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Degradation of Spacesuit Fabrics Exposed to Low Earth Orbit

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Abstract

Two different outer spacesuit fabrics were exposed to the wake-side low Earth orbit (LEO) environment for two years in order to determine their long term durability in the space environment. One sample each of the Teflon® fabrics that covered Apollo spacesuits and the Orthofabric that covers the Space Shuttle and ISS suits was flown on the ISS as part of the ORMatE-III experiment. Results were compared with previous experiment on MISSE-7 which had similar exposure conditions on the ISS for 18 months, as well as β-cloth exposures on the LDEF for 5.7 years and an ISS battery ORU that was exposed for 8 years. Both ORMatE-III samples darkened considerably, probably due to UV and high energy particle radiation. Spectral analysis showed increased absorption in the shorter than 500 nm portion of the spectrum, but became more reflective in the 500 to 1800 nm region, and as a result, there was little change in the absorptance of the fabrics. Measurement of the 2.5 to 25 μm spectra indicated that there was only a small change in the emittance of the fabrics in the 250 to 700 K. Thus, although on long exposure the spacesuits are expected to darken to the eye, their thermal properties will likely remain nearly constant for the Apollo FEP fabric, and will degrade only slowly for the Orthofabric. Although these sample were too small to characterize their mechanical properties, degradation of the MISSE-7 samples as well as metalized FEP films on the Hubble Space Telescope thermal shields suggest that long term exposure of these fabrics to the space radiation environments will cause them to embrittle.

Introduction

Although in the short-term NASA missions beyond Earth orbit are in flux, it is clear that in the future NASA astronauts will be spending more time in extra vehicular activities (EVA). This means that future spacesuits will need to be durable to the space environment. Yet, at this time there has been little experimental work on the effects of the environment on spacesuit materials, particularly the soft goods that make up the outer layer of the pressure garment assembly (PGA). The outermost material of the spacesuit is either polytetrafluroethylene (PTFE) or fluorinated ethylene propylene (FEP). These materials are chemically inert, flexible, and have excellent thermal radiation properties having a both a high solar reflectance (low integrated solar absorptance, α) and a high thermal emittance, ε. Three forms have been commonly used; β-cloth, which is PTFE coated glass fibers; FEP fabrics, used on the Apollo suits; and Orthofabric, PTFE co-woven with Nomex® and Kevlar®, with the PTFE layer being on the outside. Since PTFE and FEP are chemically similar, it is expected that they would behave similarly in the space environment, and this has proven to be the case.

Linton first evaluated the durability of β-cloth to the space environment as part of the Long Duration Exposure Facility (LDEF), a large free-flyer that was placed into orbit by the Space Shuttle Challenger in April 1984 and retrieved by the Space Shuttle Columbia in January 1990 (Ref. 1). The β-cloth sample was exposed for 5.7 years in a constant orientation of 22° off of the ram direction. The environmental exposure was characterized as including 8,680 estimated sun hours of UV radiation, an atomic oxygen (AO) fluence of 8.17×10^{21} atom/cm^2, a proton (0.05 to 200 MeV) fluence of 10^9/cm^2, an electron fluence of 10^{12}/cm^2 for 50 keV to 10^8/cm^2 for 3.0 MeV, and about 32,000 thermal cycles. They found that the more exposure the β-cloth had to AO, the darker it became. They attributed this to increased light absorption from the more highly textured surface and the exposed glass on the surface. They also found that the PTFE polymer erosion did not release glass fibers. In addition, the glass fibers prevented continued erosion of the PTFE. The backside of the sample did not change appreciably from the starting material.

In a second, longer space exposure study, Gaier characterized β-cloth from a battery orbital replacement unit (ORU) on the International Space Station (ISS) that had been exposed to the space environment for 8.6 years (Ref. 2). It was found that the material darkened, with the α increasing by as much as 20 percent, with the peak difference in the UV portion of the spectrum. The ε over a temperature range of 300 to 700 K was essentially unchanged. It was concluded that the darkening was probably caused by radiation damage, primarily of the glass fibers, as no significant contamination of the surface was found. No gross mechanical weakening of the fibers was noted, though mechanical properties were not explicitly measured.

The concern about the synergistic effects of lunar dust abrasion and radiation damage prompted the inclusion of the Spacesuit Fabrics Exposure Experiment on the Materials International Space Station Experiment-7 (MISSE-7). In this experiment, pristine and dust-abraded samples of outer layer spacesuit fabrics were flown on the wake-side Passive Experiment Container (PEC) on the ISS for approximately 18 months, from November 2009 to May 2011. They were exposed to the space radiation environment of LEO, which is similar to that of the moon, though reduced in particle radiation because many of the solar wind ions are captured by the van Allen radiation belts, well above ISS orbit. The long-term exposure in LEO was conducted in order to shed light on the extent to which spacesuit fabrics degraded in long-term exposure on the moon, and how dust abrasion affects it. Unintended exposure to AO during the reorientation of the ISS introduced an additional degradation mechanism (Ref. 3).

Comparison of pre- and post-flight characterizations of the MISSE-7 fabrics showed that space radiation darkened and reddened PGA fabrics. As a result of space exposure, the α of the FEP fabric increased by 27 percent, and that of the Orthofabric increased by 38 percent. The α of FEP fabric abraded with JSC-1A lunar simulant increased by 7 percent, and JSC-1A abraded Orthofabric increased by 9 percent. For both cases most of their spectra could be explained as a linear addition of the fabric and the dust, though the correlation did not hold in the visible and UV wavelengths for the Orthofabric. Spectroscopically, a lunar dust laden Apollo 12 spacesuit sample from astronaut Alan Bean darkened, but did not appreciably redden, though it appears redder to the eye. No evidence of contamination was seen in the energy dispersive spectroscopy (EDS) results, suggesting that the discoloration was due to radiation damage. Even though the samples were positioned on the wake-side, because the ISS periodically reorients the samples were exposed to the equivalent of about 38 days of ram AO. Evidence for this was seen in the oxidation of silver-coated fasteners and the etching of fabric fibers. The erosion seen in the fibers was quantitatively consistent with previously reported values for the AO erosion yields of the materials. Space exposure decreased the ultimate tensile strength and elongation to failure of the Alan Bean Apollo 12 spacesuit filaments by a factor of 4 and increased the elastic modulus by a factor of 2. The severity of the degradation of the fabric samples over the 18-month exposure period demonstrates the necessity to find ways to prevent or mitigate radiation damage to spacesuits when planning extended missions to the moon.

In an attempt to assess the durability of spacesuit fabrics on Mars, Larson has reported the results of UV exposure from Hg-Xe lamps meant to simulate the UV exposure on the surface of Mars (Ref. 4). They observed a “yellowing discoloration” in all the materials they tested, including Teflon fabric and Orthofabric, lending credence to the MISSE-7 conclusion that the darkening of the fabrics was caused by solar radiation. They also report a decrease in both the tensile strength and elongation to break, and minimal mass loss.

An opportunity to gather more data on the effects of the space environment on space suit fabrics presented itself when two spots opened up on the Optical Reflector Materials Experiment III (ORMatE-III) which flew on the ISS with MISSE-8 in 2011-13.

Space Exposure

MISSE-8/ORMatE-III was launched aboard the final flight of the Space Shuttle Endeavor (STS-134) on May 16, 2011. The ORMatE-III wake exposure trays were placed on ELC-2 by ISS Expedition 28 NASA Astronaut Ron Garan during a spacewalk on July 12, 2011. A photograph of the ORMatE-III on orbit with the samples discussed in this paper highlighted is shown in Figure 1. They were retrieved 728 days later by ISS Expedition 36 ESA Astronaut Luca Parmitano via EVA on July 9, 2013, and returned to Earth inside the SpaceX Dragon capsule on May 18, 2014 as part of the SpX-3 Mission. The ORMatE-III samples were part of the down-mass cargo from the mission that was returned to the Port of Long Beach via marine vessel on May 20, 2014, two days after splashdown. Sea water was found inside the Dragon capsule, possibly related to the fact that it was in the ocean 11 h before it was recovered, but preliminary checks indicated that no scientific equipment had been damaged (Ref. 5). The capsule was transferred to NASA at the SpaceX McGregor test facility in Texas (Ref. 6).

The fluence of AO the samples were exposed to was determined by the erosion of Kapton® H witness coupons using well documented standard procedures (Ref. 7). As expected, the wake surface received a relatively low fluence of 8.80×10^{19} atoms/cm^2, about 1.9 percent of the ram fluence (Ref. 7). For comparison, the AO fluence for the MISSE-7 Spacesuit Fabrics Exposure Experiment was calculated to be $2.9\pm0.3\times10^{20}$ atoms/cm^2, about 3.3 times higher (Ref. 8). Computations of the zenith solar exposure have been conducted by the Naval Research Laboratory (NRL) and were determined to be 6,100±1,000 equivalent sun hours (ESH) (Ref. 9). The wake surface solar exposures were approximated using the ratios of the MISSE 7 ram and wake to zenith ratios, respectively, because MISSE 8 was flown in the same location on ISS as MISSE 7 (ELC-2 Site 3), and yielded an estimate of 3200±200 ESH (Ref. 10). This is 60 percent higher than the 2000 ESH exposure experienced by the MISSE-7 Spacesuit Fabrics Exposure Experiment (Ref. 11). So the ORMatE samples were exposed to the space environment 33 percent longer than the MISSE-7, receiving about 60 percent more ESH solar radiation, but only received one-third the exposure to AO. The higher AO exposure of the MISSE-7 samples is probably due to the reorientation of ISS that was required for Space Shuttle docking, during which the "wake" samples of MISSE-7 were actually in a ram orientation, whereas the ORMatE-III samples were exposed after the Space Shuttle era.

Figure 1.—On-orbit Photo of ORMatE-III with the Apollo FEP sample circled in red and the Orthofabric sample circled in yellow.

Methods and Materials

The ORMatE-III Spacesuit Fabrics Exposure Experiment included two samples of spacesuit fabric, Apollo FEP and Orthofabric. During the Apollo program, most of the outer surface of the PGA was made of β-cloth, but areas that were expected to see heavy wear, such as the knee were made of woven FEP fabric (Ref. 12). Although most of the PGAs were made with a plain-weave FEP, in some cases a twill-weave FEP was used. The Apollo FEP sample was of plain weave FEP cut to a circle about 22 mm in diameter, with an exposed area of about 19.6 mm, or 3.0 cm^2. PGA design has progressed since the Apollo era, and the suits worn by astronauts in their return to the moon will probably not have an outer layer of woven FEP. The current PGAs used in Space Shuttle and International Space Station EVAs use Orthofabric (Fabric Development) as the outermost layer. Orthofabric is a two layer plain weave face tied to back of 400 denier Gortex® (W.L. Gore & Associates), 200 denier Nomex® (DuPont), and 400 denier Kevlar® (DuPont). The yarn count is 51×41/in. (20×16/cm) on the face, and 39×33/in. (15.3×13/cm) on the back. The fabric weight is 15.0 oz/yd^2 (0.355 kg/m^2), with a thickness of 0.027 in. (0.69 mm). The outer Gortex® layer of is made from expanded PTFE, so although the two fabric types are very different, they both have fluorinated hydrocarbons as the outermost material. The Orthofabric sample was cut to a circle about 25 mm in diameter, with an exposed area of about 22.7 mm, or 4.0 cm^2.

To the extent possible, pre-flight and post-flight analyses were done using the same protocols used for the MISSE-7 samples which are detailed in the MISSE-7 pre-flight report (Ref. 13). Imaging included survey photography; optical microscopy at magnifications of 7.1×, 10×, 25×, 50×, and 100×; and a Hitachi S-4700 Field Emission Scanning Electron Microscopy (FESEM) at 250×, 500×, 1000×, and 5000× magnifications. Half of each sample was coated prior to FESEM examination with a few tens of nm of Pt to decrease the amount of charging in the electron beam. The one aspect that was different between the pre-flight and post-flight analyses was the sampling areas. Whereas one of the goals of the pre-flight characterization was to establish the baseline structure, in the post-flight analysis changes and anomalies were the target. For example, in the FESEM five regions were surveyed pre-flight, but only two major regions of the post-flight, one that was exposed and one that was shielded by the sample holder. Within those regions images were taken that were representative of the whole, and of areas of anomalous wear. Energy dispersive x-ray spectroscopy (EDS) was also used post-flight to examine the samples for contamination. This was done in conjunction with the FESEM such that the elemental composition of specific microscopic areas of the samples could be determined.

Optical spectroscopy was performed on the fabrics to look for signs of degradation. Of particular concern was whether the thermal properties would change such as to impose an additional heat load on the suit. Total reflectivity ($\rho(\lambda)$), was measured with a Cary 5000 (Varian) spectrophotometer equipped with an integrating sphere over wavelengths (λ) from 250 to 2500 nm in increments of 1 nm, at a scan rate of 600 nm/min. A deuterium lamp was used to illuminate the samples to measure the 250 to 350 nm data, and a halogen lamp to illuminate the samples to measure the 350 to 2500 nm data. Immediately prior to measuring each sample, a spectrum of the Spectralon® was collected as a sample, to determine whether the baseline was still valid. In all instances the deviations in the baseline were less than 1 percent.

The $\rho(\lambda)$in the mid-infrared region (wavelength 2.5 to 25 μm) was measured using an iS50 Nicolet Spectrophotometer (ThermoFisher) equipped with a Pike integrating sphere measured on a deuterated triglycine sulfate (DTGS) detector. Data were collected using OMNIC software. Since all of the incident energy must be transmitted, reflected, or absorbed, assuming the samples were opaque, their absorptivities ($\alpha(\lambda)$) can be calculated using Equation (1).

$$\alpha(\lambda) = (1 - \rho(\lambda)) \tag{1}$$

The α can be obtained by integrating the $\alpha(\lambda)$ over all values of λ, and convolving it with the ASTM air mass zero solar spectral irradiance table E–490–00 expressed as a fraction of the solar spectrum ($S(\lambda)$).

In practice nearly all of the solar energy is emitted between 250 and 2500 nm, so the approximation shown in Equation (2) can be made with little loss of accuracy.

$$\alpha \approx \sum_{250\,\mathrm{nm}}^{2500\,\mathrm{nm}} \alpha(\lambda) S(\lambda) \tag{2}$$

Kirchhoff's law of thermal radiation leads to the expression for the emissivity ($\varepsilon(\lambda)$) below, Equation (3).

$$\varepsilon(\lambda) = \alpha(\lambda) \tag{3}$$

The total integrated emittance (ε) was approximated by summing the $\varepsilon(\lambda)$ times the normalized blackbody irradiance values for a given wavelength and temperature ($B(\lambda,T)$) over the wavelength range of the spectrum, Equation (4). There is little lost in approximating ε over the temperature range of 250 to 700 K by using λ from 2.5 to 25 µm.

$$\varepsilon \approx \sum_{2.5\,\mu\mathrm{m}}^{25\,\mu\mathrm{m}} \varepsilon(\lambda) B(\lambda, T) \tag{4}$$

It is important to note that, because of the limited range of the wavelength region probed by the IR spectra, there is a corresponding limited temperature range for which this analysis is valid. Temperatures below about 250 K or above about 700 K would require input over a wider wavelength range. This study did not attempt to calculate ε outside of the 250 to 700 K window.

Results and Discussion

Survey Photography

Upon return of the flight samples to the NASA Glenn Research Center, they were removed from the Kapron® protective shipping bags and photographed. Figure 2 shows the visual comparison of the two fabric samples on exposure to the space environment. It can be seen in the photograph that space exposure darkened the fabrics and gave them a somewhat reddish tint. This will be explored quantitatively in the spectroscopy section of the study. When the samples were removed from the flight holder, the perimeter area of the fabric that was shielded from the environment by being under the edge of the sample holder was readily visible in the figure. The color change was somewhat greater than those observed on post-flight analysis of the MISSE-7 samples (Ref. 14).

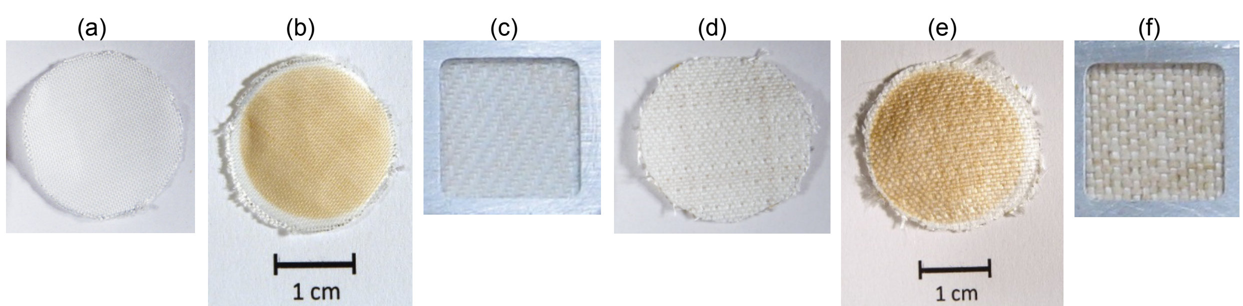

Figure 2.—Photographs of the Apollo FEP fabric before (a) and after (b) exposure and Orthofabric before (d) and after (e) exposure to 2 years wake-side exposure on ORMatE-III. The MISSE-7 Apollo FEP (c) and Orthofabric (f) exposed samples are shown for comparison.

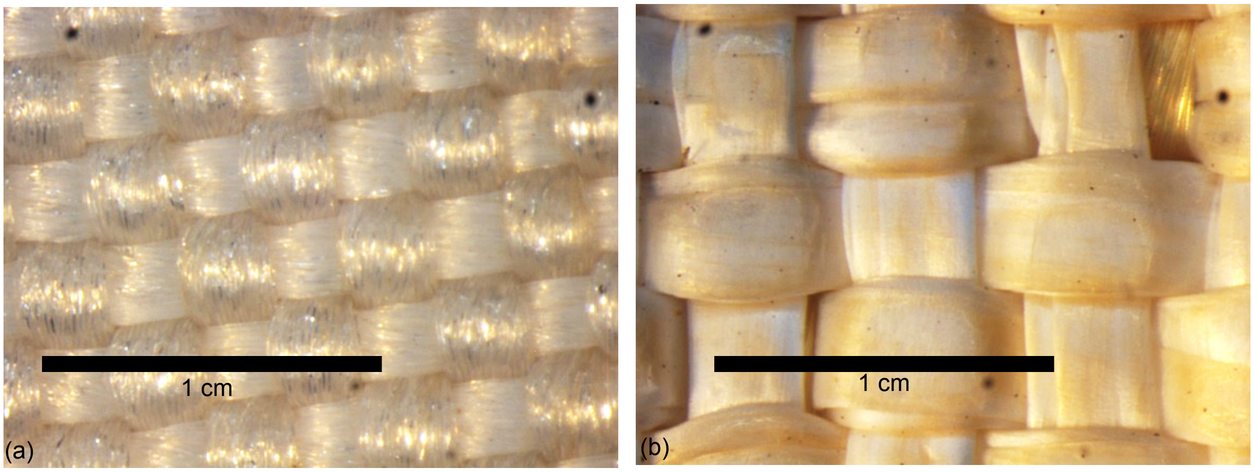

Figure 3.—Optical micrographs of ORMatE-III Apollo FEP fabric (a) and Orthofabric (b) at 50× magnification.

Optical microscopy of both ORMatE-III fabrics showed no apparent mechanical damage at 50× magnification, as can be seen in Figure 3. The discoloration of the FEP fabric appears to be relatively uniform. This is in contrast to the Orthofabric, where there was considerable variation in the discoloration of the fibers. Note a Kevlar® yarn is visible in the upper right portion of the photo. Although this is similar in color to the discoloration, there does not appear to be a color gradient towards it, so it is not thought to be a contamination source. As was our conclusion from the MISSE-7 test, the discoloration is probably due to radiation damage of the PTFE. This is also consistent with the ORU results. The β-cloth in those samples showed noticeable darkening in areas that were not shadowed by surrounding ISS structure. That study also found no direct evidence of contamination as a contributor to the darkening. As noted above, Linton also observed darkening of the β-cloth on LDEF which he attributed to increased surface texture and darkening of exposed glass fibers.

From the spatial distribution of discoloration, we speculate that it may be correlated with stress concentrations within the fibers. The fabric samples showed no apparent mechanical damage up to a magnification of 100×.

Electron Microscopy

The samples were clamped into the sample holder by a region about 2 mm around the circumference. As can be seen in Figure 2, this region of the samples was protected from solar radiation and AO exposure. FESEM images of this protected region of the Apollo FEP sample are shown in Figure 4.

The fibers appear to have been flattened in places, probably from being pinched in the sample holder. But even at high magnification (5000×) no other damage or texture was present. Interestingly, the presence of fine filaments with a diameter ~100 nm and a length of 10 to 30 μm was noted on the surface of the fibers (Figure 4(b)) and stretched across the gaps between the fibers (Figure 4(c)). These were not seen in protected areas of the MISSE-7 samples. The origin of these filaments is unknown. It is speculated that these are places where the fibers were in contact and then pulled apart as the fabric flexed and the filaments were drawn from places of high adhesion.

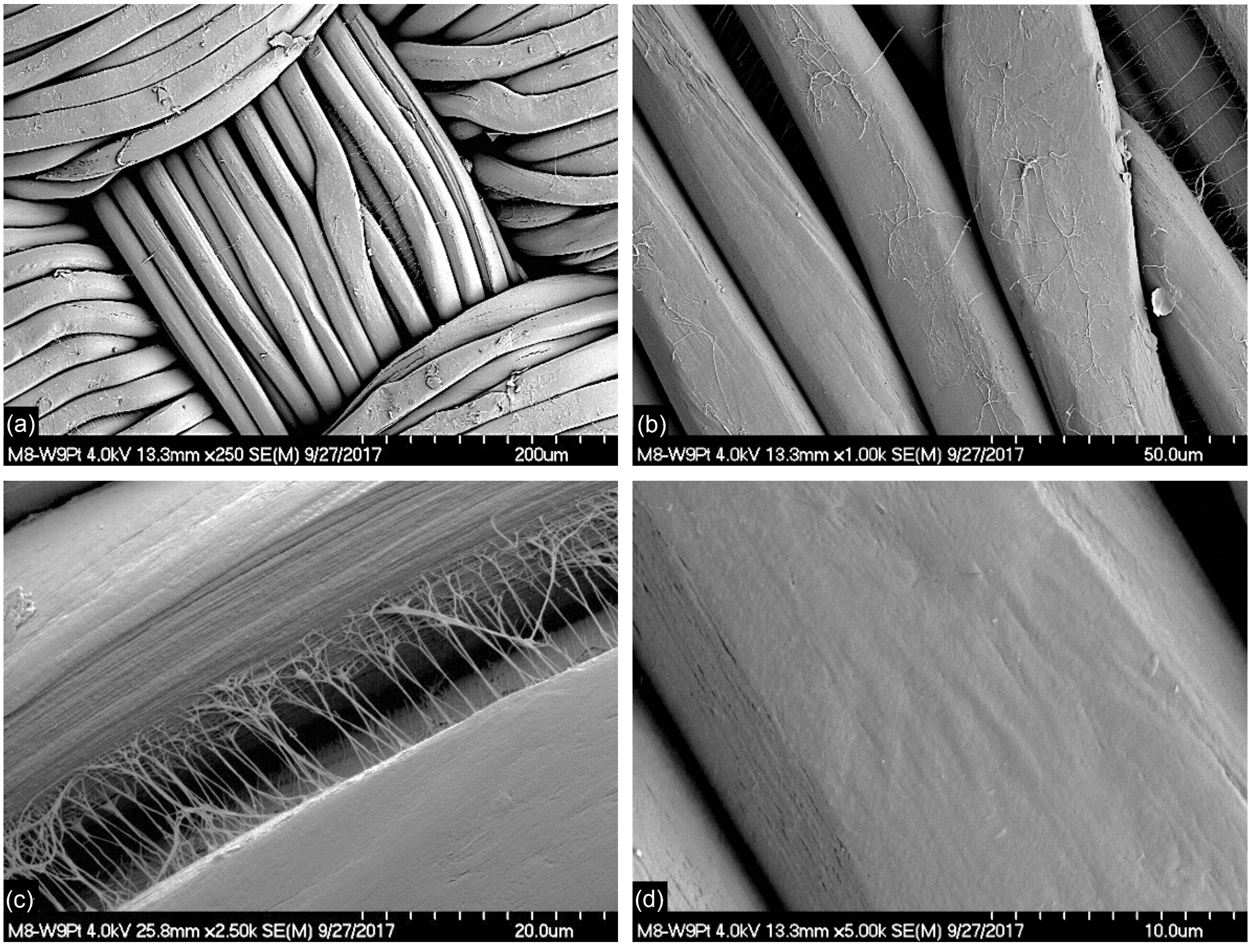

Figure 4.—FESEM images of the protected region of the ORMatE-III Apollo FEP fabric at (a) 250×, (b) 1000×, (c) 2500×, and (d) 5000×.

FESEM images of the exposed area of the ORMatE-III Apollo FEP fabric sample are shown in Figure 5. The most striking difference between this and the unprotected regions is the presence of fine texture in the exposed sample which is increasingly visible as the magnification increases. The fine filaments seen between the protected fibers are not seen in the exposed area, probably because the filaments have been etched away by the AO. Similar texture was seen in the MISSE-7 samples (Figure 6) and was attributed to AO erosion that occurred principally during those periods when the ISS was reoriented so that the samples were in the ram direction. The texture was somewhat more developed in the MISSE-7 sample, which is consistent with its receiving a third more ram AO exposure. Similar texturing was observed in both the ORMatE-III and LDEF β-cloth samples (Figure 6).

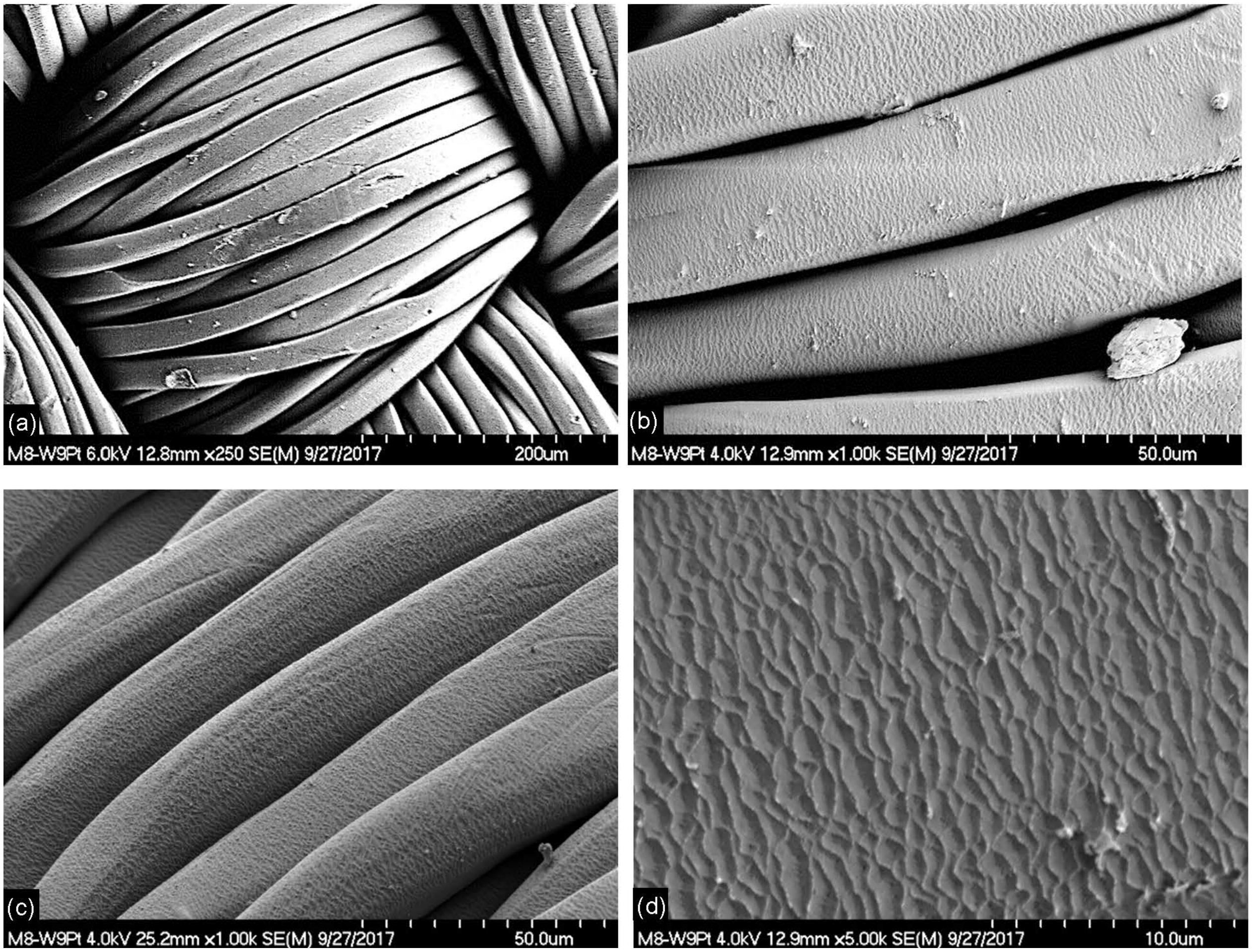

Figure 5.—FESEM images of exposed ORMatE-III Apollo FEP fabric at (a) 250×, (b, c) 1000×, and (d) 5000×.

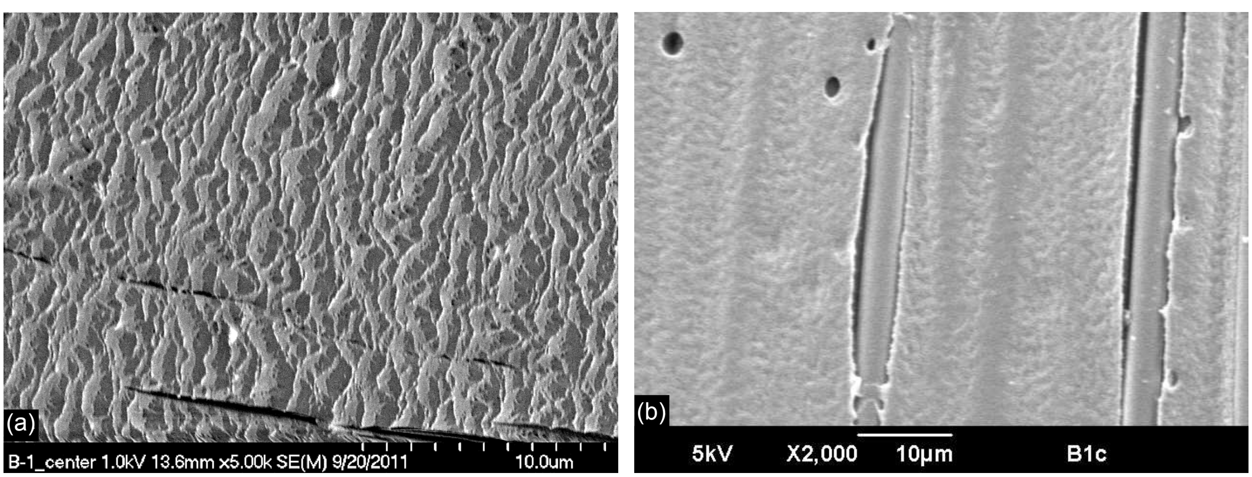

Figure 6.—FESEM images of exposed MISSE-7 Apollo FEP spacesuit fabric at (a) 5000×, and ORU β-cloth at (b) 2000× show texture similar to that observed in the ORMatE-III samples.

FESEM images of the protected Orthofabric are shown in Figure 7. The fibers were about 8 times larger than the Apollo FEP fibers with a diameter of more than 400 μm compared to about 25 μm. The stresses generated in the larger fibers resulted in numerous longitudinal cracks. The same fine filament structure within the cracks was observed as was noted between the protected Apollo FEP fibers, and was seen with increasing clarity as the magnification increased. The similar morphology suggests that the intra-fiber and inter-fiber filaments were formed by a similar mechanism, the failure of an adhesive bond. No other damage or texture was seen even at high magnification (5000×).

FESEM images of the exposed area of the ORMatE-III Orthofabric sample are shown in Figure 8. The same axial cracks were seen in the exposed sample that were present in the protected. And a similar texture that was etched in the exposed Apollo FEP fabric here also was increasingly visible as the magnification increases. There also appeared to be fewer of the fine filaments within the fiber cracks, presumably because they also were etched away by the AO. Once again, similar texture was seen in the MISSE-7 samples (Figure 9) and was attributed to AO erosion that occurred principally during those periods when the ISS was reoriented so that the samples were in the ram direction.

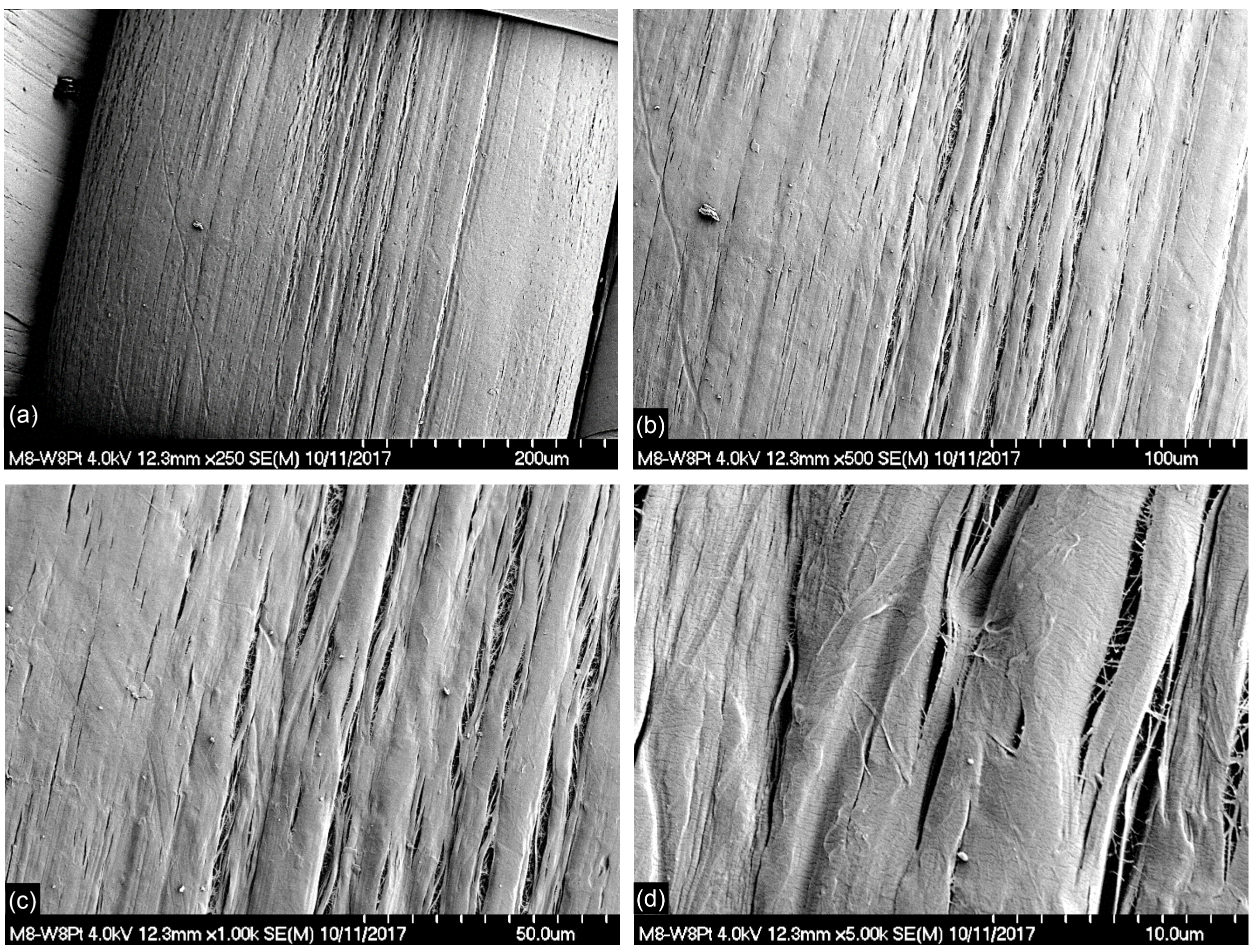

Figure 7.—FESEM images of the protected region of the Orthofabric at (a) 250×, (b) 1000×, (c) 2500×, and (d) 5000×.

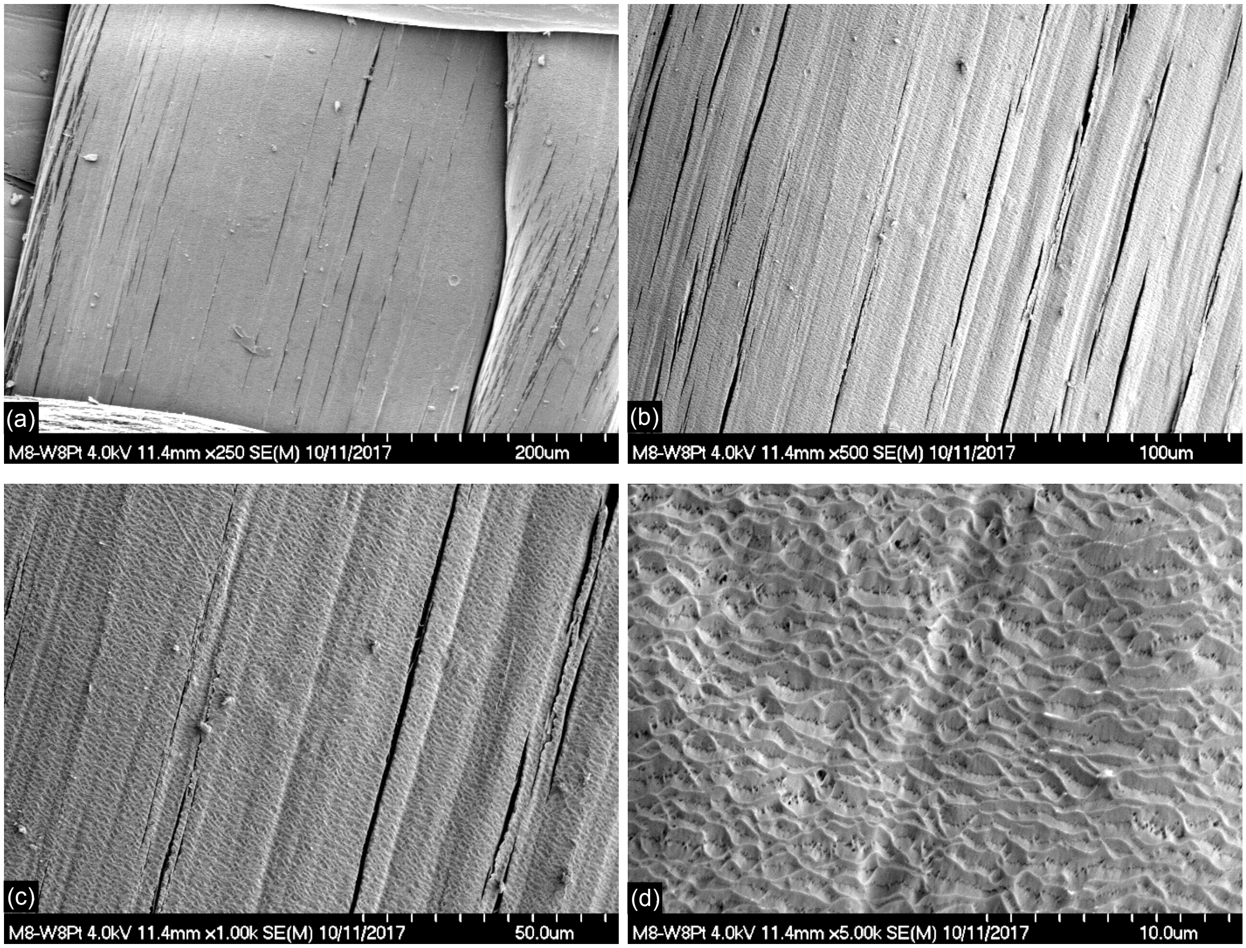

Figure 8.—FESEM images of exposed Orthofabric at (a) 250×, (b) 500×, (c) 1000×, and (d) 5000×.

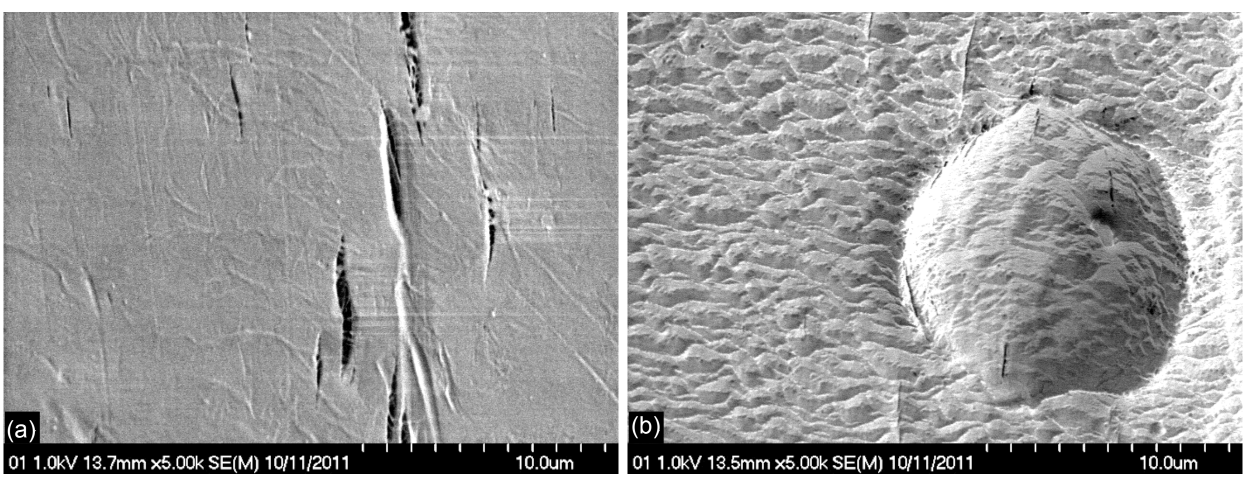

Figure 9.—FESEM images of MISSE-7 Orthofabric at 5000× showing (a) the lack of texture in the protected area and (b) the texture in the exposed area. The 10 μm crater shown in (b) was the result of a debris strike prior to erosion texturing.

Spectroscopy

EDS spectra were collected over several regions of the fabric samples with an excitation energy of 6 keV. Figure 10 and Figure 11 show typical spectra of the ORMatE-III Apollo FEP fabric and Orthofabric, respectively. The empirical formula for both FEP and PTFE is CF_2 and this was confirmed in the spectra. Slight variations in the 2:1 F:C ratio occurred as different areas were sampled, but none deviated excessively. The Pt coating was clearly visible in the spectra, but no contamination peaks were observed. Shown are the positions of the Si and O because silicones are expected to be the most likely contaminant. There was no discernable Si peak and small oxygen peak was attributed to water adsorbed from the atmosphere during storage. The ORU β-cloth EDS analysis had similar results.

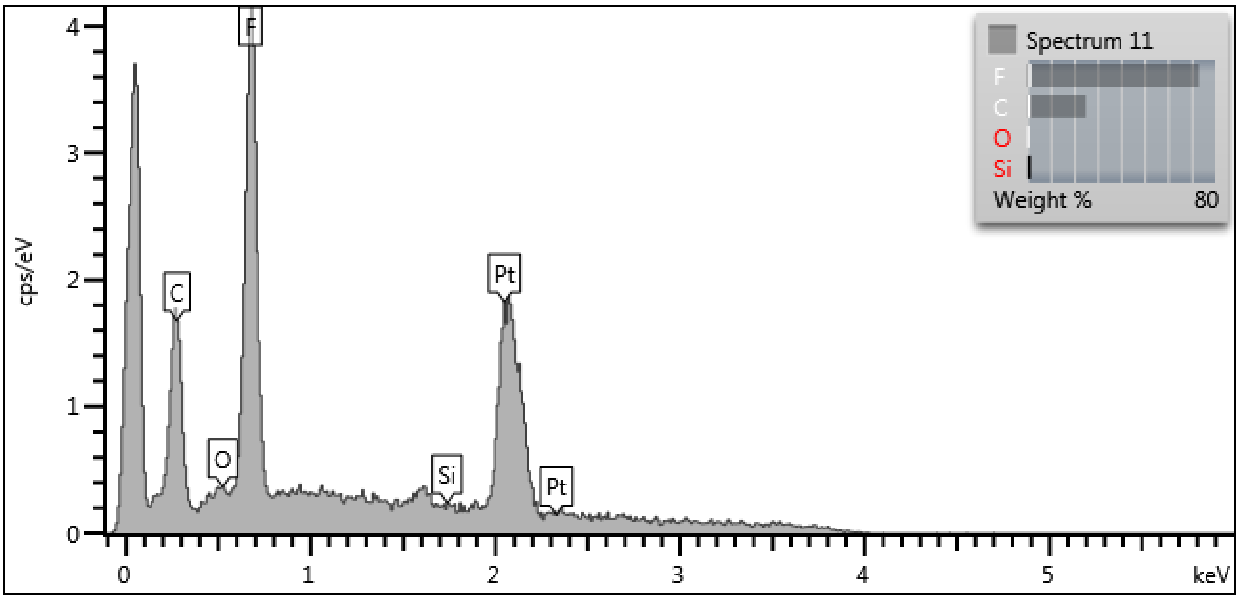

Figure 10.—Typical energy dispersive x-ray spectrum (EDS) of the ORMatE-III Apollo FEP fabric sample taken over a 400×500 μm region.

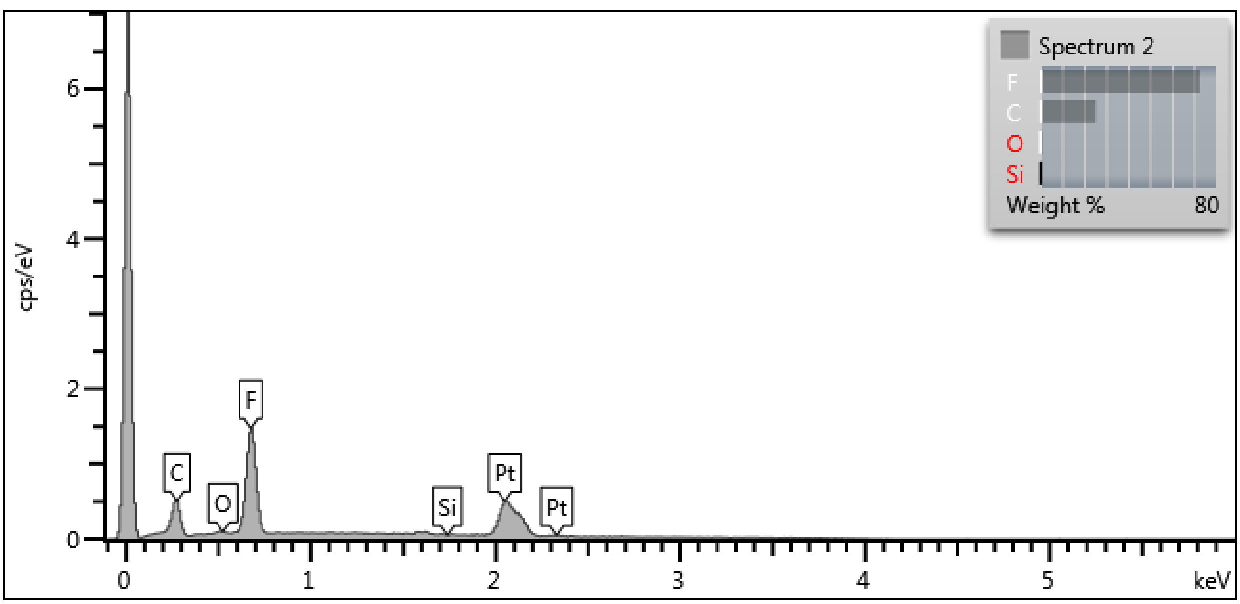

Figure 11.—Typical energy dispersive x-ray spectrum (EDS) of the ORMatE-III Orthofabric sample taken over a 400×500 μm region.

The reflectance spectrum in the 250 to 2500 nm wavelength range is important because that is the region where the sun emits over 99 percent of its radiated energy. The more solar radiation a spacesuit absorbs the heavier will be its heat load, so a high reflectivity is important to maintain a comfortable temperature inside the suit. The spectra of the two fabrics in this wavelength region are shown in Figure 12. It can be seen immediately that the FEP in the Apollo fabric had a much different spectrum than the PTFE of the Orthofabric, with PTFE having many more spectral features 1300 to 2000 nm region.

The ORMatE-III Apollo FEP spectrum (Figure 12(a)) looked very different from the pristine MISSE-7 samples. Like the darkened regions of the ORU β-cloth it was much less reflective in the UV region, below 400 nm. However, it was much more reflective in the IR region, with the crossover occurring at about 550 nm, than any of the other three samples. The spectral feature at 1354 nm was much deeper and shifted to 1386 nm. Similarly, the feature at 2215 nm was also much deeper. The differences between the MISSE-7 and ORMatE-III may be related the to 60 percent higher ESH solar exposure. In the UV-visible part of the spectrum the ORU β-cloth spectrum had a deeper absorption in the 250 to 300 nm range, was comparable in the 300 to 400 nm range and then intermediate between the MISSE-7 and the ORMatE-III throughout most of the IR range. This gives a consistent picture of the main degradation region being in the UV part of the spectrum.

The α calculated from the ORMatE-III Apollo FEP spectrum was 0.215, fairly similar to the 0.22 calculated for the pristine material. (It is difficult to compare the ORU data because, not only did it vary from 0.24 to 0.30, but it also had exposed glass fibers which are much less reflective than the FEP.) The higher UV absorption was nearly offset by the lower IR absorption, so even though there was appreciable darkening of the fabric to the eye (Figure 2) the α, and so the solar thermal load, was comparable. However, since solar exposure increases the UV absorption, and UV absorption breaks chemical bonds, the mechanical properties of the fabric can be expected to degrade in an ever accelerating pace as the exposure increases.

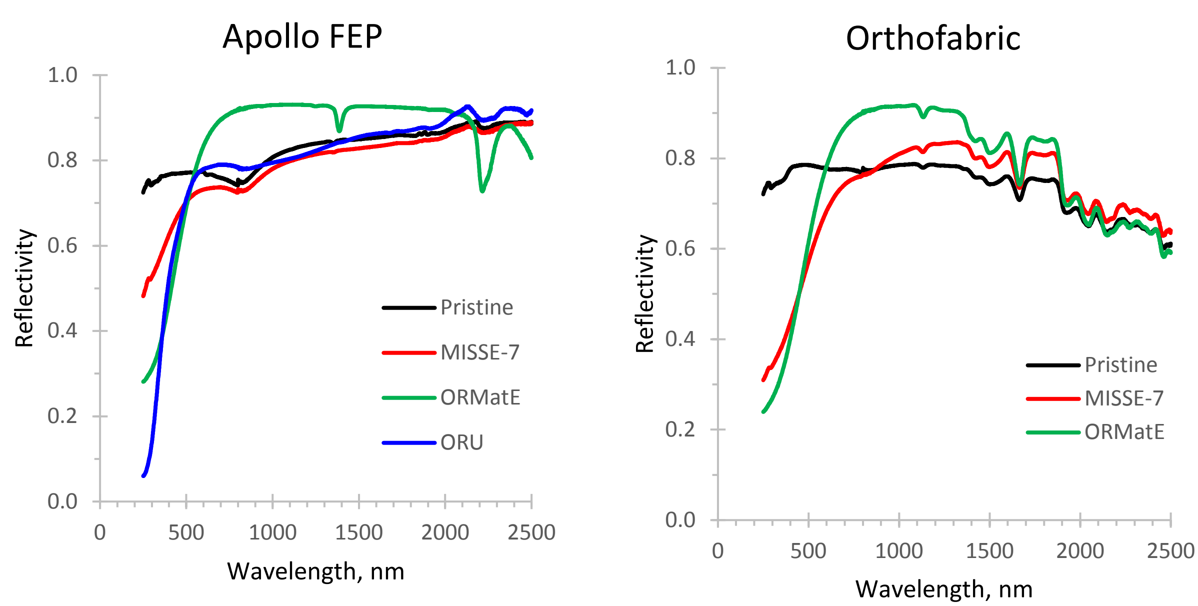

Figure 12.—The 250 to 2500 nm spectra of the Apollo FEP and Orthofabric samples flown on the ORU, MISSE-7 and ORMatE-III.

In contrast, the ORMatE-III Orthofabric spectrum showed the same spectral features as pristine Orthofabrics, but more highly absorbing in the below 500 nm region, more reflective in the 500 to 1800 nm region, and unchanged above 1800 nm. The greater absorption in the below 500 nm region was consistent with the reddish color to the eye. The α was calculated from this spectrum 0.267, as compared to 0.24 for pristine Orthofabric. Even more so than in the case of the FEP fabric, the degradation of the MISSE-7 fabric appeared to be intermediate, due to the lower ESH of the sample. With increasing exposure the UV absorption increased and the IR absorption until about 1800 nm decreased.

The 2.5 to 25 μm infrared spectra of the samples were measured in order to determine the effect of space exposure of their ε. The calculated ε as a function of temperature for pristine and ORMatE-III fabric samples is shown in Figure 13. Little change was seen in the ε. Interestingly, the ε of the Apollo FEP fabric decreased slightly and that of the Orthofabric increased slightly. In both cases the effect became more pronounced at higher temperatures, with the Apollo FEP fabric decreasing from 1 to 6 percent of the range of 250 to 700 K, and the Orthofabric increasing by 1 to 3 percent over the same range. Thermal IR spectra for the MISSE-7 samples were not collected and so are not available for comparison.

The thermal performance of a material is space is characterized by the energy is will absorb from the sun, which is primarily in the 250 to 2500 nm wavelength range, and the energy it emits in the thermal infrared region, which is temperature dependent. This is commonly express in terms of the α/ε. For Apollo FEP fabric, the 300 K α/ε is 0.358 for both pristine and ORMatE-III. This implies that, although there will be material changes on exposure to the space environment, the thermal properties will be unchanged, or at least minimal. In the case of Orthofabric, the α/ε was 0.335 for the pristine fabric, and 0.368 for ORMatE-III fabric. This implies that over time the ability of the Orthofabric to reject heat will slowly degrade. If these tests are typical, the degradation rate will be about 10 percent over two years. But as noted above, as the α degrades it becomes more absorbing in the UV region, so the degradation would not be expected to be linear, but the rate of degradation would increase as exposure time increases.

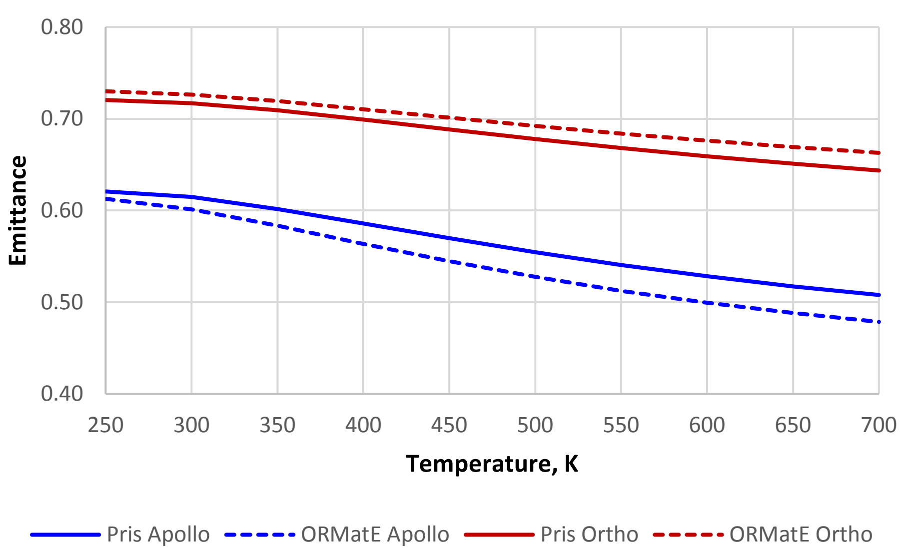

Figure 13.—The emittance as a function of temperature determined from the 2.5 to 25 μm spectrum for pristine Apollo FEP fabric, pristine Orthofabric, and the same fabrics exposed on ORMatE-III.

Conclusions

Two different outer spacesuit fabrics were exposed to the wake-side low Earth orbit environment for two years in order to determine their long term durability in the space environment. One sample each of the Teflon® fabrics that covered Apollo spacesuits and the Orthofabric that covers the Space Shuttle and ISS suits was flown on the ISS as part of the ORMatE-III experiment. Results were compared with previous experiment on MISSE-7 which had similar exposure conditions on the ISS for 18 months, as well as β-cloth exposures on the LDEF for 5.7 years and an ISS battery ORU that was exposed for 8 years.

Both ORMatE-III samples were darkened considerably. The EDS spectra showed no evidence of contamination, so the primary agent of the darkening is thought to be UV and high energy particle radiation. Spectral analysis showed increased absorption in the shorter than 500 nm portion of the spectrum, consistent with the reddish color of the darkening. But on exposure both fabrics became more reflective in the 500 to 1800 nm region, and as a result, there was little change in the α of the fabrics. Measurement of the 2.5 to 25 μm spectra indicated that there was only a small change in the ε of the fabrics in the 250 to 700 K. Thus, although on long exposure the spacesuits are expected to darken to the eye, their thermal properties (α/ε) will remain nearly constant for the Apollo FEP fabric, and will increase only slowly for the Orthofabric.

In addition to the darkening, at high magnification texturing of the fabrics was seen and taken as evidence of exposure to AO. The AO erosion was less developed than that of the MISSE-7 samples, which had a higher fraction of the exposure time in an AO-ram position. Although these sample were too small to characterize their mechanical properties, degradation of the MISSE-7 samples as well as metalized FEP films on the Hubble Space Telescope thermal shields suggest that long term exposure of these fabrics to the space radiation environments will cause them to embrittle.

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