For: Advanced Materials

Title: Small-scale mechanical characterization of space-exposed fluorinated ethylene propylene recovered from the Hubble Space Telescope

Authors: J.S. Jones[a*], J.A. Sharon[b**], J. Mohammed[a], K.J. Hemker[b]

[a]Materials Engineering Branch, NASA Goddard Space Flight Center, Greenbelt, MD USA

[b]Department of Mechanical Engineering, Johns Hopkins University, Baltimore MD USA

*Corresponding author

**Currently at Sandia National Laboratories, Albuquerque, NM USA

Abstract

Multi-layer insulation panels from the Hubble Space Telescope have been recovered after 19.1 years of on-orbit service and micro-tensile experiments have been performed to characterize the effect of space exposure on the mechanical response of the outermost layer. This outer layer, 127 μm thick fluorinated ethylene propylene with a 100 nm thick vapor deposited aluminum reflective coating, maintained significant tensile ductility but exhibited a degradation of strength that scales with severity of space exposure. This change in properties is attributed to damage from incident solar flux, atomic oxygen damage, and thermal cycling.

Keywords: Hubble Space Telescope, space-exposed fluorinated ethylene propylene, small-scale testing, chain scission, digital image correlation

Background and Introduction

The Hubble Space Telescope was launched into low earth orbit in April of 1990 with multi-layer insulation (MLI) panels providing thermal control and environmental protection for much of its hardware and equipment bays. The outermost layer of MLI is made of 127 μm thick fluorinated ethylene propylene (FEP) with a 100 nm thick vapor deposited aluminum layer (Al-FEP) on the inner face which helps to shield sub-layers of the MLI. Based on observations during previous servicing missions and ground analysis of returned material, this outer layer of Al-FEP is known to degrade in the on-orbit environment[1][2]. In May 2009 during Hubble Servicing Mission 4, two full MLI blankets from equipment Bay 5 and Bay 8 of the telescope were replaced and returned to earth. The retrieved MLI blankets were brought back for evaluation of the extent of on-orbit degradation and characterization of its causes. These Al-FEP blankets had been in low earth orbit since Hubble's deployment, with regions varying in exposure to solar radiation, thermal cycling, space debris, and atomic oxygen. Previous NASA studies[1][2][3][4] were performed to understand the combined effect of temperature cycling and solar radiation on the Al-FEP. When characterizing the mechanical response, those studies tested macro-scale samples using conventional tensile platforms and the results indicate a decrease in strength with increased space exposure; however, preparing samples free of edge flaws was a challenge and prohibited measurement of the full stress-strain response. The retrieved Bay 5 and Bay 8 MLI blankets were highly damaged and cracked, which limits the material available for traditional full-scale testing of mechanical properties. In the current study, small-scale mechanical testing, as reviewed by Hemker and Sharpe[5], was employed to overcome these challenges and to quantify the inherent Al-FEP mechanical degradation of three sections from Hubble's MLI that experienced different levels of exposure.

All of the MLI sections analyzed from the two equipment bays had been on orbit for 19.1 years. Such an extended amount of time in low earth orbit subjects the MLI to damage from ultraviolet and x-ray radiation, thermal cycling, and exposure to atomic oxygen, all of which can degrade the material during service. Ultraviolet and x-ray radiation from the sun as well as a strong flux of protons and electrons from the lower Van Allen belt penetrate the Al-FEP and react with the polymer. Other NASA researchers have made estimates regarding the fluence of x-rays, protons, and electrons[4], though it remains challenging to isolate and quantify the specific contribution each factor has on the Al-FEP. In general, depending on the temperature conditions, these radiation events can cause either chain scission and/or chain cross-linking[6][7]. The scission events, which are more prevalent at low temperatures (below 80ºC), cause the breaking of polymer bonds and can lead to reduced molecular weight and strength[1][3][8][9] if not countered by cross-linking[10]. Cross-linking, more prevalent at higher temperatures, is thought to increase both the stiffness and the strength of the Al-FEP[11]. Thermo-mechanical cycles due to temperatures associated with Hubble's orbital path can also damage the MLI. The Al coating has a coefficient of thermal expansion roughly four times lower than the FEP. A simple calculation using textbook property values[12][13] for aluminum and reported values for FEP (DuPont[14]) indicate that the thermal strain mismatch between the two materials can approach 0.3% at 40°C; equivalent to an elastic stress on the order of 200 MPa in the aluminum. At these levels, repeated thermally driven expansion and contraction of the Al-FEP could potentially form cracks or delamination of the Al coating and compromise the ability of the panel to reflect radiation. Furthermore, atomic oxygen is known to react with the space-exposed FEP at the surface, resulting in a thickness reduction[9][15][16]. Full details on the environmental factors of low earth orbit are outlined by Dever et al.[16], and it has been shown that strength and ductility are influenced by a combination of these factors [1][2][3].

Results and Discussion

The Hubble Space Telescope is positioned at an altitude of approximately 600 km above the earth and has an orbit inclination of 28.5 degrees[1], effectively keeping the MLI panels at the same orientation with respect to the sun. This configuration is shown in Figure 1, with +V3 indicating the solar facing direction. For the material examined in this study, Bay 8 was almost directly solar facing at an angle of 15 degrees from the sun's normal (+V3) while Bay 5 was at an angle of 75 degrees from +V3.

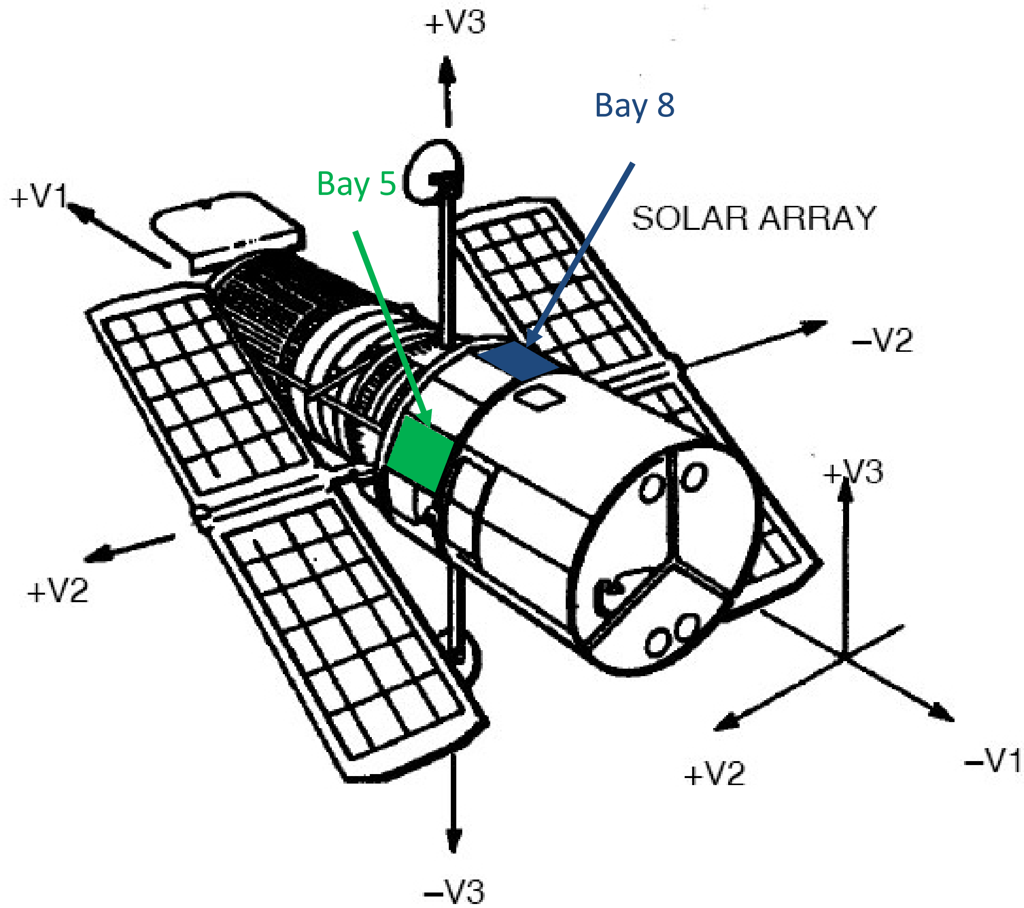

Figure 1: Schematic of the Hubble Space Telescope identifying Bay 5 and Bay 8 panels relative to the sun. +V3 is the nominally solar facing direction.

In addition to differences in solar angle between Bay 5 and Bay 8, there were portions of Bay 8 that had been covered with a 50 µm thick Al-FEP patch since 1997, after 6.9 years of full exposure, during Servicing Mission 2. Some non-environmental damage was also imparted on the blankets as a result of the patch process and/or handling during the retrieval process. Much of the material was also wrinkled, fractured, or curled up on orbit and thus experienced local differences in exposure conditions.

At least 10 unique regions of the outer FEP were identified on the Bay 5 blanket and 19 on the Bay 8 blanket, based on appearance and environmental exposure. Of these various regions from the two blankets, three were analyzed for this study, each with a unique history with respect to total exposure time, radiation flux, temperature fluctuation, and overall condition. From Bay 5, Region 1 was selected because it was relatively flat in orbit (i.e. not wrinkled or curled up) and free from handling damage and therefore any material degradation could be attributed to space environmental effects. For the same reason, Region 1 was selected from Bay 8. From the portion of Bay 8 that had been patched since 1997, region 11 was selected. Due to its shielding, this region is predicted to have reduced exposure to ultraviolet radiation and atomic oxygen[2]. Also, a sample of pristine Al-FEP that was never exposed to the space environment was analyzed for comparison.

All sections spent 19.1 years in orbit, with Region 1 of Bay 8 experiencing the most severe environmental exposure due to its solar facing inclination, followed by the patched Region 11 of Bay 8, and lastly Region 1 of Bay 5, which was at a less intense angle. The exposure levels, based on equivalent solar hours, were estimated to be 24,300 hours for region 1 of Bay 5, 30,300 hours for the patched region (region 11) of Bay 8, and 89,300 hours for the un-patched region (region 1) of Bay 8[4]. These equivalent solar hour estimates were determined by accounting for the time in orbit, the percent of time the material was shielded by the earth, and a region's nominal angle with respect to the sun. This metric is meant to give an effective amount of time at an equivalent normal incidence, but does not take into account other environmental effects such as atomic oxygen. In terms of thermal fluctuations, both bays and all regions underwent 110,000 cycles with temperatures estimated to range from -175°C to 0°C for Bay 5 and between -175°C to 40°C for Bay 8[4]. The as-fabricated material consisting of the FEP film[14] with a thin layer of vapor deposited Al had a nominal thickness of 127μm; however, prolonged exposure to space resulted in cracking of FEP as well as cracking and partial delamination of the Al coating. Reductions in FEP thickness of 4% to 39% were measured. This reduction in thickness is similar to that measured by Dever et al.[15] and can be attributed to atomic oxygen damage. The exposure history and thickness evolution of the FEP regions tested in this study are summarized in Table 1, along with a summary of results from the mechanical testing.

Table 1: Estimated exposure details and mechanical test results for the selected film regions

	Pristine	**Bay 5 Reg. 1**	**Bay 8 Reg. 11**	**Bay 8 Reg. 1**
Exposure Time (years)	0	19.1	6.9 (+ 12.2 patched)	19.1
Effective Angle of Incidence	N/A	75 deg	15 deg	15 deg
Equivalent Solar Hrs	N/A	24,300	30,300	89,300
No. Thermal Cycles	0	110,000	110,000	110,000
Temp range	N/A	-175°C to 0°C	-175°C to 40°C	-175°C to 40°C
Final Thickness	127 μm	122 μm	110 μm	78 μm
Ult. Strength (MPa)	17	14.2	15.9	13.1
Failure Strain (%)	>100	27 to 45	18 to 35	22 to 38

Due to the highly degraded nature of the material, careful sample preparation and small-scale tensile tests were necessary to minimize the influence of defects such as micrometeorite damage and cracking caused by space environmental exposure and handling during retrieval. To fabricate the tensile specimens, a rotary tool with a miniature diamond blade was employed to cut long rectangular strips from retrieved portions of the MLI panel, as shown in Figure 2. This technique produced smooth edges, thereby reducing the likelihood of premature failure from edge roughness.

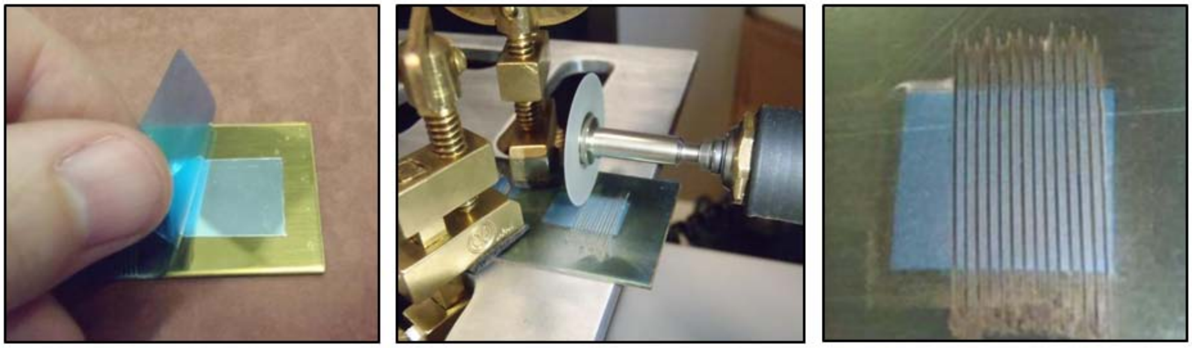

Figure 2: Specimen sectioning procedure. Samples were placed on a brass plate and held under a static film (left) to prevent shifting while parallel slices were made using a 150 micron thick diamond blade (center) to create 400 micron wide specimens (right).

The mechanical testing was carried out using a custom built micro-scale tensile apparatus as described by Gianola et al.[17] which was fitted with custom grips and equipped with high resolution tension-compression 100g (Cooper Instruments, model LFS 242-.25) and 250g (FUTEK Advanced Sensor Technology, Inc., model LSB200) load cells. Alignment of the loading axis with the tensile axis of the film was achieved using a 5-axis motorized stage with 30nm resolution (New Focus™ Picomotors™ from Newport Corporation). An adjoining linear actuator (New Focus™ Picomotor™) was used to load the sample in tension. The ends of the samples were bonded to the grips using a UV curable adhesive (Norland 123) that allowed for sample adjustment prior to permanent bonding. The experiments were displacement-controlled at a quasi-static strain rate of $5x10^{-4}$ s^{-1} and strain was measured using non-contact digital image correlation[18]. This system is shown schematically in Figure 3.

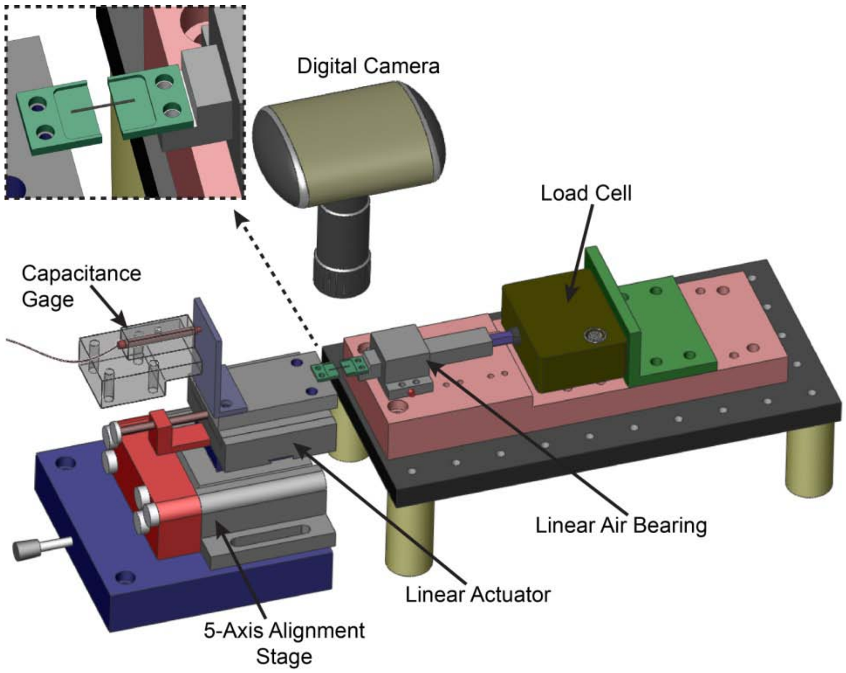

Figure 3: Schematic of the small-scale mechanical test system utilized in this study. A digital camera captures images of the sample during deformation for strain measurement. The load assembly with air bearing and load cell extend to the right of the test region (highlighted in inset). The alignment stage and linear actuator are to the left of the test region. A capacitive displacement gauge was used to monitor actuator motion. The gauge length (space between grips) for each specimen was at or near 3 mm.

Because of the difficulty of retrieving specimens and deteriorated nature of the MLI blankets, only a small amount of material was available for each specimen group. All microtensile specimens exhibited nearly elastic--perfectly plastic behavior with extended regions of tensile ductility. The pristine samples were inherently very ductile and elongations were obtained greater than 100%, which is larger than could be accommodated by the existing test setup. For this reason, only one representative test for the pristine material is reported and only the portion of the data which was measured optically is reported. For each exposure case, the specimens exhibited consistent results for the elastic response, yield strength, and flow behavior. By contrast the total strain to failure was found to vary from specimen to specimen by as much as an 18% difference in strain, possibly due to pre-existing micro-scale flaws. All materials with space exposure exhibited a significant drop in strength relative to the pristine material. In terms of mechanical degradation, the measured decrease in ultimate tensile strength (UTS) increased with increasing exposure, culminating in a drop of 23% for the Bay 8 Region 1 panel which was oriented normal to the sun with 19.1 years of exposure. The overall solar exposure of Bay 8 Region 1 was considerably higher than Bay 5 Region 1, and this corresponded to significantly lower strength for the Bay 8 material. It should be noted that the Region 11 portion of Bay 8 had comparatively lower degradation and higher strength because this section of the panel was patched and did not experience direct un-shielded exposure to the space environment for all 19.1 years in space. When comparing the higher strength of the patched Region 11 of Bay 8 with the lower strength of the un-patched, solar-grazing angled Bay 5 Region 1, the higher number of equivalent solar hours for the former appears to be contradictory. It should be noted though that the equivalent solar hour metric does not account for the damage imparted by thermal cycling or atomic oxygen. This observation then suggests that directly scaling mechanical strength with equivalent solar hours may serve as a "rule of thumb" but is not sufficient to comprehensively describe the weakening of the Al-FEP. The degradation rate of the polymer may also be non-linear in time with accelerated decay of the material at later stages owing to chain scission events, compounded with damage from the atomic oxygen and thermo-mechanical cycling. The stress-strain (engineering convention) plots for all tests are shown in Figure 4. The UTS values for the exposed material and the observed reduction with increasing exposure are in-family with reports from previous NASA Service Mission materials[1][2][3], but because the small scale testing approach utilized in this study enabled samples to be created without large scale defects, the full loading spectrum could be reported. From the stress-strain profiles in Figure 4 and test images shown in Figure 5 one can identify the elastic regime, yielding, necking, cold drawing, a small degree of strain hardening, and failure.

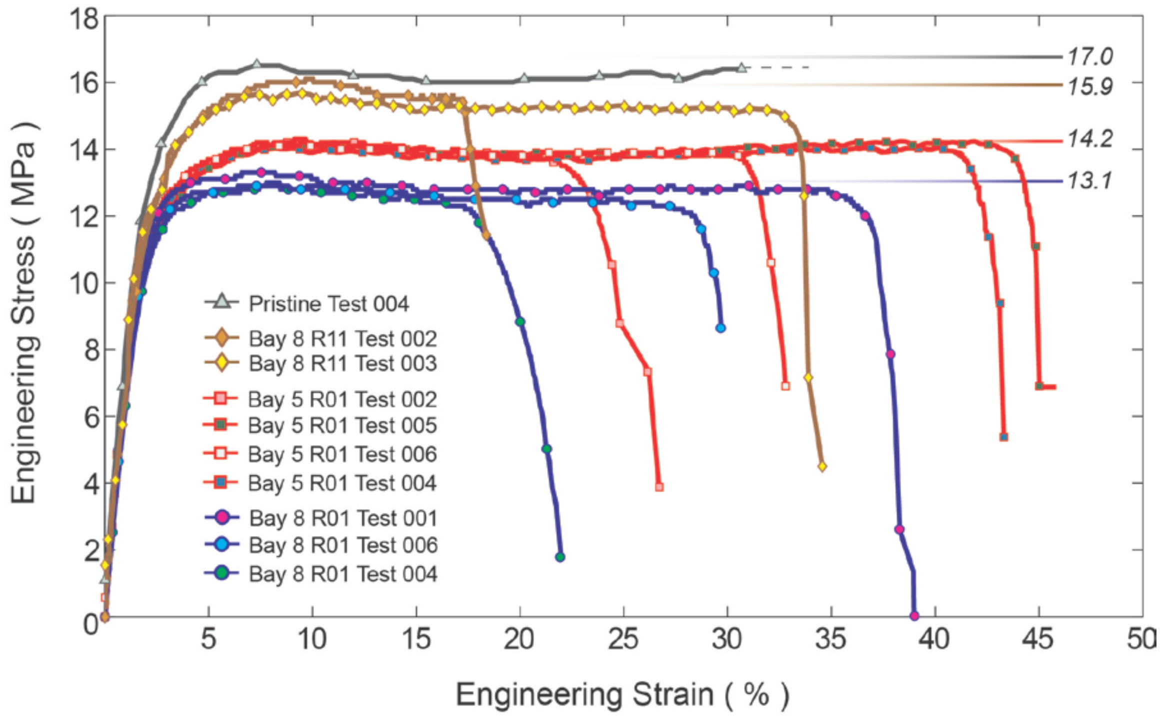

Figure 4: Stress-strain response of tested specimens. All tests were run at a quasi-static strain rate of $5x10^{-4}$ s^{-1}, except for the pristine which was tested at $8.33x10^{-3}$ s^{-1} and not taken to failure. Average UTS for each specimen group is denoted by the italicized value to the right of the curves.

Not only are differences in strength observed between the differently exposed regions, but also in the failure mode. While all samples exhibited greater than 20% tensile ductility, the films from Bay 8 Region 1 which had the most severe on-orbit environment failed via edge cracking, while the films from Bay 5 failed by necking instability, as depicted in Figure 5. Evidence of local crazing was also observed in the highly strained regions of all of the Bay 5 samples. This observation suggests that prolonged space exposure not only degraded the strength of the Al-FEP but also alters the internal structure of the polymer resulting in a change in the failure path.

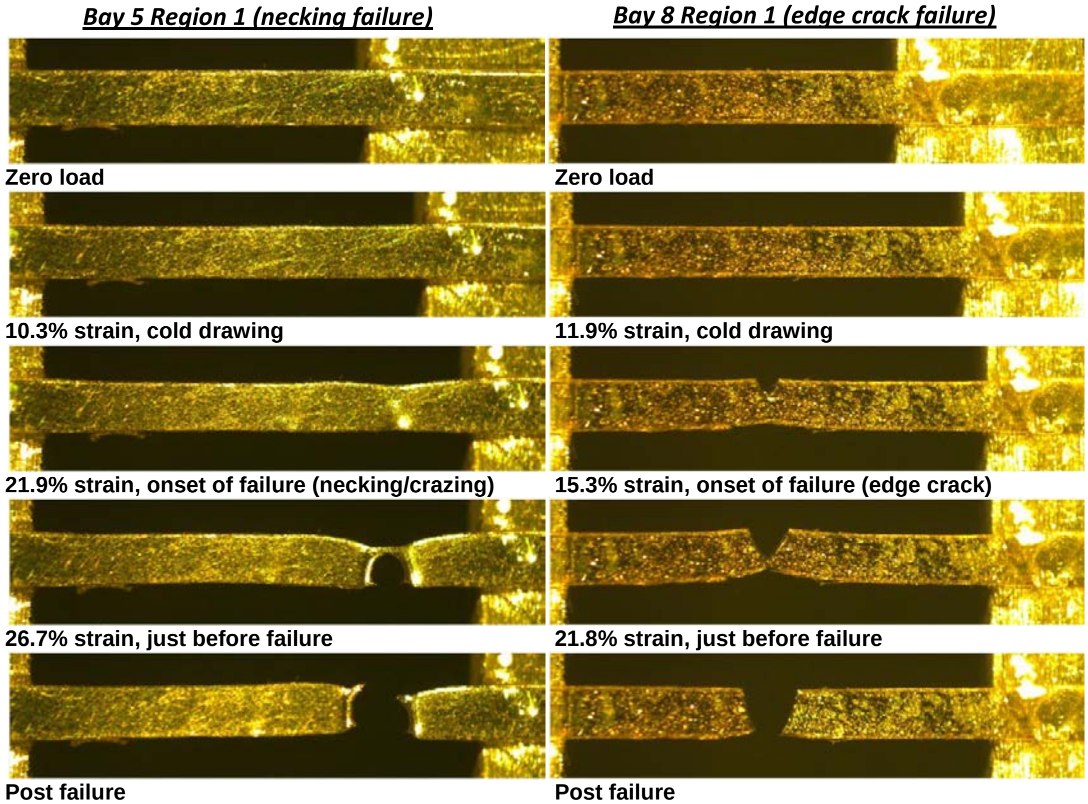

Figure 5: Representative event sequence for Bay 5, Region 1 (left column) and Bay 8, Region 1 (right column) showing two distinct failure modes, as described under each image. The initial gauge length for each specimen was 3.0 mm and the strain values shown are engineering strain.

The results reported here suggest that the irradiation of the FEP, which involves chain scission since temperatures were below 80°C[8][11] (max on-orbit temperature was 40°C), shorten the polymer's backbone[19] as evidenced through a measured reduction in the mechanical strength. Furthermore, damage contributions from the eroding effects of atomic oxygen are present, as exemplified by a pronounced reduction in thickness of the Al-FEP (see table). The deterioration contribution due to thermal cycling could not be quantified. Laboratory thermal cycling of pristine FEP at temperature swings representative of low earth orbit (independent of other space environmental factors) has not been shown to significantly reduce tensile performance[3][20]. However, visual observations of cracking in the Al—which were more prevalent in the higher temperature Bay 8 material, could be explained by mechanical stresses induced by thermal cycling.

This study shows that longer space exposure times for Al-FEP in low earth orbit results in a significant reduction in strength and elongation, providing additional insights to the existing body of work from previous NASA Service Missions. The use of small-scale testing, which enabled several tests from sections roughly only 1 cm^2 in size, made it possible to not only test this scarce and damaged material, but to report the full elastic and plastic behavior of the material since samples could be prepared without prohibitive large-scale defects. Furthermore, the use of digital image correlation as a strain measurement technique made possible the observation that prolonged exposure will shift the failure mode of the Al-FEP from ductile necking to more brittle-like fracture. Future work would be directed towards further analytical characterization of the different regions to understand compositional differences (notably the patched region), testing of other regions with different exposure histories, and a thorough assessment of the microstructure of the fracture surfaces to better understand degradation mechanisms.

Acknowledgements

The authors would like to thank Michael J. Viens and Daniel L. Polis from the NASA Goddard Space Flight Center and Kim K. de Groh from the NASA Glenn Research Center for collaboration and useful feedback. We would also like to acknowledge the Johns Hopkins University and in particular, William N. Sharpe, Jr. for cooperation and use of laboratory resources.

References

[1] J.A. Townsend, P.A. Hansen, J.A. Dever, K.K de Groh, B.A. Banks, L. Wang, C. He, *High Perform. Polym.* **1999**, *11*, 81-99.

[2] J.A. Dever, K.K. de Groh, R.K. Messer, M.W. McClendon, M. Viens, L. Len Wang, J.D. Gummow, *High Perform. Polym*. **2001**, *13*, S373-S390.

[3] K.K. de Groh, J.R. Gaier, R.L. Hall, M.P. Espe, D.R. Cato, J.K. Sutter, D.A. Scheiman, *High Perform. Polym*. **2000**, *12*, 83-104.

[4] K.K. de Groh, D.L. Waters, J.S. Mohammed, B.A. Perry, B.A. Banks, "Analyses of Hubble Space Telescope Aluminized-Teflon Insulation Retrieved After 19 Years of Space Exposure." Astrophys Space Sci Proc., Springer-Verlag Berlin Heidelberg **2013**, *32*, pp.13-26.

[5] K.J. Hemker, W.N. Sharpe Jr., *Annu. Rev. Mater. Res.* **2007**, *37*, 93-126.

[6] K. Dawes, L.C. Glover, *Physical Properties of Polymers Handbook: Effects of Electron Beam and g-Irradiation on Polymeric Materials*, AIP, New York, NY **1996**, pp. 557-576.

[7] D.J.T. Hill, S. Mohajerani, A.K. Whittaker, U. Scheler, *Polymer Int*. **2003**, *52*, 1725-1733.

[8] Y. Rosenberg, A. Siegmann, M. Narkis, S. Shkolnik, *J. of Applied Polym. Sci*. **1992,** *45*, 783-795.

[9] F.A. Rasoul, D.J.T. Hill, G.A. George, J.H. O'Donnell, *Polym. Adv. Technol*. **1998**, *9*, 24-30.

[10] U. Lappan, U. Geißler, U. Gohs, S. Uhlmann, *Macromolecular Materials and Engineering* **2009**, *294 (8)*, 510-515.

[11] G.H. Bowers, E.R. Lovejoy, *I & EC Product Research and Development*, **1962**, 89-92.

[12] Properties of Pure Metals, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, Vol 2, *ASM Handbook*, ASM International, **1990**.

[13] Gale, W.F. and T.C. Totemeier, *Smithells Metals Reference Book*, Burlington: Elsevier Science & Technology, **2003.**

[14] DuPont FEP information bulletin available from www.dupont.com

[15] J.A. Dever, *Low Earth orbital atomic oxygen and ultraviolet radiation effects on polymers* **1991**, NASA Technical Memorandum 103 711.

[16] J.A. Dever, K.K. de Groh, B.A. Banks, J.A. Townsend, J.L. Barth, S. Thomson, T Gregory, W. Savage, *High Perform. Polym.* **2000**, *12*, 125-139.

[17] D.S. Gianola, W.N. Sharpe, M. Legros, K.J. Hemker, *TMS Lett* **2004**, *1*, 149-150.

[18] http://www.mathworks.com/matlabcentral/fileexchange/12413; last accessed September 2010.

[19] H.F. Mark, in *American Chemical Society Symposium Series 229*, **1983**.

[20] J.A. Dever, K.K de Groh, B.A. Banks, J.A. Townsend, *High Perfom. Polym*. **1999**, *11*, 123-140.