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GROUND LABORATORY SOFT X-RAY DURABILITY EVALUATION OF ALUMINIZED TEFLON FEP THERMAL CONTROL INSULATION

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SUMMARY

Metallized Teflon fluorinated ethylene propylene (FEP) thermal control insulation is mechanically degraded if exposed to a sufficient fluence of soft x-ray radiation. Soft x-ray photons (4 to 8 Å in wavelength or 1.55 to 3.2 keV) emitted during solar flares have been proposed as a cause of mechanical properties degradation of aluminized Teflon FEP thermal control insulation on the Hubble Space Telescope (HST). Such degradation can be characterized by a reduction in elongation-to-failure of the Teflon FEP. Ground laboratory soft x-ray exposure tests of aluminized Teflon FEP were conducted to assess the degree of elongation degradation which would occur as a result of exposure to soft x-rays in the range of 3 to 10 keV. Test results indicate that soft x-ray exposure in the 3 to 10 keV range, at mission fluence levels, does not alone cause the observed reduction in elongation of flight retrieved samples. The soft x-ray exposure facility design, mechanical properties degradation results and implications will be presented.

1. INTRODUCTION

Aluminized and silvered Teflon fluorinated ethylene propylene (FEP) thermal control insulation has been used for many years on numerous spacecraft to reflect solar radiation from the sun as well as emit infrared radiation to maintain thermal control of spacecraft. The Hubble Space Telescope (HST) made extensive use of such insulation for thermal control purposes.

The HST was launched in April of 1990 and had servicing missions in December of 1993 and February of 1997. During the first servicing mission (SM1) samples were retrieved which had been exposed for 3.6 years in low Earth orbit. Full thickness cracking was observed in 0.127 cm thick silvered Teflon which had been exposed to approximately 20 056 equivalent sun hours (ESH) of solar radiation exposure and in 0.127 cm aluminized Teflon which had been exposed for 16 670 ESH (refs. 1 to 3).

Although the cracking occurred in areas which may have stress concentrations, the surface cracking was both unexpected and from an unknown cause. Subsequent to these observations, soft x-rays emitted from the sun during periods of solar flares have been proposed as a possible cause of embrittlement of the Teflon FEP (ref. 3). Soft x-rays emitted from the sun during solar flares are orders of magnitude more intense than during non-flare conditions as can be seen in figure 1 (ref. 4).

Although Teflon FEP absorbs relatively little solar radiation at visible wavelengths of light, it is highly absorbent in the vacuum ultraviolet to soft x-ray range from 25 eV (500 Å) to 3000 eV (4 Å) over a path length of 0.127 mm. However, at higher energies in the soft x-ray photon energy range, Teflon FEP becomes more transparent as energy increases. Figure 2, which is a plot of the x-ray transmittance of Teflon FEP as a function of energy, indicates that energies between 3 and 10 keV photons hold the potential to penetrate full thickness into 0.127 cm thick Teflon FEP and to have some interactions with the polymer chains because some finite absorption occurs (ref. 5).

Further impetus to examine the possibility that soft x-rays in this range were contributing to the embrittlement of Teflon FEP in space occurred in February of 1997 at the time of the HST second servicing mission (SM2) when the Teflon FEP had been in low Earth orbit for 6.8 years. During this servicing mission numerous cracks in the aluminized Teflon FEP thermal control insulation were observed (see fig. 3). A small sample which was removed from HST (shown in the upper area of fig. 3) and returned to Earth indicated that there was a near zero elongation to failure compared to pristine elongation of 200 to 400 percent (ref. 6). Thus, an effort was initiated to produce x-rays in the 3 to 10 keV energy range and to expose Teflon FEP samples to soft x-ray fluences typical of what would be expected in space. The purpose was to determine if a reduction in strain-to-failure could be replicated that would match what had been observed in the materials retrieved from the HST.

2. APPARATUS AND PROCEDURE

2.1 Soft X-ray Exposure System

An electron beam evaporator system was selected to produce soft x-rays in the desired energy range because the electron impact energies of the system were approximately 10 keV and the continuum soft x-ray radiation energies covered the 3 to 10 keV energy region of interest. The electron beam evaporator system was operated in a manner such that the electron current was set low enough not to melt the electron beam evaporator targets but still could produce x-rays at the proper exposure for the Teflon FEP samples. Figure 4 is a drawing of the electron beam evaporator system configured to produce soft x-rays rather than to evaporate materials.

A section view drawing of this same system is shown in figure 5. Two types of targets were used: aluminum and molybdenum. The aluminum target required careful control of the electron beam current to prevent the target from melting. As can be seen from figures 4 and 5, the electron beam evaporator targets were configured in an inclined manner to allow the highest flux of incident emitted x-rays to irradiate the FEP test materials. This was accomplished by making the top surface of the target inclined at an angle 6 to 8 degrees relative to the plane of the FEP samples being exposed. A molybdenum target with water cooling was also used in the facility because it allowed higher electron currents to contribute proportionally greater fluxes of x-rays. The higher atomic number of molybdenum compared to aluminum also produces greater x-ray flux, because the flux of continuum radiation is proportional to the atomic number (ref. 7). Both the aluminum and molybdenum targets can produce intense radiation at the characteristic K_α energies of 1.49 and 17.44 keV, respectively, if the electron energy is above those values. The operation of the electron beam soft x-ray source was ultimately conducted so that the K_α line was not possible to be emitted for the molybdenum target because the electron energy was set at 8 to 10 keV. Low energy x-rays as well as electrons were also prevented from impinging upon the FEP targets by passing the x-rays through one or two sheets of 2 μm aluminum foil. Figure 6 is a plot of the transmittance of soft x-rays through two sheets of 2 μm aluminum foil as a function of energy (ref. 5). If one multiplies the transmittance spectra of figure 6 by the continuum emission spectra for 10 keV electron impingement upon a molybdenum target, one would obtain the energy dependent flux which would impinge upon test samples as configured in figures 4 and 5.

Figure 7 shows the relative soft x-ray flux dependence upon energy for a molybdenum target with a 10 keV electron beam after passing the x-rays through 4 μm of Al foil. Although there is no K_α characteristic radiation from the molybdenum target at the energies used, there is some potential for a higher order of radiation such as L_α at 2.29 keV. However, the intensity of this characteristic line is less than the K_α, and the 4 μm thick aluminum foil attenuates the intensity of the L_α radiation such that it is only 17.7 percent of its incident flux.

The x-ray exposure tests were conducted in a manner so as to simulate the photon fluences relevant to the HST mission. The HST soft x-ray fluence in the 12.40 to 1.55 keV (1 to 8Å wavelength) range was 252.4 J/m^2 at the time of the SM2 (ref. 5). The anticipated fluence between the next planned servicing mission (SM3) in 2000 and completion of the mission in 2010, is 397.4 J/m^2 (ref. 8). Measurement of the flux in the soft x-ray experiment was performed using a Model AXUV-20 HE1 photodiode from International Radiation Detectors, Inc. which had a 100 percent quantum efficiency over the range of photon energies capable of being produced by the soft x-ray source.

2.2 Tensile Properties Testing

The pristine and soft x-ray exposed samples as well as samples retrieved from the HST first servicing mission were evaluated for tensile strength and elongation to failure by means of a tensile testing apparatus operated according to ASTM Standard D 638, using Type V "dogbone" configured tensile specimens which measured 0.953 cm long and 0.318 cm wide in the narrow test area. The strain rate for these tests was controlled to be 1.27 cm/min. The ultimate tensile strength and elongation to failure was computed by means of stored digital information as the tensile testing progressed with strain and elongation data points being recorded at a rate of 1000/sec.

3. RESULTS AND DISCUSSION

Several difficulties occurred during the testing which caused more inconvenience than impact on the results. The first complication was partial melting of the aluminum foil which occurred until the placement of the foils was changed to be sufficiently away from the targets as shown in figures 4 and 5. The second complication resulted from the electron beam current varying in spite of the fact that the current set point was fixed. This caused some uncertainty in the control of the soft x-ray fluence. However, the photodiode provided the actual number of joules/m^2 and most of the resulting exposures were reasonable approximations of the desired fluence levels. Table I shows the results of the soft x-ray exposures and the tensile properties for pristine, HST Teflon FEP and soft x-ray exposed Teflon FEP from this ground laboratory experiment. The soft x-ray fluence shown in table I for the samples exposed in the laboratory for 18,000 sec was calculated based on the crude approximation that the average electron current was the same as for the samples exposed for 390 sec and the fluence was proportionally increased with corrections for the electron beam energy, lack of Al foil and differences in atomic number of the target metal.

As can be seen in table I, the Teflon FEP samples from HST (SM1) had an elongation to failure of 41.0 percent as compared to the pristine Teflon FEP of 198.2 percent. It is important to note that the pristine Teflon FEP sample differs from the retrieved HST samples by more than simply the differences in soft x-ray exposure. This is because the retrieved samples were also subjected to electron and proton radiation, approximately 21,000 thermal cycles (–100 to 50 °C), VUV, UV and visible radiation of approximately 11,339 ESH. As one can readily see, the fluence of laboratory soft x-rays required to produce a reduction in elongation similar to that observed from the space retrieved samples (14,500 J/m^2), is 2 orders of magnitude greater than the in-space fluence.

When the FEP samples were exposed to a fluence of ~400 J/m^2 (which is greater than the SM2 fluence) as would be expected between HST SM3 in 2000 and the end of the mission in 2010, there is almost negligible reduction in tensile properties. Thus, it appears that soft x-rays in the range of 3 to 10 keV, at mission fluences do not alone cause the embrittlement or reduction in elongation to failure that has been observed on retrieved HST samples. The observed degradation must be a result of some other single cause or a synergistic combination of causes, because soft x-rays alone do not produce the observed degradation at representative fluences.

Thermal cycling has been considered as a possible synergistic contributor along with radiation exposure, to the reduction in elongation observed from space retrieved FEP Teflon. When an additional 1191 thermal cycles were added to an SM1 (11,339 ESH) sample retrieved from space, an additional 14.1 percent reduction in strain-to-failure resulted. Based on the fact that the SM1 sample, as retrieved, had 21,000 thermal cycles on it, the additional thermal cycles represents 5.7 percent of 21,000 cycles. These data appear to show a significant effect of thermal cycling on the degradation of tensile properties. One must keep in mind that, due to a very limited supply of samples, these results are for only 1 as-received and 1 thermal cycled SM1 exposed sample.

4. CONCLUSIONS

Aluminized and silvered Teflon FEP samples were exposed to soft x-rays produced by electron beam exposure of aluminum and molybdenum targets to simulate the possible mechanical properties degradation effects observed on samples retrieved from the HST servicing missions. Soft x-rays at high fluences in the energy range of 3 to 10 keV were found to produce reductions in elongation-to-failure which were similar to those observed from retrieved HST samples. Aluminized Teflon FEP samples exposed in low Earth orbit for 3.6 years on HST indicated reductions in strain-to-failure of ~79 percent. However, exposure of similar samples to ground laboratory soft x-ray at fluences representative of mission fluences produced reductions in elongation-to-failure of only ~11 percent. Thus the observed reduction in elongation-to-failure must be due to some other environmental single cause or a synergistic combination of causes.

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TABLE I.—FEP TEFLON SOFT X-RAY AND TENSILE PROPERTIES RESULTS

5 mil FEP sample description	Energy, keV	Target	Al foil barrier	Laboratory soft x-ray exposure time, sec	Soft x-ray fluence, J/m^2	UTS, MPa (psi)	Percent elongation (relative to Pristine FEP)
Pristine Al-FEP (Ave. of 9)	--	------	---	----	0	19.2 ± 1.8 (2792 ± 263)	197 ± 20 (100%)
HST Al-FEP SM1 (11,339 ESH)	--	------	---	----	[b]131.8	13.6 (1973)	41.0 (20.8%)
HST Al-FEP SM1 (11,339 ESH) + 1191 thermal cycles (-100 to +50 °C)	--	------	---	----	[b]131.8	14.7 (2136)	26.9 (13.7%)
Soft X-ray Al-FEP	8	Angled Mo (No cooling)	None	18,000	[c]≈14,500	14.9 (2156)	20.4 (10.4%)
Soft X-ray Al-FEP SM3-2010 exposure (Ave. of 16)	10	Angled Mo Watercooled	[a]4 μm	390 ± 51	[d]457 ± 50	16.1 ± 1.3 (2349 ± 194)	176 ± 25 (89.3%)
Pristine Ag-FEP	--	------	---	----	0	18.9 ± 2.5 (2741 ± 360)	539 ± 95 (100%)
Soft X-ray Ag-FEP (Ave. of 5)	8	Angled Al (No cooling)	None	18,000	[c]≈4100	13.7 ± 0.3 (1981 ± 42)	141 ± 31 (26.2%)

[a] Top layer of Al foil barrier degraded.

[b] Based on in-space measurements on the GOES spacecraft.

[c] Based on photodiode measurements from the 390 sec exposure, below, corrected for energy and lack of Al foil barrier and target atomic number.

[d] Based on photodiode measurements.

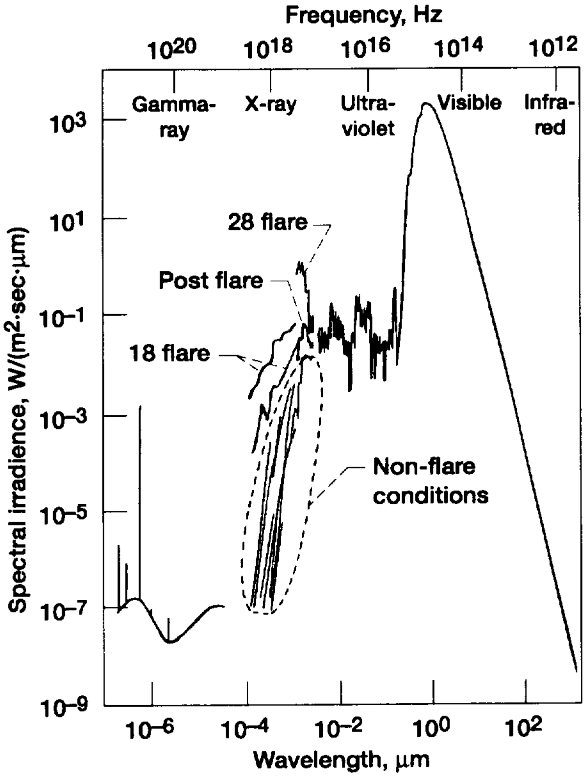

Figure 1.—Solar flux as a function of wavelength and frequency.

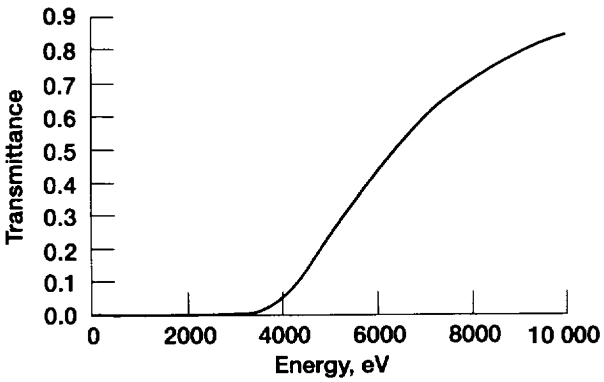

Figure 2.—Energy dependence of transmittance of soft x-rays through 0.127 mm thick Teflon FEP.

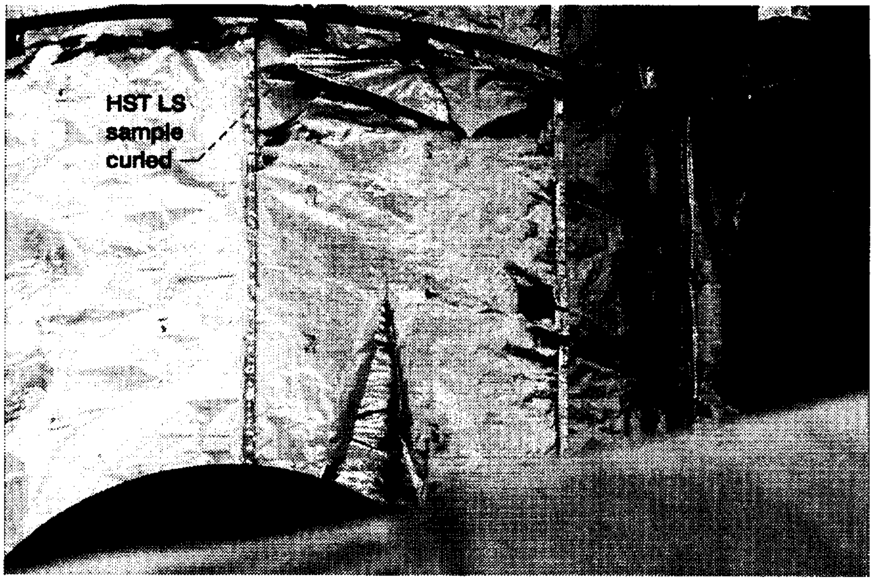

Figure 3.—Photo taken during HST servicing mission 2 showing cracked aluminized Teflon FEP.

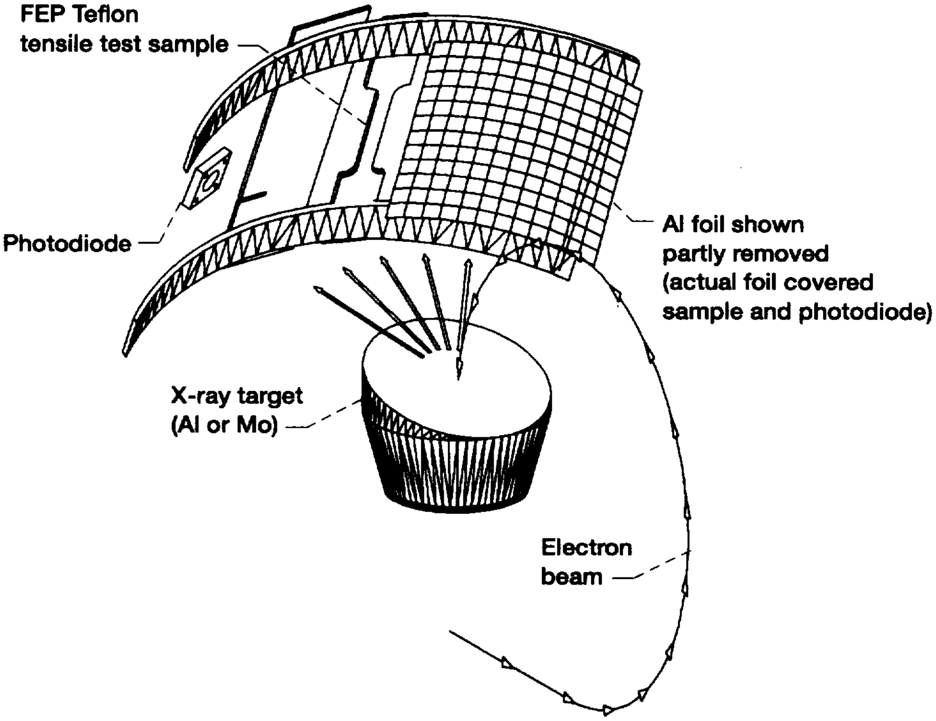

Figure 4.—Drawing of electron beam evaporator system configured to expose Teflon FEP sample to soft x-rays.

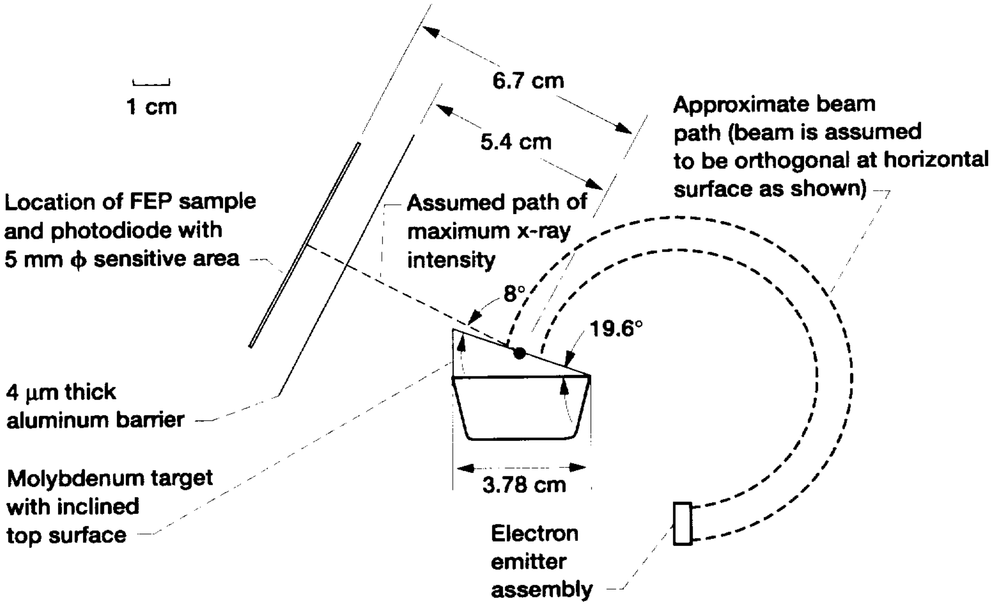

Figure 5.—Section view drawing of electron beam evaporator system used to expose Teflon FEP sample to soft x-rays.

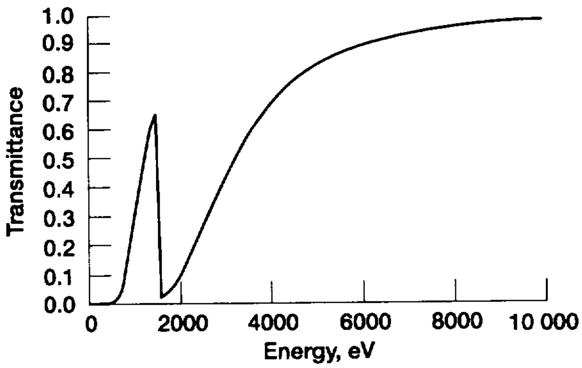

Figure 6.—Plot of the transmittance of soft x-rays through two sheets of 2 μm aluminum foil as a function of energy.

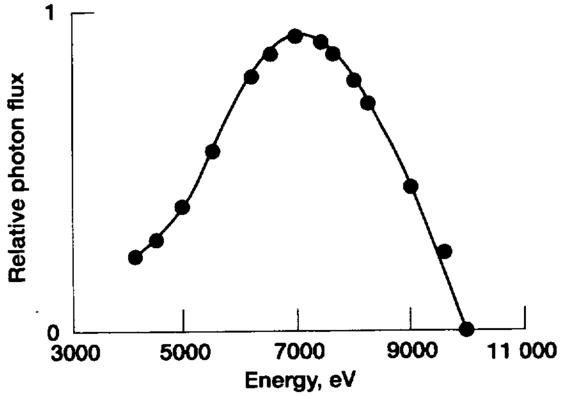

Figure 7.—Relative soft x-ray flux dependence upon energy for a molybdenum target with 10 keV electrons and passing the x-rays through 4 μm of aluminum foil.

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