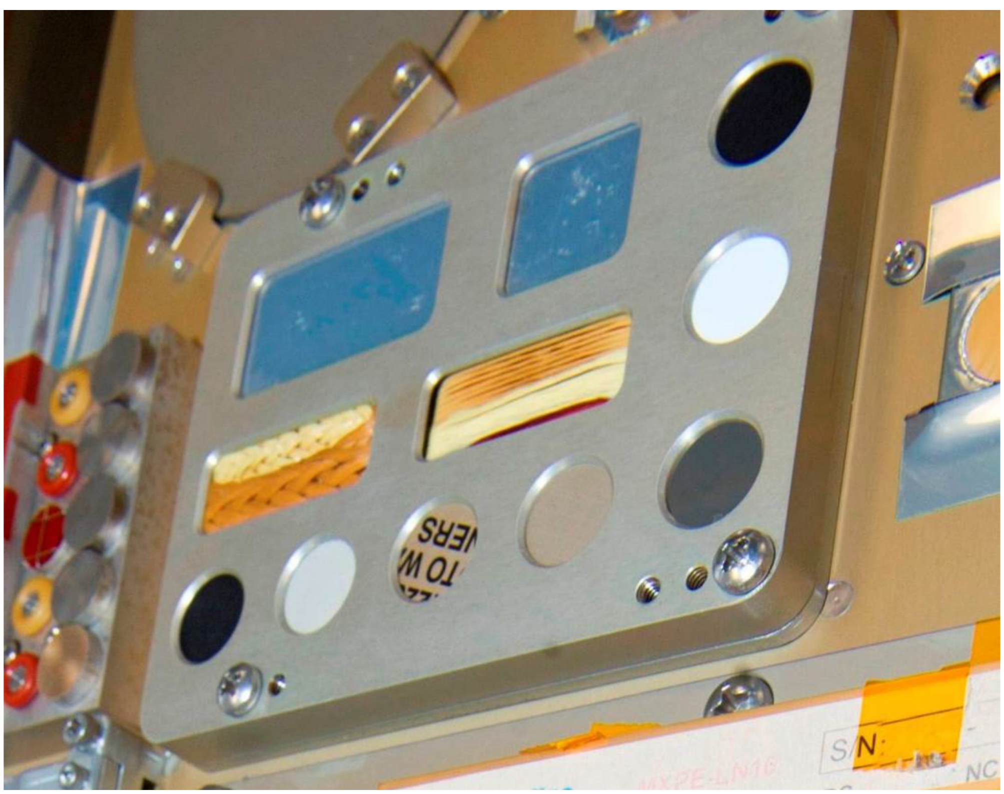


Figure 8. Sample holder from MISSE-7B wake side, postflight.

Figure 9. Ram-side Kevlar (top) and Vectran (bottom) cord, postflight, with Kapton witness sample (erosion visible in center).

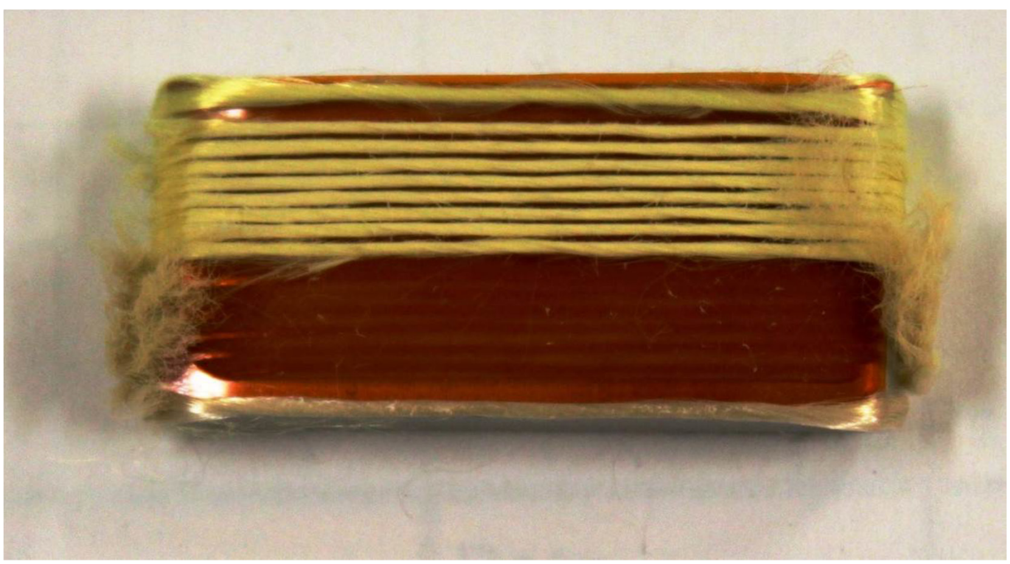


Figure 10. Ram-side yarn samples, postflight. Kevlar on top. Only wisps of Vectran remain.

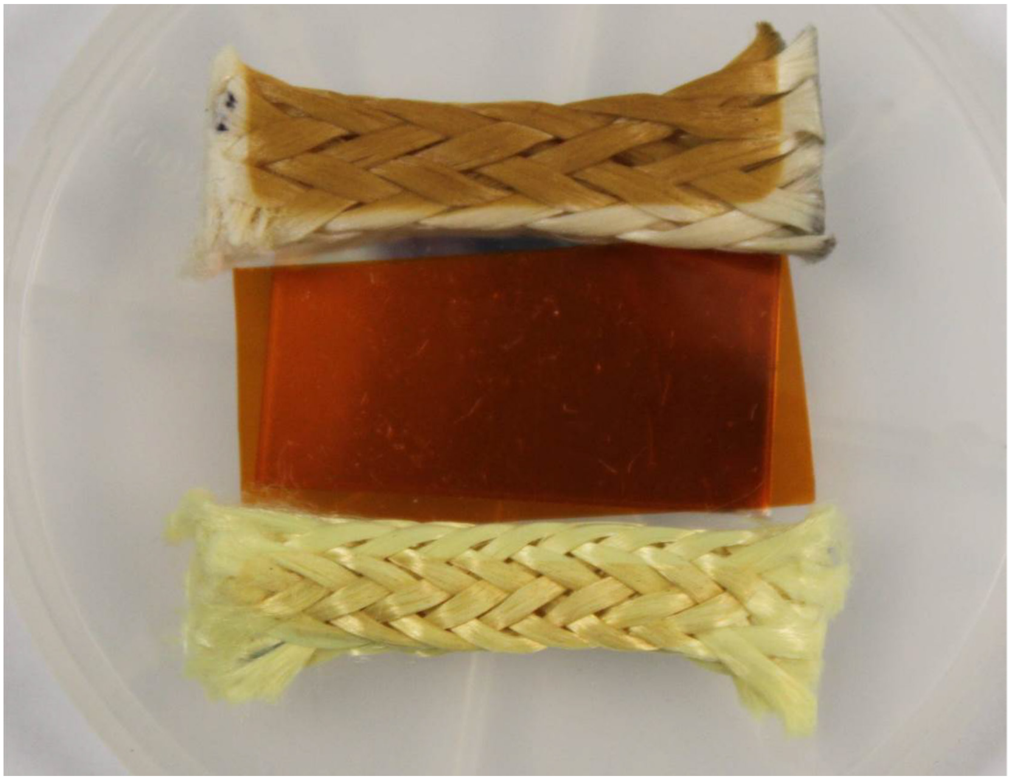


Figure 11. MISSE-7B wake-side Vectran cord (top) and Kevlar cord (bottom), postflight.

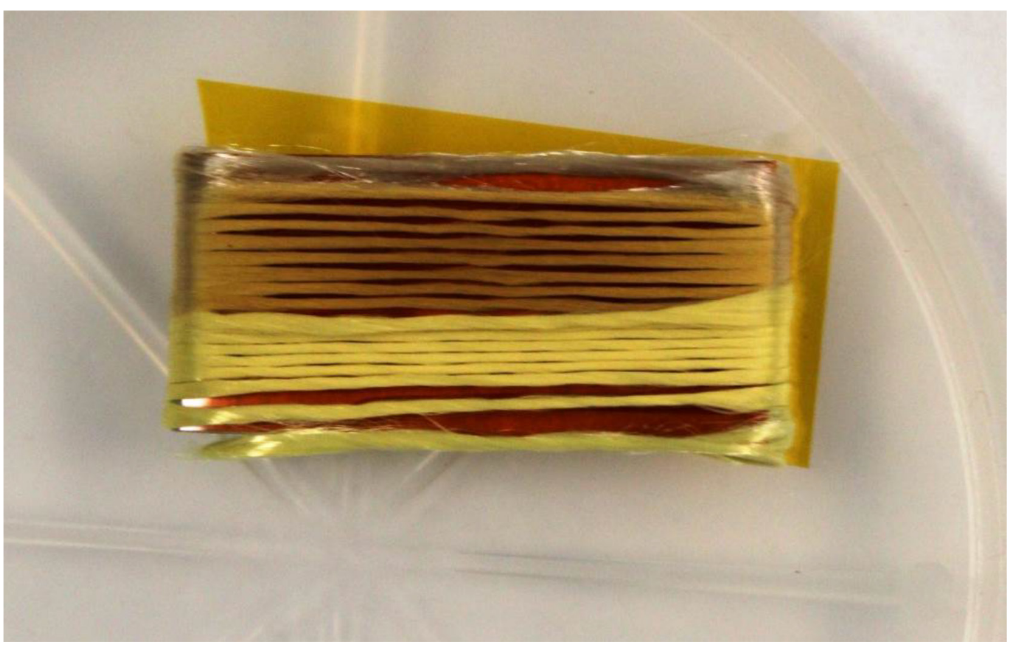


Figure 12. Wake-side Vectran yarn (top) and Kevlar yarn (bottom), postflight.

Figure 13. Kevlar strap taped down in empty space between N7-W and N9-W trays, postflight.

Table 3 gives the measured weights preflight and postflight for Kevlar flown on MISSE. Woven or braided materials do not give good results in AO reactivity calculations; however, the numbers presented here are for an idea of the level of AO erosion since thickness loss was not measured. The yarn samples were wrapped around a shim and were not disassembled after flight by MSFC.

Table 3. Mass changes for Kevlar samples.

Sample	Material	Preflight Mass (g)	Postflight Mass (g)	Δ Mass (mg)
M1 Wake 2-E11-8	Fabric	0.13693	0.13359	–3.34
M1 Wake 2-E11-28	Fabric	0.13143	0.12814	–3.29
M2 Ram 2-E7-23	Fabric	0.14197	0.11682	–25.15
M2 Ram 2-E7-28	Fabric	0.14637	0.11807	–28.30
M7B Ram N10-R-9	Cord	0.34192	0.33545	–6.47
M7B Wake N10-W-9	Cord	0.36918	0.36881	–0.37

4. NOMEX

As mentioned previously, MSFC tested two candidate tether materials for the Tethered Satellite System in 1986 and 1987. This section includes the tether with strength fibers of Kevlar with an outer weave of Nomex.

Samples of the Nomex/Kevlar tether were exposed to thermal vacuum, UV radiation, AO, and electron and proton radiation at the expected levels for a 14-day Space Shuttle mission at an altitude of 264 miles (425 km). All of the samples were 4-foot sections and were tensile tested to failure after simulated space environment exposure. The thermal vacuum testing was for 55 hours at 125 ºC in vacuum less than 1×10^{-3} torr. The UV radiation exposure was for 55 ESH in vacuum less than 1×10^{-3} torr vacuum. The AO exposure is only given as "two minutes at the highest setting," according to Wills's memorandum, in a plasma asher. Only the middle 3 inches of tether were exposed in the UV and AO exposures.

Electron and proton radiation exposures were performed in the Radiation Effects Facility using the Van de Graaff accelerators available at that time. Samples were exposed to 1×10^{13} and 1×10^{14} electrons/cm^2 of 400 keV energy and 1×10^{13} and 1×10^{14} protons/cm^2 of 1 MeV energy while under vacuum on the order of 1×10^{-6} torr. Only the middle inch of tether was exposed to radiation.

The Nomex tether indicated a 9.7% loss in strength due to UV exposure but no significant loss in strength for the other exposures. Cortland Cable Company of New York made the flight tether for the Tethered Satellite System with a Nomex outer braid (fig. 14).

Figure 14. Tethered satellite tether of Nomex outer braid, Kevlar strength fibers, with center core of Nomex and copper wire insulated with Teflon™.[3]

Similar to the Tethered Satellite System Nomex is the Nomex used for extravehicular activity (EVA) toolbags. MSFC received nine Nomex straps of the series 1311EV172 for ground simulation exposure in the AOBF. The reason for this test was to determine the remaining life on an orbital replacement unit toolbag left outside in the space environment for several months. The samples were designed for pull testing. The flat side of the samples faced the AO and vacuum UV radiation (fig. 15). The AO fluence for this test was two samples each at 6-month, 12-month, and 18-month equivalent exposure for the International Space Station, or 2.5×10^{21}, 5×10^{21}, and 7.5×10^{21} atoms/cm^2, respectively.

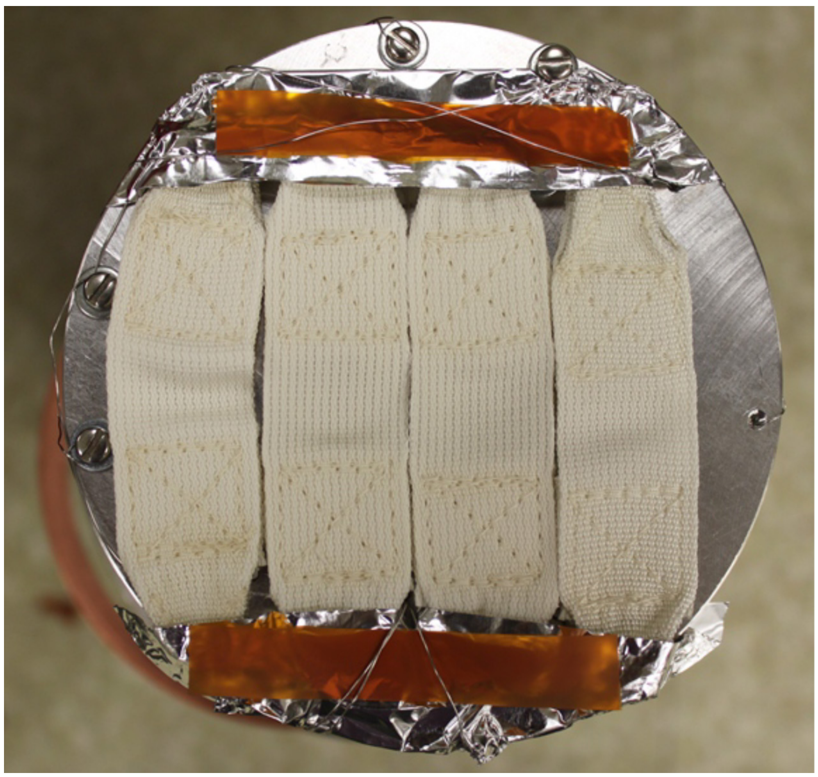


Figure 15. Nomex strap samples in holder for simulated AO exposure. Kapton strips above and below monitor AO fluence.

Exposed Nomex samples indicated slight darkening during exposure, with solar absorptance of 0.34 to 0.35 before exposure and 0.35 to 0.37 after exposure. Emittance was consistently 0.90 ± 0.01.

The strap samples exposed to 7.5×10^{21} atoms/cm^2 shed large particles as the AO eroded the fabric. This structural degradation agrees with the tensile test results (reported in "Testing of AO-Exposed Nomex Strap Samples," Oceaneering Engineering Memorandum EVAM-01386, dated 04/28/2017) of a low of 60.1 lb (18-month-equivalent exposure) and a high of 742.92 lb (6-month-equivalent exposure). The 12-month samples were between 490.79 and 654.45 lb.

Three kinds of Nomex were flown on MISSE-1 and MISSE-2: nonstretch brown Nomex fabric, green Nomex fabric, and 5-mil-thick Nomex 410 film. All optical property measurements (shown in table 4) were made using a black background behind the samples. Solar absorptance calculations were not corrected for transmission through the samples. Figure 16 is a normal light photo of unexposed nonstretch Nomex. Figures 17 and 18 show the AO erosion and UV degradation, respectively. Figure 19 shows the reflectance curves for these samples.

Table 4. Optical properties of Nomex.

Sample	Material	Solar Absorptance		Infrared Emittance	
		Preflight	Postflight	Preflight	Postflight
Control	Nonstretch fabric	0.604	0.610	0.86	0.87
M2 Ram 2-E8-26	Nonstretch fabric	0.608	0.645	0.86	0.89
M2 Wake 1-E10-16	Nonstretch fabric	–	0.630	–	0.86
Control	Green fabric	0.776	0.775	0.90	0.90
M2 Ram 2-W1-2	Green fabric	0.772	0.775	0.89	0.91
M1 Wake 2-W2-14	Green fabric	–	0.758	–	0.90
M1 Wake 2-W2-14	Green inner layer fabric	–	0.739	–	0.91
M1 Wake 2-E11-4	410 film	0.345	0.540	0.85	0.88
M1 Wake 2-E11-19	410 film	0.381	0.568	0.86	0.88
M1 Wake 2-E11-26	410 film	0.376	0.584	0.86	0.88

Figure 16. Control nonstretch Nomex sample.

Figure 17. MISSE-2 ram-facing, nonstretch Nomex, sample 2-E8-26, postflight. Significant AO erosion.

Figure 18. MISSE-2 wake-facing, nonstretch Nomex, sample 1-E10-16, postflight.

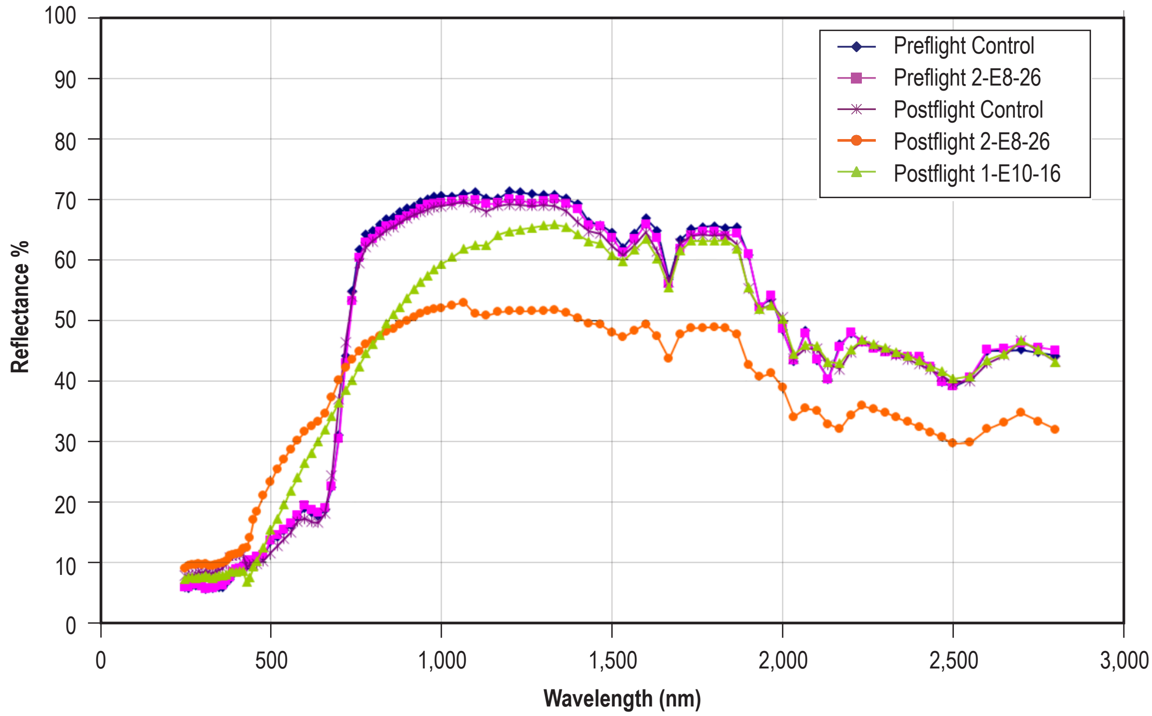


Figure 19. LPSR measurements for nonstretch Nomex.

Figures 20–22 show the green Nomex control sample and flight samples postflight, while figure 23 lists the green Nomex's LPSR measurements. Darkening of the flight samples was noted, with a brownish tinge for the 2-W2-14 sample. The preflight and postflight measurements of the control sample were in good agreement with each other above 430 nm. Optical property measurements were made on the next inner layer of the 2-W2-14 sample as an indication of what the preflight reflectance curve for that sample may have looked like.

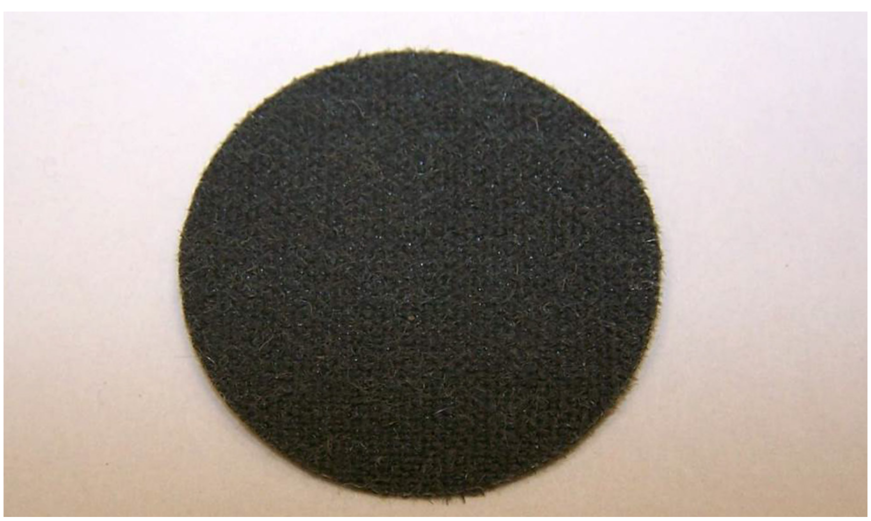


Figure 20. Control green Nomex sample.

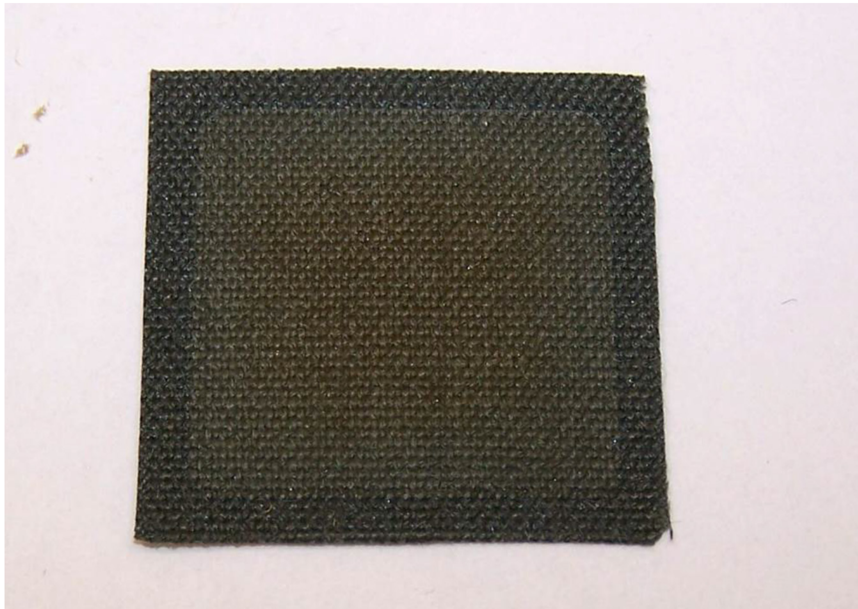


Figure 21. Postflight green Nomex, sample 2-W1-2.

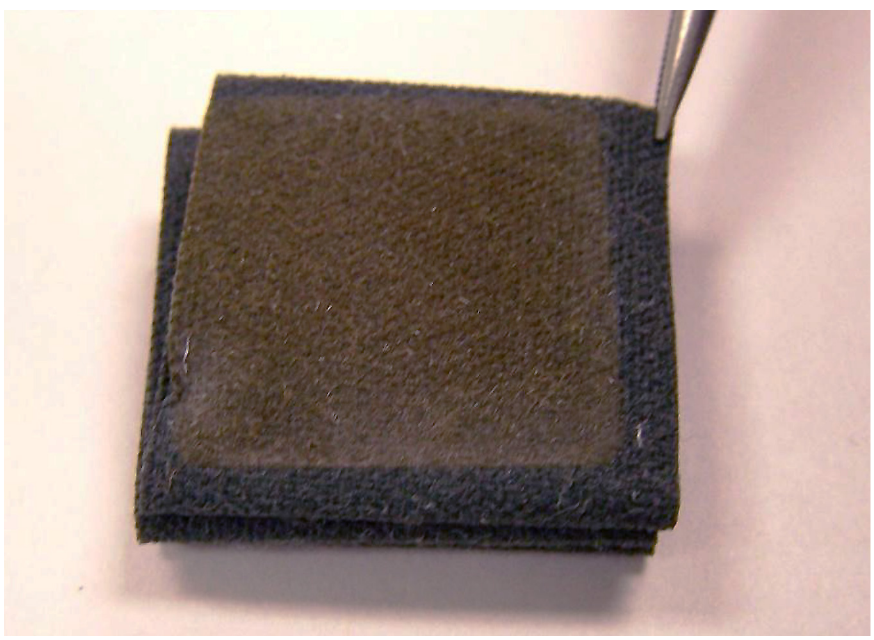


Figure 22. Postflight green Nomex, sample 2-W2-14.

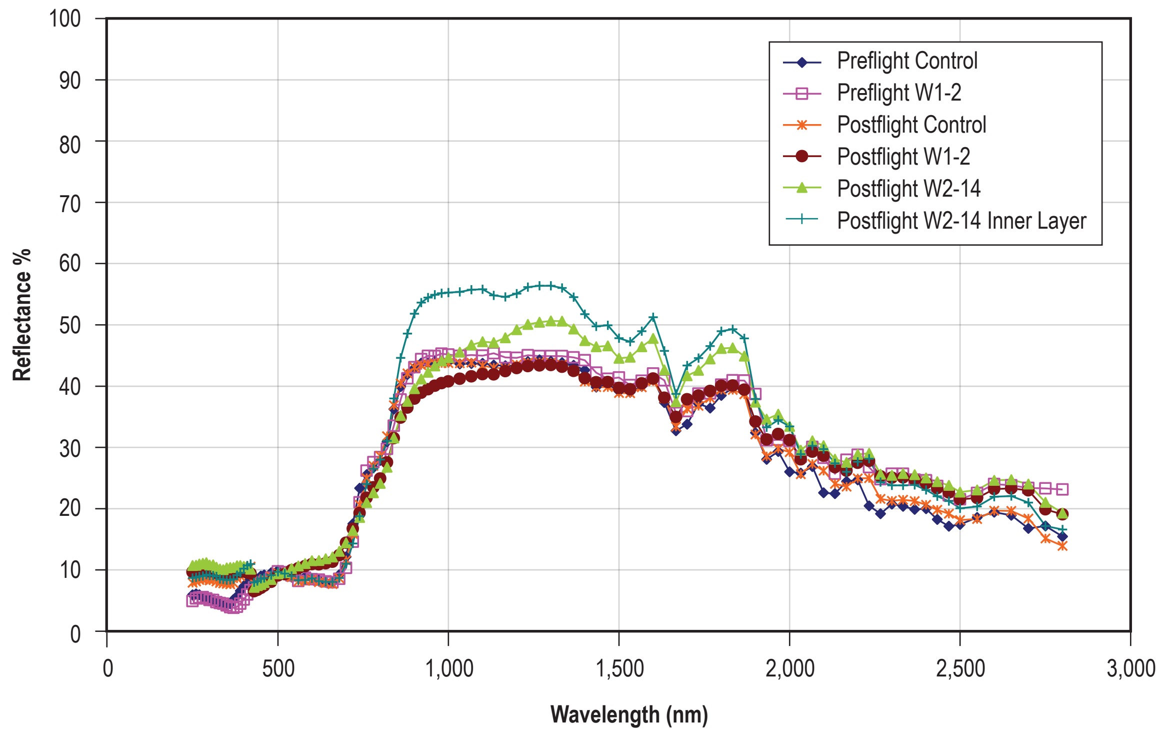


Figure 23. LPSR measurements for green Nomex.

Table 5 shows the mass changes for Nomex. Assuming a density of 0.72 g/cm^3 for the Nomex 410 2-E11-4 and 2-E11-19 samples, the calculated erosion yield, or AO reactivity, is approximately 3×10^{-24} cm^3/atom. Figure 24 shows a postflight MISSE-1 wake-facing Nomex 410 sample, while figure 25 shows a MISSE-2 ram-facing sample. Figure 26 is a graph showing the reflectance of Nomex 410 that survived MISSE-1 flight.

Table 5. Mass changes for Nomex.

Sample	Material	Preflight Mass (g)	Postflight Mass (g)	Δ Mass (mg)
M2 Ram 2-E8-26	Nonstretch brown fabric	0.11852	0.07382	–44.70
M2 Ram 2-W1-2	Green fabric	0.15007	0.14579	–4.28
M2 Ram 2-E7-9	410 film	0.06181	0.02106	–40.75
M1 Wake 2-E11-4	410 film	0.05910	0.05819	–0.91
M1 Wake 2-E11-19	410 film	0.05913	0.05820	–0.93
M1 Wake 2-E11-26	410 film	0.06039	0.05966	–0.73

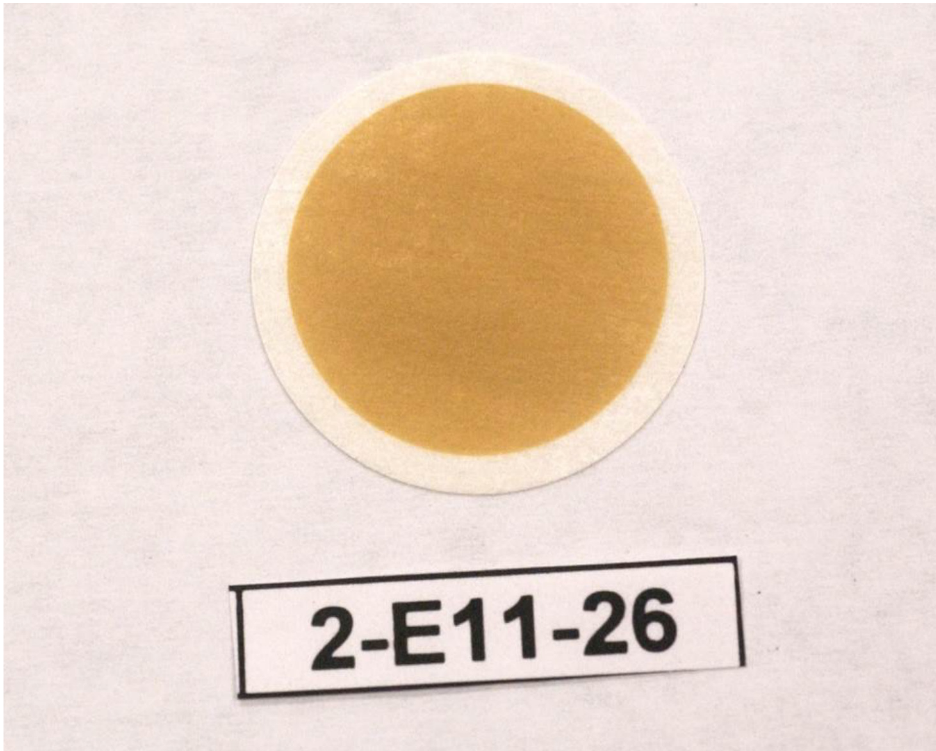


Figure 24. MISSE-1 wake-facing Nomex 410, postflight.

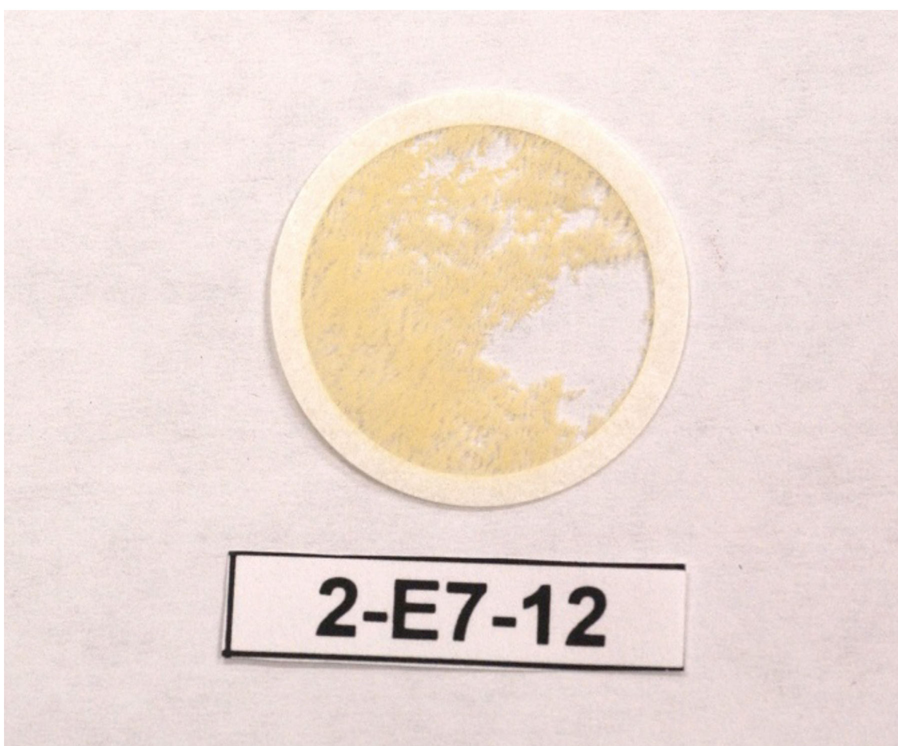


Figure 25. MISSE-2 ram-facing Nomex 410, postflight.

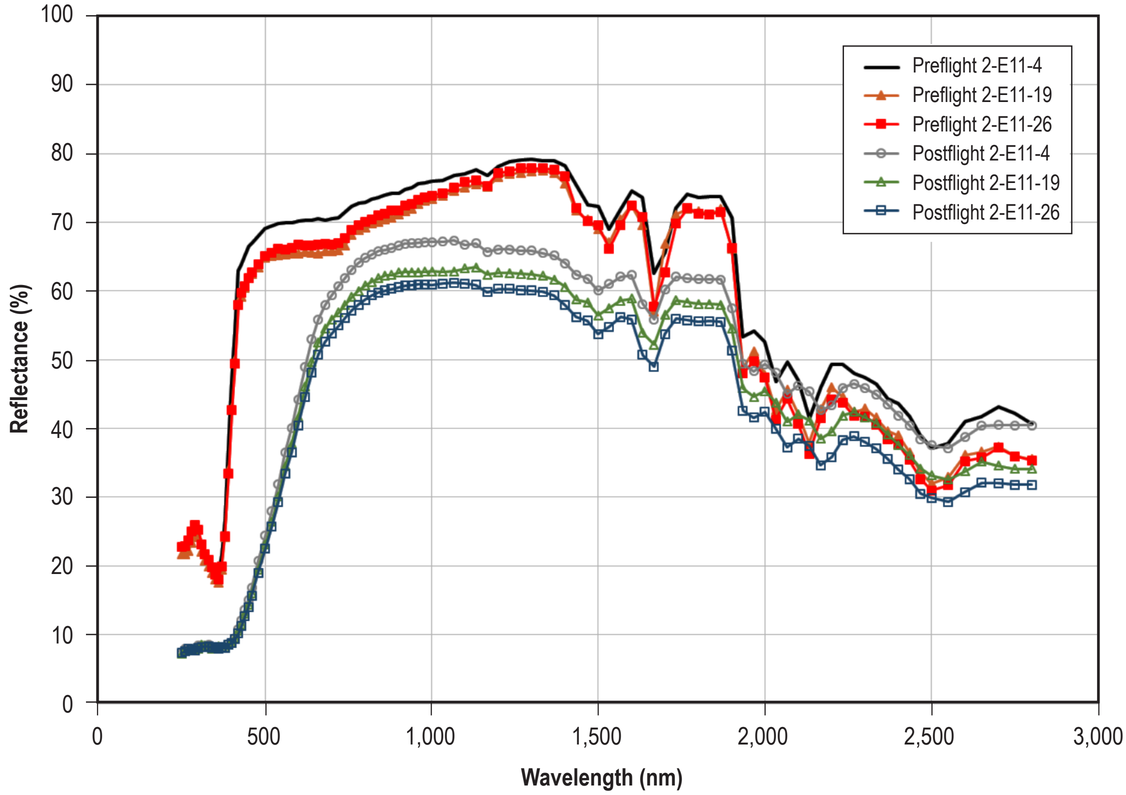


Figure 26. Reflectance of Nomex 410 that survived MISSE-1 flight.

5. VECTRAN

Vectran was exposed in the MSFC AOBF as part of the ProSEDS testing and was heavily eroded.[4] Figure 27 shows the ProSEDS Vectran test sample exposed to approximately 1×10^{21} atoms/cm^2 of AO. Atomic oxygen reactivity was calculated to be approximately 7.5×10^{-24} cm^3/atom.

Figure 27. Vectran fiber after AOBF exposure of 1×10^{21} atoms/cm^2.

Samples of Vectran HS with T150 finish were flown on MISSE-1, MISSE-2, and MISSE-4. The T150 finish was referred to as “0.5% oil on yarn weaving finish” in the product literature. The ram environment for MISSE-1 and MISSE-2 was $8\pm1\times10^{21}$ atoms/cm^2 of AO (depending on proximity to airlock) and 5,000–6,000 ESH of UV. The wake environment for MISSE-1 and MISSE-2 was $1.3\pm0.2\times10^{20}$ atoms/cm^2 of AO and approximately 5,000 ESH of UV. The MISSE-1 and MISSE-2 samples also underwent approximately 23,000 thermal cycles of –40 to 40 ºC. The ram environment for MISSE-4 was $2.1\pm0.3\times10^{21}$ atoms/cm^2 of AO, approximately 1,200 ESH of UV, and approximately 5,800 thermal cycles. Mass changes for Vectran samples are shown in table 6.

Table 6. Mass changes for Vectran samples.

Sample	Material	Preflight Mass (g)	Postflight Mass (g)	Δ Mass (mg)
M1 Ram 2-W1-15	Fabric	0.08468	0.08390	–0.78
M7B Ram	Cord	0.61871	0.61347	–5.24
M7B Wake	Cord	0.64788	0.64080	–7.08

The MISSE-1 and MISSE-2 Vectran samples were UV-darkened yet uneroded, shown in figures 28 and 29, respectively. The ram-facing sample had a glassy appearance consistent with silicate formation. The differences in the effect of AO on the MISSE Vectran samples were likely due to the presence of the weaving finish or other oil on the cord that was not present on the ProSEDS yarn.

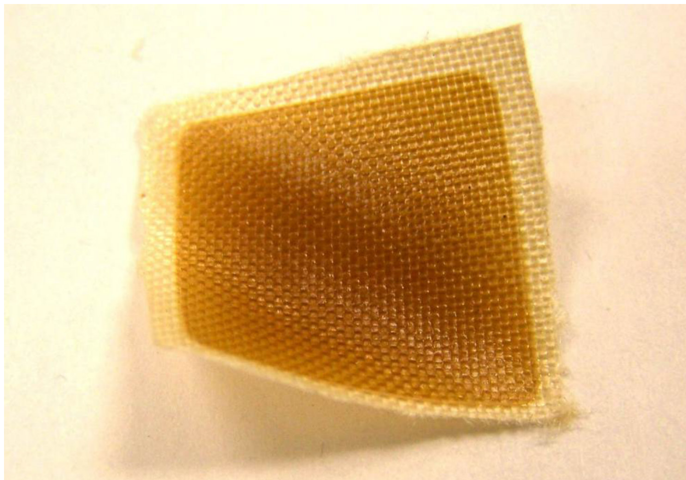


Figure 28. MISSE-1 ram-side Vectran sample 2-W1-15, postflight.

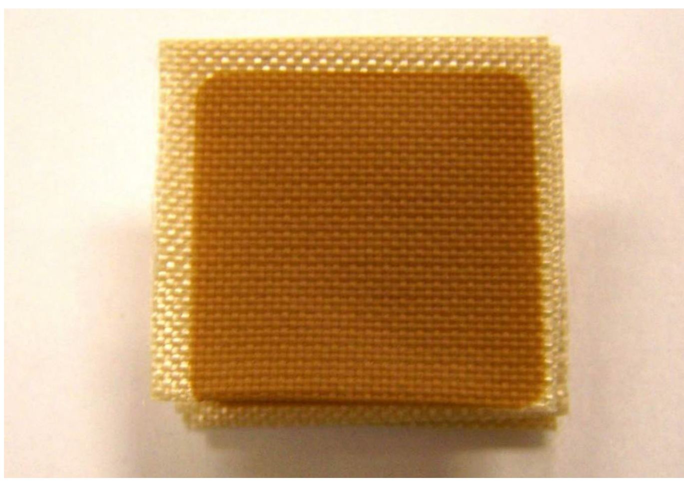


Figure 29. MISSE-2 wake-side sample of Vectran 2-W3-4, postflight.

Optical property measurements (table 7) showed higher reflectance and, therefore, lower absorptance for the MISSE-2 wake sample because the sample was a long strip accordion-folded and had an unexposed Vectran backing instead of the black background used for all the samples. Optical property measurements were made on the next inner layer as an indication of what the preflight reflectance curve for that sample may have looked like. Figure 30 shows the reflectance curve for MISSE-1 and MISSE-2 Vectran samples.

Table 7. Optical properties of Vectran samples.

Sample	Material	Solar Absorptance		Infrared Emittance	
		Preflight	Postflight	Preflight	Postflight
Control	Fabric	0.600	0.603	0.85	0.86
M1 Ram 2-W1-15	Fabric	0.603	0.751	0.89	0.87
M2 Wake 2-W3-4	Fabric	—	0.582	—	0.88
M2 Wake 2-W3-4	Inner layer fabric	—	0.417	—	0.86

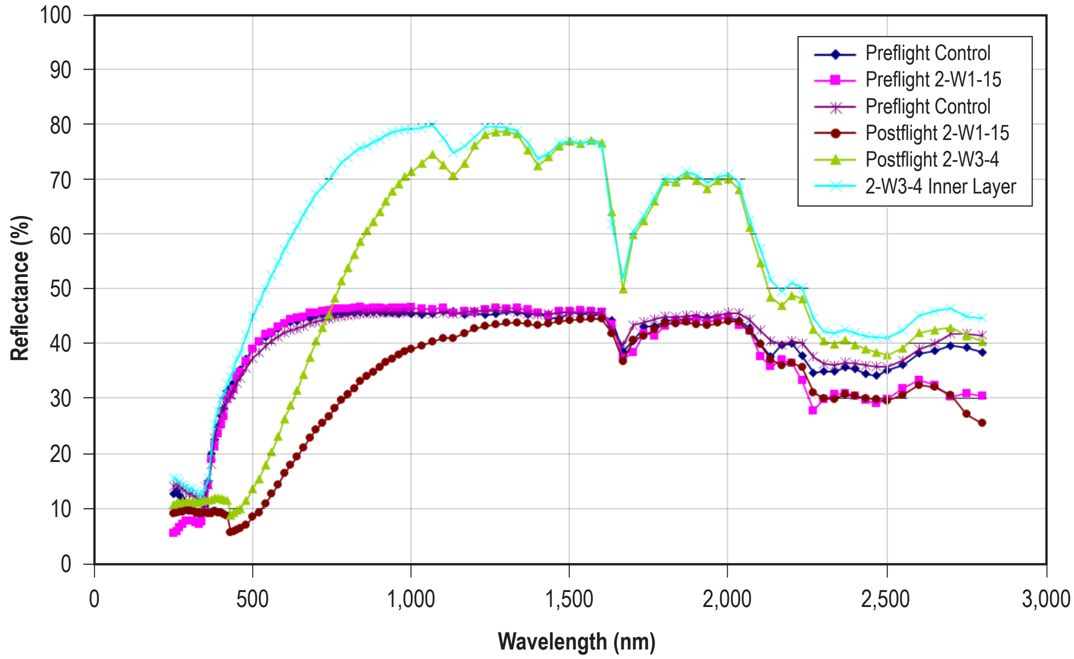


Figure 30. Reflectance curves for MISSE-1 and MISSE-2 Vectran samples.

MISSE-7B had yarn and cable samples of Kevlar and Vectran on both the ram and wake sides in the N10 sample holders. These were previously shown in figures 6–12. The MISSE-7B ram side was exposed to $4.2 \pm 0.1 \times 10^{21}$ atoms/cm^2 of AO and approximately 2,750 ESH of UV radiation. The MISSE-7B wake side had an AO fluence of $2.9 \pm 0.3 \times 10^{20}$ atoms/cm^2 and UV exposure of approximately 2,060 ESH. The MISSE-7B samples underwent approximately 8,700 thermal cycles, generally between –40 and 40 °C.

The Vectran yarn without any weaving treatment was completely eroded away from the ram side of MISSE-7 and visibly eroded on the wake side. The Vectran cord from MISSE-7 was strongly darkened by UV exposure, in agreement with Vectran fabric from the earlier MISSE flights. It was apparent that the preflight bakeout of the Vectran cord did not drive off the weaving oil. Preflight bakeout was 100 °C for 24 hours in 2×10^{-6} torr or better vacuum.

6. ULTRA-HIGH MOLECULAR WEIGHT POLYETHYLENE

Ultra-high molecular weight polyethylene (UHMWPE), sold as either Dyneema or Spectra, was a candidate material for ProSEDS and also the Momentum Transfer Electrodynamic Reboost tether.

Dyneema tethers were exposed to AO along with Kevlar tethers as part of the ProSEDS investigation. The exposure is discussed in section 3. The Dyneema tether exposed to 1.07×10^{21} atoms/cm^2 failed with normal handling during removal from the test fixture and was not tensile tested. Figure 31 shows the tensile strength versus the AO fluence for the Dyneema tether.

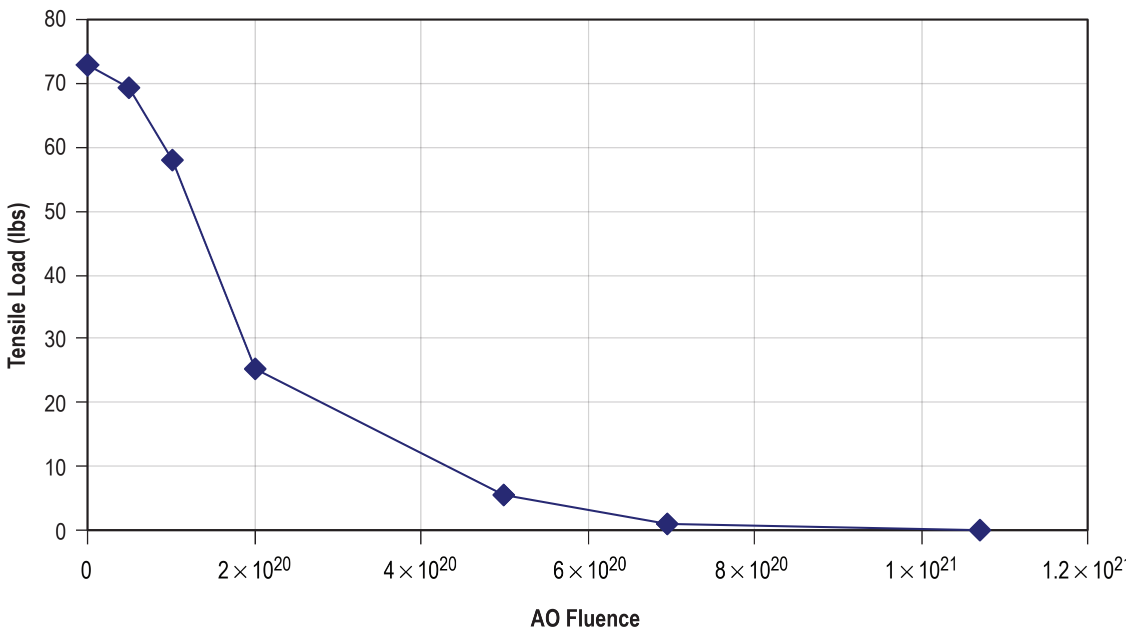


Figure 31. Tensile strength versus AO exposure for Dyneema tether.

A tether experiment flown on MISSE consisted of one tray of seven tether samples on the ram side of MISSE-2 and a matching tray on the wake side of MISSE-1. The seven samples were:

(1) ProSEDS insulated conductive tether consisting of 7-28 AWG aluminum wire around 16 tow Kevlar 49 core, insulated with Triton TOR-BP.

(2) Triton TOR F-size thread.

(3) ProSEDS conductive tether consisting of 7-28 AWG aluminum wire around 16 tow Kevlar core, coated with Triton C-COR polymer, which is a solution of Triton clear oxygen resistant polymer doped with polyaniline.

(4) Kapton to monitor AO erosion.

(5) Bare 28 AWG aluminum wire wrapped around poly (p-phenylene-2,6-benzobisoxazole (PBO)) core.

(6) Dyneema UHMWPE.

(7) Triton Triflex—nickel-plated Kevlar weave.

Photographs taken during Shuttle fly-arounds and EVA indicated that the UHMWPE on the ram-facing side had failed in tension after 9 months on orbit due to an AO attack and 1 lb preload (~1.7×10^{21} oxygen atoms/cm^2) (fig. 32) and completely eroded away by 14 months. The UHMWPE on the wake-facing side did lose 19.6% of its mass due to AO erosion. The erosion yield, or AO reactivity, was calculated to be approximately 5.1×10^{-24} cm^3/atom. The other failures on these trays were the complete erosion of the Kapton and the failure in tension of the aluminum wire wrapped around the PBO core.

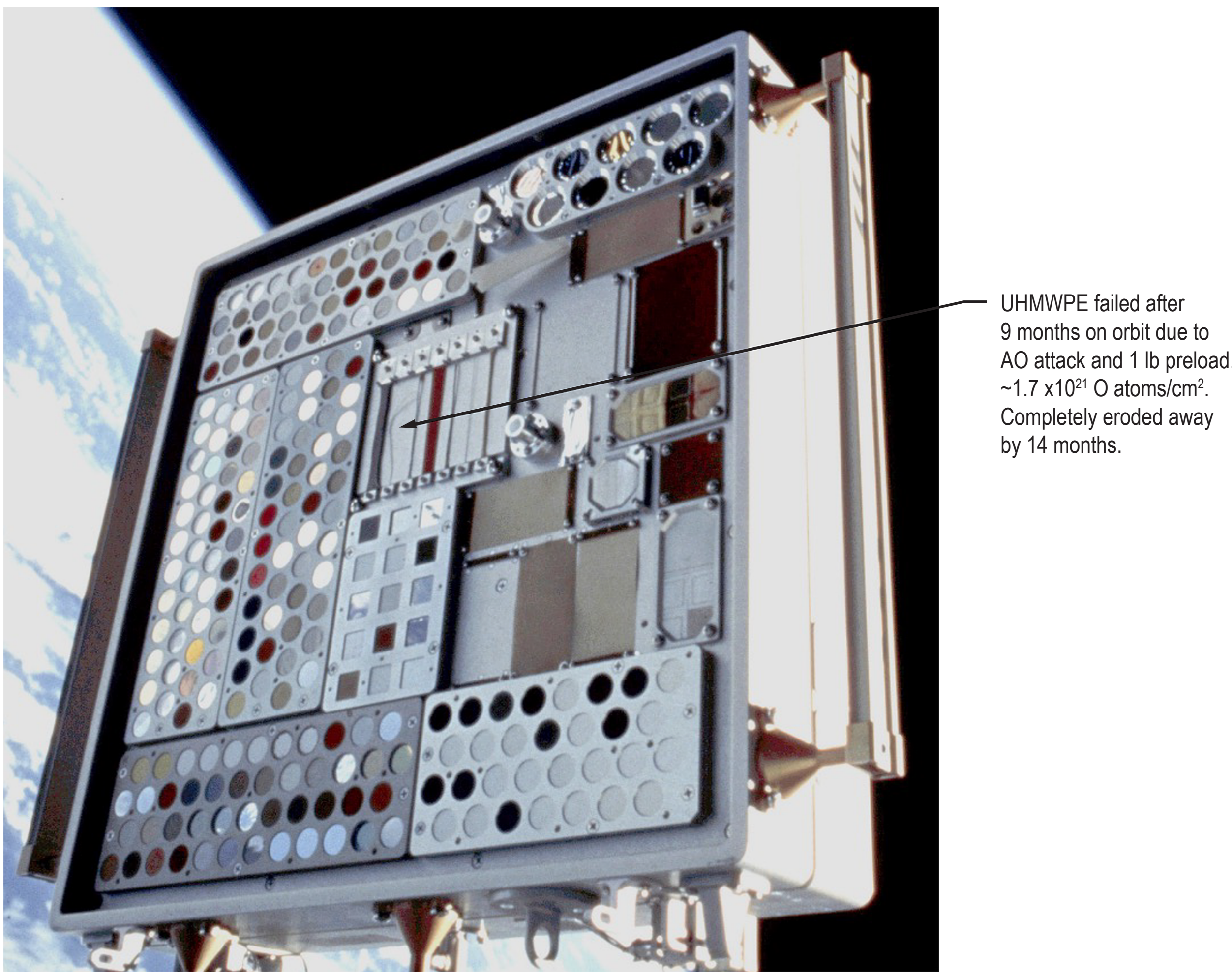


Figure 32. Ram-facing side of MISSE-2 after 9 months in space.

Spectra cloth was later flown on MISSE-7 and MISSE-8. The MISSE-7B ram side was exposed to $4.2 \pm 0.1 \times 10^{21}$ atoms/cm^2 of AO and approximately 2,750 ESH of UV radiation. The MISSE-7B wake side had an AO fluence of $2.9 \pm 0.3 \times 10^{20}$ atoms/cm^2 and UV exposure of approximately 2,060 ESH. The MISSE-7B samples underwent approximately 8,700 thermal cycles, generally between –40 and 40 ºC. The two MISSE-8 Spectra samples were flown on the nadir side, so despite being exposed to space for over 2 years, these samples only received $3.6 \pm 0.1 \times 10^{19}$ atoms/cm^2 and 800 ± 300 ESH (fig. 33). This cloth was about 33% transmissive in the near UV to near infrared wavelengths and about 21% transmissive in the 3 to 30 μ wavelengths. Slight yellowing was noted. Optical properties of Spectra are given in table 8.

Figure 33. MISSE-8 nadir side Spectra, postflight.

Table 8. Optical properties of Spectra fabric samples backed with aluminized Kapton.

Sample	Solar Absorptance		Infrared Emittance	
	Preflight	Postflight	Preflight	Postflight
Control	–	0.229	–	0.57
M7 Wake N11-R-3	0.221	0.266	0.57	0.53
M8 Nadir M8A-41	0.223	0.254	0.57	0.55
M8 Nadir M8B-24	0.224	0.263	0.57	0.56

7. ORTHO-FABRIC

Ortho-Fabric is a blend of Gore-Tex, Kevlar, and Nomex. As stated in section 1, Gore-Tex is ePTFE. Only one sample was flown on MISSE-2 and received approximately 8×10^{21} atoms/cm^2 of AO, 6,000 ESH of UV, and approximately 23,000 thermal cycles of –40 to 40 ºC. This sample, 2-E8-25, lost 42.05 mg due to AO erosion (figs. 34 and 35). Figure 36 shows the reflectance measurements of Ortho-Fabric.

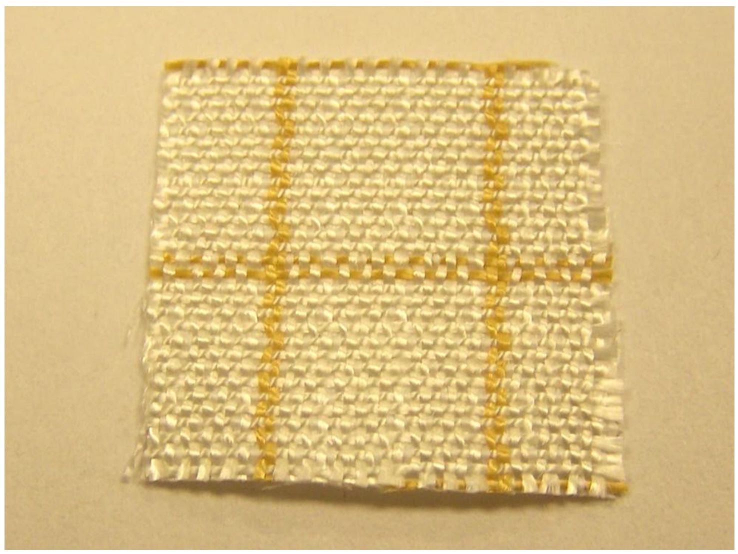


Figure 34. Control Ortho-Fabric sample.

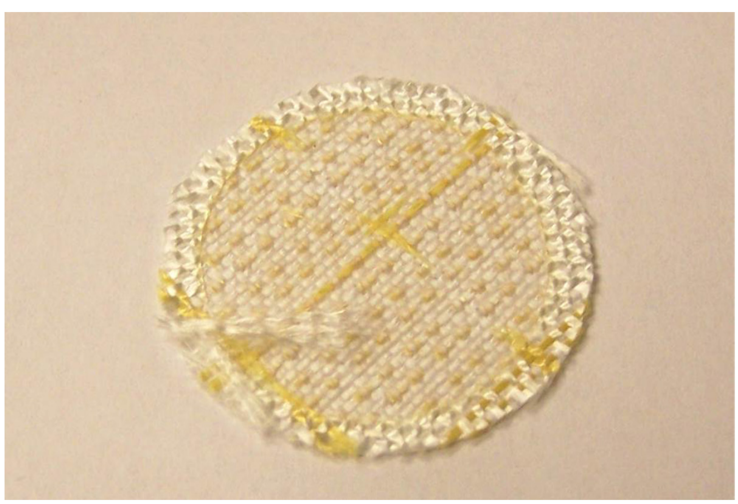


Figure 35. Flight Ortho-Fabric sample 2-E8-25.

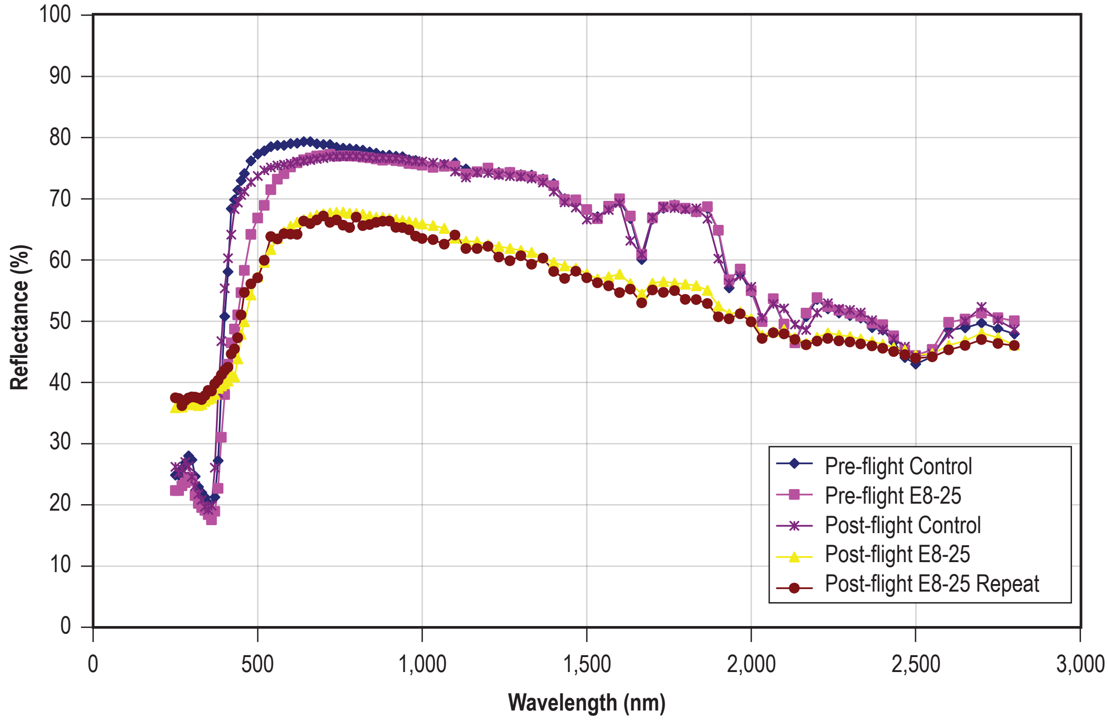


Figure 36. Reflectance measurements of Ortho-Fabric.

All optical property measurements were made using a black background behind the sample. Solar absorptance calculations were not corrected for transmission through the sample (table 9).

Table 9. Optical properties of Ortho-Fabric samples.

Sample	Material	Solar Absorptance		Infrared Emittance	
		Preflight	Postflight	Preflight	Postflight
Control	Ortho-Fabric	0.308	0.332	0.85	0.86
2-E8-25	Ortho-Fabric	0.347	0.425	0.85	0.86

8. OBSERVATIONS AND CONCLUSIONS

All of these polymer fibers were eroded by AO except for those with weaving oil, such as the Vectran fabric. A sizable exposure to AO, e.g. $>1\times10^{21}$ atoms/cm^2, will likely impact mechanical properties of fabrics and straps. Thin tethers may be affected by as little as 2×10^{20} atoms/cm^2 of AO. Mechanical properties may also be affected by hard vacuum removing moisture. Kevlar 49 is preferred over Kevlar 29 due to moisture content.

Kevlar, white Nomex straps, green Nomex fabric, samples of Nomex 410, Spectra fabric, and Ortho-Fabric were slightly darkened by UV exposure. Nonstretch Nomex faded due to UV exposure. The Vectran yarn without any weaving treatment was completely eroded on the ram side of MISSE-7 and visibly eroded on the wake side. The Vectran fabric and cord from several MISSE flights were strongly darkened by UV exposure. It is apparent that the preflight bakeout of the Vectran cord did not drive off the weaving oil.

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14. ABSTRACT
A variety of high-performance fibers, including Kevlar, Nomex, Vectran, and Spectra, have been tested for durability in the space environment, mostly the low Earth orbital environment. These materials have been tested in yarn, tether/cable, and fabric forms. Some material samples were tested in a simulated space environment, such as the Atomic Oxygen Beam Facility and solar simulators in the laboratory. Other samples were flown on the International Space Station as part of the Materials on International Space Station Experiment. Mass loss due to atomic oxygen erosion and optical property changes due to ultraviolet radiation degradation are given. Tensile test results are also presented, including where moisture loss in a vacuum had an impact on tensile strength.

15. SUBJECT TERMS
space environment, polyimide, polyethylene, tether, atomic oxygen, ultraviolet radiation

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